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Edited by Rashmi Laddha
E-mail: drrashmirdaga@gmail.com
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Evaluation of compressive strength and dimensional stability in recycled Type III dental stone mixtures: An *in vitro* study

Devupalli Sudha Madhuri, Gujjalapudi Mahalakshmi, Nibha Kumari Singh*, Sabakousar Patil, Anjaneyulu Gasthi & Udayagiri Madhusudhana Rao

Department of Prosthodontics and crown and Bridge Government Dental College and Hospital, Kadapa, Andhra Pradesh, India; *Corresponding author

Affiliation URL:
https://gdchkadapa.com/

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Author contact:
Devupalli Sudha Madhuri - E-mail: sudhamadhuridevupalli75@gmail.com
Gujjalapudi Mahalakshmi - E-mail: dr.gmahalakshmi@gmail.com
Nibha Kumari Singh - E-mail: drnibhaksingh@gmail.com
Sabakousar Patil - E-mail: sabakousarpatil@gmail.com
Anjaneyulu Gasthi - E-mail: anjimds@gmail.com
Udayagiri Madhusudhana Rao - E-mail: madhu.6c999@gmail.com

Abstract:
The reuse of dental stone is important for cost reduction and sustainability, but its effect on material properties remains unclear. Therefore, it is of interest to evaluate the compressive strength and dimensional stability of recycled Type III dental stone and its mixtures with standard dental stone in different ratios. Recycled gypsum was prepared from preclinical casts through pulverization and calcination and five groups were tested using a universal testing machine and stereomicroscope. The results showed that compressive strength ranged from 14.39 MPa (recycled) to 51.74 MPa (control) and dimensional change ranged from 0.0240 to 0.3300, with both parameters increasing significantly with higher proportions of standard dental stone ($p = 0.000$). Thus, recycled dental stone alone showed inferior properties, whereas its combination with standard gypsum improved performance, indicating that partial replacement can be used without major compromise in quality.

Keywords: Recycled gypsum, Type III dental stone, compressive strength, dimensional stability, dental recycling

Background:
Gypsum products are among the most widely used materials in dentistry, particularly for the fabrication of diagnostic casts, working models and dies. Their dimensional accuracy, mechanical strength and surface detail reproduction play crucial roles in ensuring the success of prosthodontic procedures and the precision of dental restorations. The behavior of gypsum under varying environmental and processing conditions has been the subject of extensive investigation for decades. Early studies by Sweeney and Taylor **[1]** demonstrated that dental plaster and stone undergo measurable dimensional changes during setting and storage, influencing the accuracy of dental models. These dimensional alterations, caused by crystal growth and water evaporation, directly affect the fit and reliability of prosthetic appliances, emphasizing the need for understanding and control over gypsum properties during manipulation. Type III dental stone, commonly known as dental stone or hydrocal is widely used due to its optimal balance between strength and expansion. However, its performance is highly dependent on processing parameters such as water-to-powder ratio, mixing technique and calcination method. The thermal dehydration process of gypsum—where calcium sulfate dihydrate is converted into hemihydrate form—is a critical factor in determining its physical characteristics. Hudson-Lamb *et al.* **[2]** reported that variations in the thermal dehydration pathway of natural gypsum significantly influence the crystal morphology and rehydration potential, thereby altering the strength and setting expansion of the final product. Proper control of the calcination temperature and time is therefore essential to obtain consistent hemihydrate quality suitable for dental use. In addition to calcination, mechanical mixing parameters also affect the density and homogeneity of dental stone. Azer *et al.* **[3]** found that vacuum mixing enhances the physical properties of gypsum materials by reducing air voids, leading to improved compressive strength and surface smoothness compared to hand mixing. This finding highlights the importance of standardized mixing protocols for ensuring reproducible results in laboratory and clinical applications. Moreover, the microstructure and thermal stability of gypsum and its derivatives have been extensively analyzed to understand their performance under different conditions. Yu and Brouwers **[4]** studied the thermal properties and microstructural transformations of gypsum during dehydration, providing insights into its stability and strength retention. Similarly, Michalakis *et al.* **[5]** emphasized that even high-strength gypsum products exhibit delayed linear dimensional changes over time, which can compromise the accuracy of definitive casts if not properly managed. Collectively, these studies underscore that the physical and dimensional behavior of gypsum materials is governed by a complex interplay of thermal, chemical and mechanical factors. Therefore, it is of interest to examine the evaluation of compressive strength and dimensional stability in recycled Type III dental stone mixtures.

