Optimizing properties of gypsum mixtures through modifications of construction gypsum board waste

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Summary

The article presents the results of utilizing modified gypsum board waste from construction and demolition debris, obtained from a real construction site and processed using a developed recycling line for construction gypsum board. The research focused on examining the impact of modification (in terms of grinding fineness) on the resulting properties of dry gypsum mixtures, with replacements in the mixture ranging from 10%, 25%, to 50% by weight for gypsum binder. Parameters such as bulk density, flexural strength, and compressive strength after 7 days from the sample production were monitored. The results indicate that, with appropriate modification, it is possible to efficiently substitute a portion of gypsum binder in dry gypsum mixtures with modified gypsum board recyclate.

Keywords*: recycling, construction and demolition waste, gypsum, gypsum board.*

Introduction

The global challenge of recycling building materials is gaining worldwide attention. While concrete is often spotlighted as a recyclable material, it is essential to recognize that various widely used materials require recycling and further processing. However, the recycling of certain building materials, including gypsum board waste, encounters challenges similar to waste from other industries, often leading to landfilling[1,2].

In recent years, the focus on dry construction, particularly in gypsum board systems, has increased. The rising demand for gypsum boards has resulted in a corresponding increase in waste generated from production, construction, reconstructions, and demolitions[2]. Presently, the majority of gypsum board waste ends up in landfills, with only a relatively small portion being reused[3].

One aspect often overlooked in recycling solutions for gypsum boards and gypsum products is that gypsum is a unique material. It is 100% recyclable indefinitely[4]. From a construction perspective, gypsum has been a valuable material for several thousand years (e.g., in ancient Egypt) due to its excellent thermal-technical properties, mechanical strength, and fire resistance. Gypsum also offers the advantage of being modifiable through additives and admixtures to enhance its properties[5].

Gypsum binder (stucco, calcium sulfate hemihydrate $CaSO_4 \cdot 1/2\ H_2O$) does not occur naturally (only as $CaSO_4$ anhydrite or $CaSO_4 \cdot 2H_2O$ calcium sulfate dihydrate). It is produced by subjecting calcium sulfate (either natural or synthetic) to high temperatures in a process called calcination, typically occurring at temperatures above 180 °C, releasing water from gypsum (calcium sulfate dihydrate) at temperatures exceeding 150 °C[6].

The fundamental equation for gypsum production is expressed as follows (Equation (1)):

$$CaSO_4 . 2H_2O + HEAT \rightarrow CaSO_4 . 1/2\ H_2O + 3/2\ H_2O \quad (1)$$

Rehydration of gypsum, leading to the formation of hardened gypsum, occurs upon mixing with water, as per Equation (2):

$$CaSO_4 . 1/2\ H_2O + 3/2\ H_2O \rightarrow CaSO_4 . 2\ H_2O + HEAT \quad (2)$$

According to these equations, gypsum can be recycled multiple times at relatively low costs, involving high temperatures (calcination) and grinding to achieve the desired grain size. The properties of the resulting calcined gypsum depend directly on the grain size and the extent of calcination (amount of

uncalcined gypsum grains). Both grain size and the presence of uncalcined gypsum grains influence the hydration process. Smaller grain sizes increase the specific surface area, accelerating the hydration reaction[7].

The contribution is primarily based on projects funded by the Technology Agency of the Czech Republic (TA ČR), specifically Trend 3 under the grant number FW03010054, titled "Recycling and Transformation of Construction Gypsum Board Waste into New Building Products and Applications with Added Value" (2021-2023). Additionally, support is acknowledged from another TA ČR project, Environment for Life 3 under the grant number SS03010302, titled "Development of Effective Tools for Minimizing the Generation of Construction and Demolition Waste, its Monitoring, and Reutilization" (2021-2023). The ongoing research is expected to continue under the framework of the HORIZON 2020+ project with the grant number 101058580, titled "Automated Solutions for Sustainable and Circular Construction and Demolition Waste Management" (2022-2026).

Materials and samples

The tested mixtures were composed of varying ratios of gypsum binder and recycled material based on gypsum board waste. The chosen gypsum binder for testing was a calcined gypsum-based binder produced from energy gypsum, referred to as REF (reference). The gypsum binder consisted of hemihydrate of calcium sulfate with a purity of 98 wt.%. The sample waste material was selected from gypsum board Type A waste according to (ČSN) EN 520[8], i.e., standard gypsum board. The waste material originated from the sorting of construction and demolition waste from the construction of family houses in Prague.

The recycled material was obtained by processing gypsum board waste using the Lavaris LAV 400/IR-SD recycling line developed by Lavaris s.r.o. in Libčice nad Vltavou[1]. For coarse processing and separation of cardboard and other (construction) impurities, a primary crusher was initially used, and the fraction 0/1 mm was separated from it (labeled as REF 0). The coarse recyclate REC 0 consisted of gypsum with a purity of around 90 wt.%, with the remainder comprising impurities in the form of cardboard remnants and various forms of calcium sulfate, which are challenging to define.

The coarse recyclate REC 0 was subsequently processed using a high-speed (high-energy) mill at various grinding levels. In the case of recyclate REC 1, it was a single-level grinding; in the case of recyclate REC 2, it was a two-level grinding, and in the case of recyclate REC 3, it was a three-level grinding. In all cases, the same grinding elements (pins) and grinding speed (100 m/s) were used.

The main task was to verify the efficiency of multiple grinding treatments on the resulting properties of the modified gypsum recyclate and its influence on the properties of the hardened gypsum paste concerning the amount of replacement used for the reference gypsum. During grinding, heat is generated due to friction, resulting in partial calcination of the recyclate. According to XRD phase analysis, recyclate REC 1 contained an unmeasurable amount of hemihydrate of calcium sulfate, REC 2 contained approximately 2 wt. % hemihydrate of calcium sulfate, and REC 3 contained from 2 to 5 wt. % hemihydrate of calcium sulfate.

The grain characteristics of the individual materials used (reference and modified recyclate) are evident in Figure 1, showing the grain size curves of the materials used. The results indicate that grinding treatment achieved a finer material than that of the reference gypsum binder. Each subsequent grinding level resulted in a finer material. Minimal differences were observed between the second and third grinding levels. The recyclate once grind (REC 1) had a grain size curve most similar to the reference gypsum binder (REF).

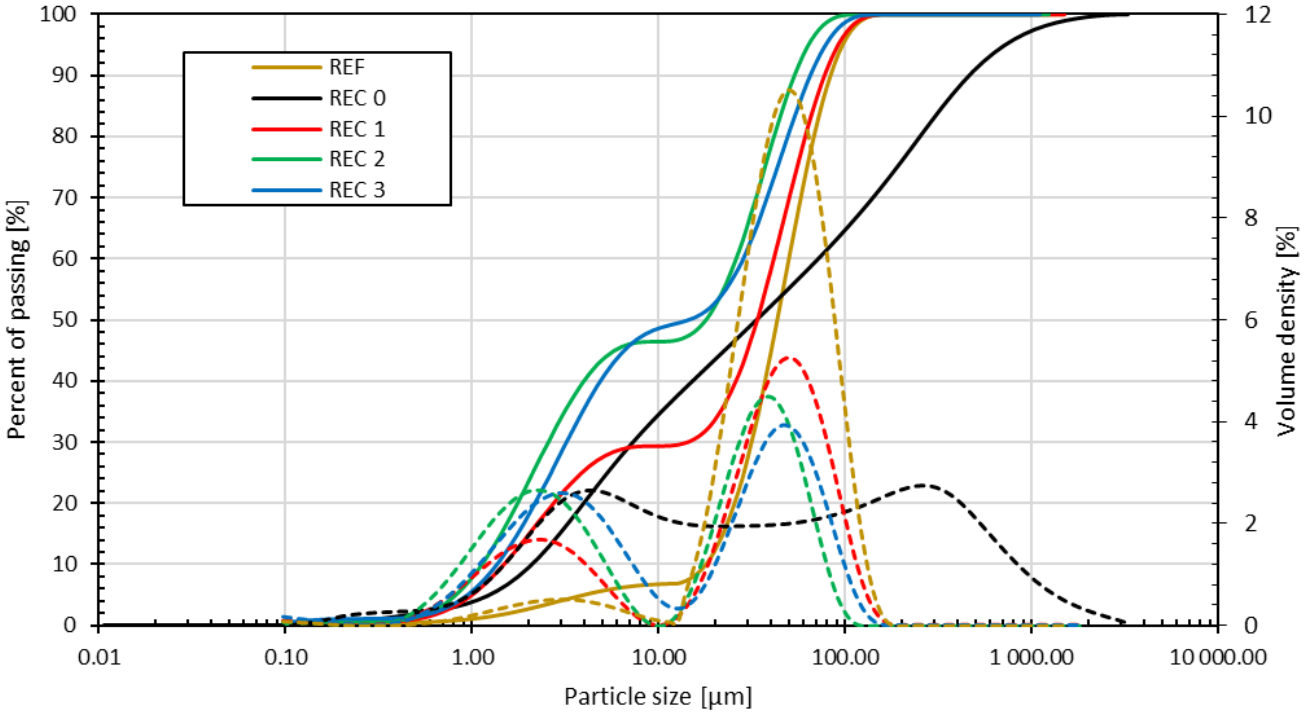

Figure 1: Comparison of the percent of passing and Volumetric density of the tested samples.

The structure of individual $CaSO_4$ crystals was characterized using electron microscopy. Scanning Electron Microscopy (SEM) was conducted with the FEG SEM Merlin from ZEISS, situated in the Electron microscopy laboratory at the University Centre for Energy Efficient Buildings. In Figure 2, the distinctive grain characteristics of the recyclate are compared with the reference gypsum binder.

Figure 2 illustrates that, during grinding, a larger quantity of fine particles is generated compared to the reference binder, validating the grain size curve depicted in Figure 1. Additionally, the impact of grinding is observable, resulting in a mild disruption of the gypsum crystal structure. This effect is attributed to the recycling process itself, consistent with findings by A. Erbs et al. in their work, where they determined three recycling cycles as the maximum limit before the crystals become unusable[9].

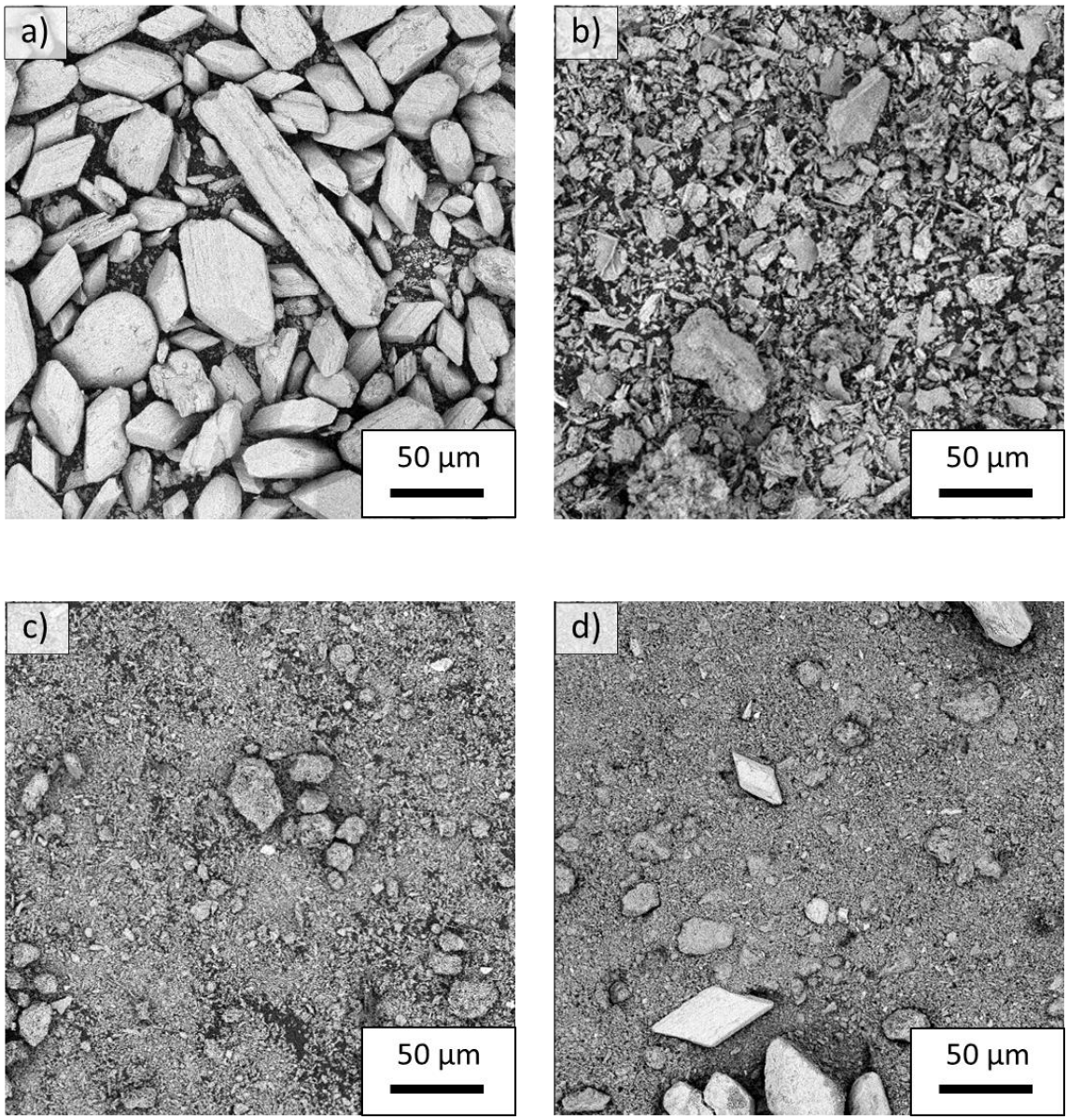

Figure 2: SEM images of the microstructure of the used gypsum-based powder materials, BSE electron detector, magnified 2 k×: a) REF, b) REC 1, c) REC 2, d) REC 3

Table 1 presents the composition of individual mixtures, with replacement amounts of the reference gypsum chosen at 10, 25, and 50 wt. %. Each mixture comprised six samples with dimensions of 40 × 40 × 160 mm, cast into rectangular molds. After casting, these samples were stored in molds in the laboratory at a temperature of 22 °C. Once removed from the mold, the samples were allowed to rest in the laboratory environment for 5 days. Subsequently, the samples were placed in a drying room and artificially dried at a temperature of 40°C.

For ease of mixture processability, a water ratio (water/gypsum) of 1.2 was used for the coarse recyclate REC 0, and for the fine recyclate (REC 1, REC 2, and REC 3), a water ratio of 1.4 was employed. The comparative parameter was the workability of the mixture with a 50 wt. % recyclate content. The workability was measured according to ČSN 72 2301[10] using a modified procedure for determining the standard consistency, with the resulting spread being 250 mm. The high water content resulted in a slow-setting binder, for which the setting time is not standardized according to ČSN 72 2301[10]. For this reason, it was not measured.

Table 1: Composition of the tested mixtures.

Set	Gypsum binder REF [g]	Recycled gypsum REC 0 [g]	Recycled gypsum REC 1 [g]	Recycled gypsum REC 2 [g]	Recycled gypsum REC 3 [g]	Water [g]	w/g [-]
Ref	1000	0	0	0	0	1200	1.2
R0_10	900	100	0	0	0	1200	1.2
R0_25	750	250	0	0	0	1200	1.2
R0_50	500	500	0	0	0	1200	1.2
R1_10	900	0	100	0	0	1200	1.4
R1_25	750	0	250	0	0	1400	1.4
R1_50	500	0	500	0	0	1400	1.4
R2_10	900	0	0	100	0	1400	1.4
R2_25	750	0	0	250	0	1400	1.4
R2_50	500	0	0	500	0	1400	1.4
R3_10	900	0	0	0	100	1400	1.4
R3_25	750	0	0	0	250	1400	1.4
R3_50	500	0	0	0	500	1400	1.4

Experimental methods

The samples were destructively tested after 7 days to determine the flexural and compressive strength using the FHF Strassentest device. The flexural strength was determined by a three-point bending test. The flexural strength testing was controlled by a constant speed of 0.5 mm/min. The distance between supports for the three-point bending test was 100 mm. The resulting flexural strength was calculated using Equation (3):

$$f_b = \frac{3 . F_{b,max} . L_s}{2 . b . a^2} \quad (3)$$

where $F_{b,max}$ is the maximum force during bending (determined during the test), L_s is the span between supports for the three-point bending test (in our case, 100 mm), b is the width of the sample, and a is the height of the sample.

The compressive strength was determined using uniaxial compression testing. Uniaxial compression tests were conducted on the fractured halves of the samples after the flexural test, with effective dimensions of 40 × 40 × 40 mm. Compressive strength testing was controlled at a constant speed of 1 mm/min. The resulting compressive strength was calculated using Equation (4):

$$f_c = F_{c,max}/ab \quad (4)$$

where $F_{c,max}$ is the maximum force during compression, and *a* and *b* represent the height and width of the sample, respectively.

All tests were conducted in accordance with the ČSN 72 2301 standard[10]. The resulting average values for compressive strength and flexural strength were calculated by excluding the highest and lowest values obtained during testing. From the measured values determined during the destructive testing, the bulk density and volumetric changes were subsequently calculated.

Results and discussion

In Figure 3, average bulk density values are compared with indicated standard deviations for samples aged 7 days after drying. The comparison reveals that, for material R0, the coarsely processed material with a fraction of 0/1 mm, there was no noticeable change in bulk density with increasing replacement content. For all mixtures with R0 replacement, it decreased from approximately 900 kg/m³ to 700 kg/m³.

Significant changes in bulk density values depending on the replacement content were observed for recycled materials R1 and R3. For the material R3 with 10% replacement, a value of 750 kg/m³ was determined, increasing to 1500 kg/m³ for 50% replacement, doubling the original value. During the drying of samples with replacements R1, R2, and R3, substantial volumetric changes occurred.

The reference material REF is composed of 98 wt. % hemihydrate of calcium sulfate, while the recycled material REC 0 is significantly coarser and has a markedly lower specific surface area, as evidenced by the particle size distribution (Figure 1). It consists of 90 wt. % gypsum (dihydrate of calcium sulfate). Primarily, in the dry gypsum mix, it acts as an inert filler but also serves as crystallization centers at the beginning of the hydration process (i.e., setting and hardening of gypsum paste) due to its fine particles.

Volumetric changes are relatively small, resulting in a slight decrease in bulk density values. For other mixtures, which are markedly finer than the reference material and consequently have a significantly higher specific surface area, the influence of replacements is pronounced.

During the initial mixing of homogenized and dry mixtures, in the case of material R3 with a ratio of 50/50 hemihydrate/dihydrate of calcium sulfate, a significant change in the water-to-gypsum binder ratio occurred. Compared to the reference set REF, this led to a considerable delay in the setting and hardening process. In the REF set, samples could be demolded after 20 minutes from mixing with water, exhibiting slight expansion typical for gypsum samples. After 20 minutes, the samples already had sufficient compressive strength, reaching their final strength after 7 days, with minimal shrinkage.

For REC 3 samples, demolding was possible only after 24 hours, and volumetric changes associated with drying continued for several days. Another effect during hydration was a reduction in the development of hydration heat, both in terms of the time course and the values of specific heat during hydration.

For sets R1, R2, and R3 with a 50/50 wt. % gypsum binder/recyclate ratio, it can be assumed that the water ratio allowed the formation of much larger crystals of calcium sulfate, which could form over a significantly longer time. Simultaneously, part of the mixing water was adsorbed by the hemihydrate from the recyclate, enveloping the grains and gradually leading to its dissolution. The solubility of dihydrate of calcium sulfate in water is approximately 0.26 g/100 g at 20 °C. Gradually, especially after demolding, the evaporation surface area increases, causing drying, while a fairly high-quality internal structure is gradually forming. After drying, the samples exhibit some deformation but remain relatively compact even with volumetric changes of up to 50%. B. Hansen and colleagues also arrived at similar results, addressing various influences of additives and sulfur content on the resulting quality of the formed gypsum crystal[11].

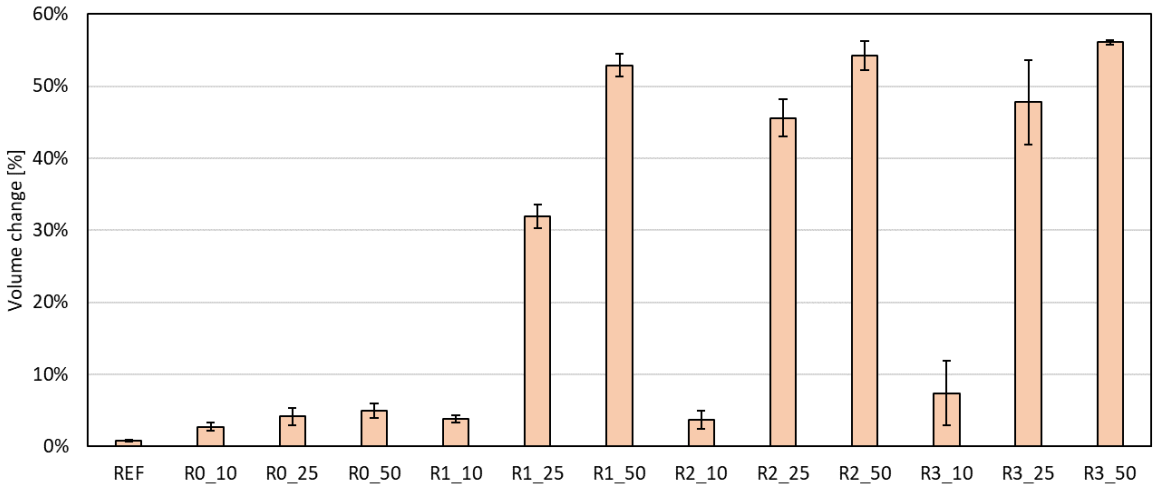

Figure 3: Comparison of the volume change of the tested samples (with standard deviations).

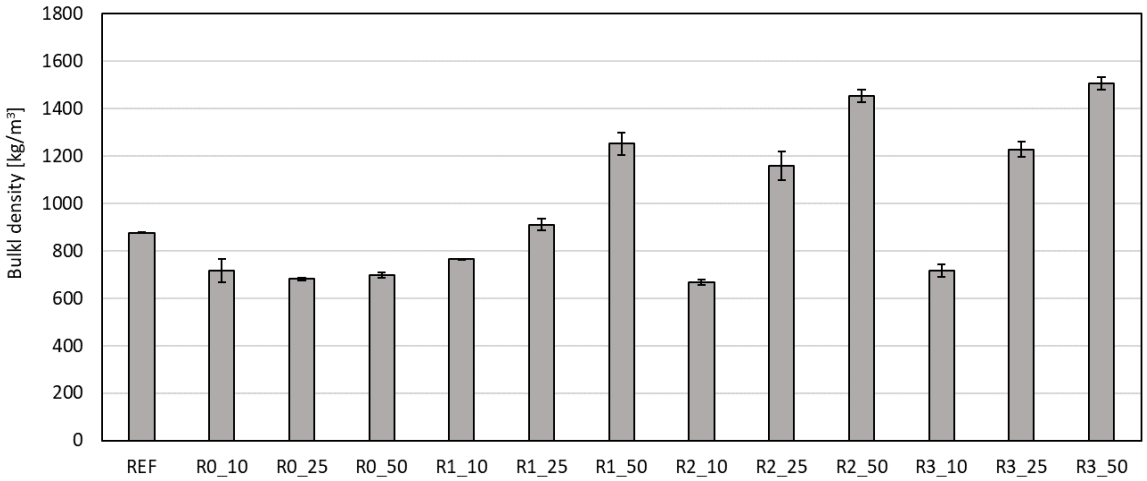

Figure 4: Comparison of bulk density of the tested samples (with standard deviations).

In Figure 5, average flexural strength values at 7 days are compared for the tested samples. Despite the high shrinkage values, it is noteworthy that relevant flexural tensile strength values were determined. Cracks did not significantly impact these values, although the standard deviations are higher than typical for hardened gypsum slurry (as seen in the reference set REF).

In comparison to the reference set, the R0 set with coarse recyclate experienced an expected decrease, with values dropping by up to a quarter at 50% replacement. For recycled materials REC 1, REC 2, and REC 3, a 10% replacement led to a decrease in flexural strengths ranging from 50% to approximately 80%. At a 25% replacement in the R1 set, values remained the same, while the R2 set experienced an increase of approximately 30%, and for the R3 set, the flexural tensile strength more than doubled.

With a 50% replacement in the R1 set, the value is comparable to the REF material, R2 showed an increase of about 40%, and the R3 set exhibited a doubling of flexural tensile strength. Furthermore, it is evident that the flexural strength values correspond to the bulk density values of samples or individual sets, showing their dependence on the amount of replacement with recyclate.

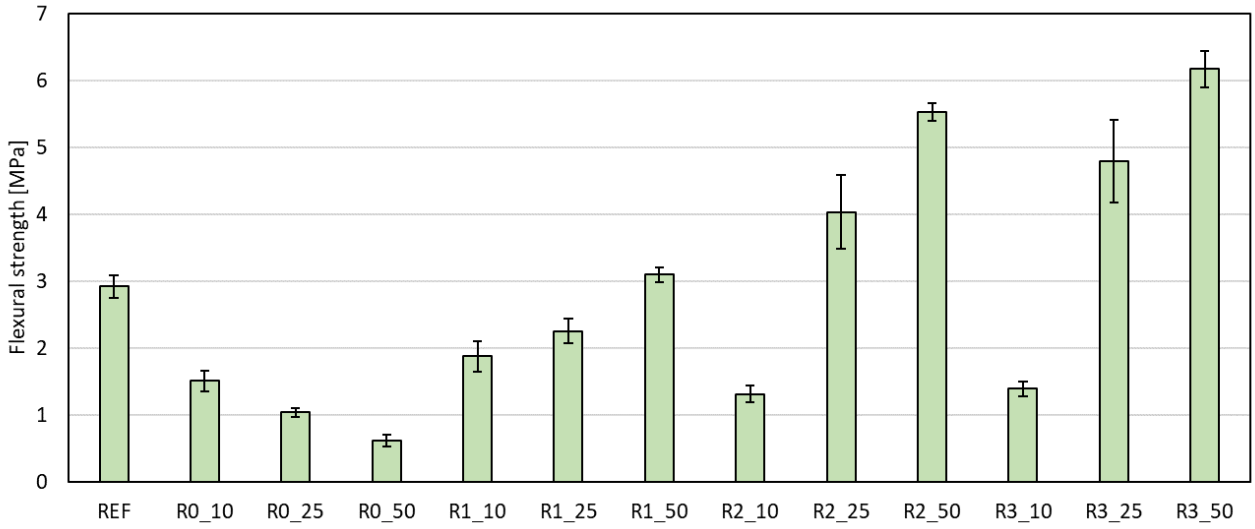

Figure 5: Comparison of the flexural strength of the tested samples (with standard deviations).

In Figure 6, average compressive strength values at 7 days are compared for the tested samples. Similar to flexural tensile strength, it is important to note that despite the high shrinkage values, relevant compressive strength values were determined.

In comparison to the reference set REF, the recycled material R0 experienced an expected decrease, with values dropping by up to a quarter at 50% replacement. For recycled materials REC1, REC2, and REC3, a 10% replacement led to a decrease in compressive strength by approximately half. At a 25% replacement in all three mixtures, there was an increase in compressive strength. With a 50% replacement in the R1 set, the value is comparable to the REF material, R2 showed an increase of more than double, and the R3 set exhibited a 2.5 times increase in compressive strength. Similar to flexural tensile strength, it is evident that compressive strength corresponds to the values of bulk densities of samples.

In the case of coarser grain size replacements, other authors achieved similar results[12]. In the case of using a larger amount of finely ground dihydrate calcium sulfate, there are no known publications because it leads to the formation of a large number of nucleation centers, and the mixture becomes unprocessable. Often, even a content below 1% by weight creates a completely unusable mixture. In our case, we circumvented this issue by using a higher water ratio[13].

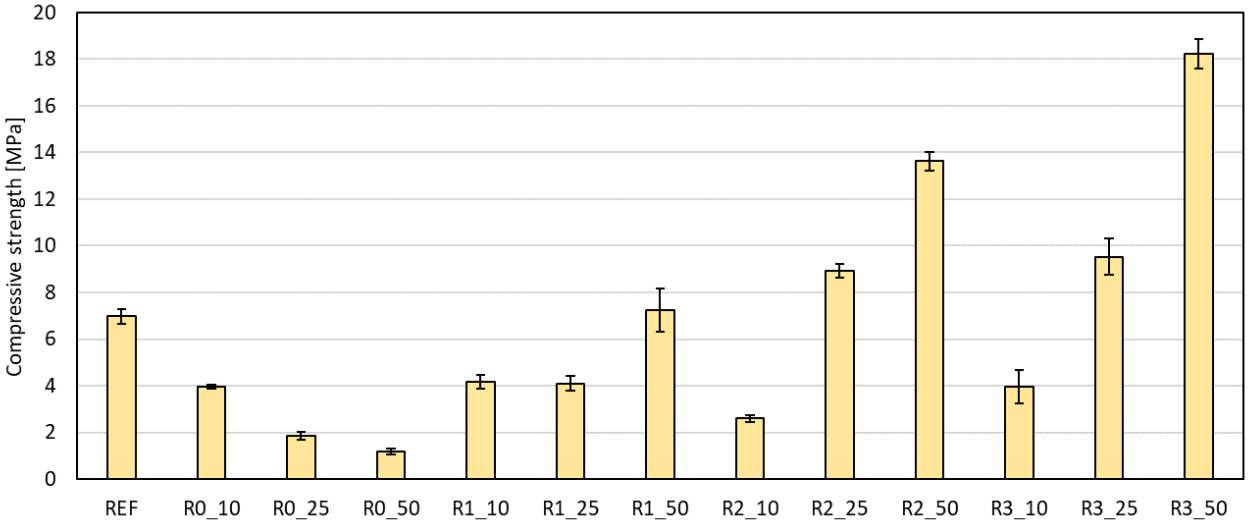

Figure 6: Comparison of the compressive strength of the tested samples (with standard deviations).

Conclusion

In conclusion, this study has emphasized the impact of the chosen recycling method on the properties of gypsum mixtures. High-speed grinding on the recycling line resulted in material refinement and increased specific surfaces. The recycled material, when used as a substitute for gypsum, plays a dual role as both a filler and a crystallization center. Despite significant shrinkage, a solid structure was achieved, albeit with high fragility. Multivariable grinding led to increased flexural and compressive strength with a growing specific surface. The material with coarse recycled content exhibited strength reduction, particularly at higher replacements.

Overall, the scientific approach to recycling construction gypsum board waste paves the way for a more sustainable and efficient utilization of these materials in construction.

Acknowledgement

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Optimalizace vlastností sádrových směsí prostřednictvím úprav stavebního sádrokartonového odpadu

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Souhrn

V příspěvku jsou prezentované výsledky využití upraveného recyklátu na bázi sádrokartonu ze stavebního a demoličního odpadu, který byl získán z reálné stavby a upravený pomocí vyvinuté linky na recyklaci stavebního sádrokartonu. V rámci výzkumu byl testován vliv úpravy (z pohledu jemnosti mletí) na výsledné vlastnosti suché sádrové směsi, náhrada ve směsi byla 10, 25 a 50 hm. % za sádru (resp. sádrové pojivo). Sledována byla objemová hmotnost, pevnost v tahu za ohybu a pevnost v tlaku po 7 dnech od vyrobení vzorků a smrštění. Z výsledků je patrné, že při vhodné úpravě, je možné efektivně nahradit část sádrového pojiva v suché sádrové směsi upraveným sádrokartonovým recyklátem.

Klíčová slova: *recyklace, stavební demoliční odpad, sádra, sádrokarton*