Methodology:
This *in vitro* study was conducted to evaluate the compressive strength and dimensional stability of recycled Type III gypsum and to compare it with standard Type III gypsum when mixed in different ratios. The investigation was carried out in the Department of Prosthodontics at the Government Dental College and Hospital, Kadapa, Andhra Pradesh. The materials and equipment used included custom-made metallic moulds for compressive strength testing (20 mm in diameter and 40 mm in length) and dimensional stability testing (40 mm in diameter), fabricated according to ADA Specification No. 19. Additional materials comprised preclinical dental stone casts, Type III gypsum, a digital weighing machine (SF 400, Neelkanth Health Care Pvt. Ltd, Rajasthan, India), measuring cylinder (Chitra Scientific Industries), rubber bowl and spatula, pulverization machine (SS Pulveriser Pvt. Ltd), hot air oven (Technico Biomedical Products Ltd), autoclave (Ideal Medical Systems, Model AC-700 Automatic), universal testing machine (ASTM

D695-15), stereomicroscope (G2 Mark RE–50X with HD camera) and a vacuum mixer (Unident Pvt. Ltd). Preclinical dental stone casts were collected from the Department of Prosthodontics and disinfected before use. The casts were broken into smaller fragments and subjected to pulverization using a pulverization machine to obtain a fine powder with a particle size of less than 0.040 mm. The powdered material, initially in dihydrate form, was then calcined to convert it into hemihydrate gypsum. This process involved drying the powder in a hot air oven at 105°C for one hour, followed by autoclaving at 128°C for 40 minutes, after which the powder was allowed to cool and dry. Stainless steel split moulds were fabricated for specimen preparation one with dimensions of 20 mm in diameter and 40 mm in length for compressive strength testing and another with a 40 mm diameter and 5 mm depth for dimensional stability testing. The latter mould was engraved with two vertical lines 25 mm apart and three horizontal lines 5 mm apart using a fiber laser with a depth of 0.5 mm, facilitating dimensional measurement. Specimens were prepared according to ADA Specification No. 25 by mixing 30 mL of water with 100 g of powder in a vacuum mixer. Five groups of specimens were fabricated: Group 1 consisted of standard dental stone (control), Group 2 of recycled dental stone, Group 3 of a 1:1 ratio of recycled to standard dental stone, Group 4 of a 2:3 ratio and Group 5 of a 3:1 ratio. For each group, 20 samples were prepared. The corresponding quantities of recycled and standard dental stone were accurately weighed using an electronic scale, mixed with water and homogenized under vacuum before being poured into the moulds. After setting, the specimens were carefully retrieved and stored under controlled conditions. Compressive strength testing was performed using a universal testing machine in accordance with ASTM D695-15 standards. Each specimen was positioned vertically and compressive load was applied until failure. The maximum load at fracture was recorded for all specimens. Dimensional stability was evaluated using a stereomicroscope equipped with a high-definition camera. Each specimen was placed on the stage plate and the distance between the two vertical reference lines (D1–D2) at line B was measured. The dimensional change was calculated using the formula: $\Delta L = 100 \times [(L1 - L2)/L1]$, where L1 represents the original line distance on the metal die and L2 the corresponding distance measured on the specimen. All data for compressive strength and dimensional stability were recorded, tabulated and subjected to statistical analysis for comparative evaluation among the groups.

Results:

The data obtained from the study were compiled and entered into Microsoft Excel 2016 and statistical analysis was performed using the Statistical Package for Social Sciences (SPSS version 20). Descriptive statistics were expressed as mean and standard deviation. Normality of the data was verified using the Shapiro–Wilk test, confirming a normal distribution. One-way ANOVA followed by the Post-Hoc Tukey test was applied to compare the compressive strength and dimensional change among the experimental groups, with the level of significance set at $p < 0.05$. The comparison of compressive strength among the five study groups showed a significant variation (**Table 1**). The mean compressive strength values for the control, recycled dental stone, recycled: Standard stone (1:1), standard: recycled (2:3) and standard: recycled (3:1) groups were 51.7415 ± 0.89678, 14.3985 ± 0.72980, 24.4810 ± 0.71444, 34.6045 ± 0.92251 and 41.3195 ± 0.78479 MPa respectively, with a statistically significant difference (p = 0.000). Post-Hoc Tukey analysis (**Table 2**) revealed that the compressive strength of the control group differed significantly from all other groups. Recycled dental stone also showed a significant difference when compared with the 1:1, 2:3 and 3:1 mixture groups. Additionally, significant differences were observed between the recycled: standard 1:1 group and both 2:3 and 3:1 groups, as well as between the 2:3 and 3:1 groups. A graphical comparison (**Figure 1**) also demonstrated a progressive increase in compressive strength with higher proportions of standard dental stone in the mix. The dimensional change values among the groups also exhibited significant variation (**Table 3**). The mean dimensional change for the control, recycled dental stone, recycled: standard 1:1, standard: recycled 2:3 and standard: recycled 3:1 groups were 0.3300 ± 0.03866, 0.0240 ± 0.02010, 0.0440 ± 0.01231, 0.0740 ± 0.01465 and 0.1740 ± 0.02683 respectively, showing a statistically significant difference (p = 0.000). Post-Hoc Tukey analysis for dimensional stability (**Table 4**) revealed a statistically significant difference between the control group and all other groups. Recycled dental stone showed significant differences with the 2:3 and 3:1 groups but not with the 1:1 group (p > 0.05). Significant differences were also noted between the 1:1 group and both 2:3 and 3:1 ratios, as well as between the 2:3 and 3:1 groups. Overall, the results indicated that both compressive strength and dimensional stability increased progressively with a higher proportion of standard dental stone. The control group (100% standard dental stone) demonstrated the highest compressive strength and dimensional change values, while the recycled dental stone alone showed the lowest. Intermediate groups (1:1, 2:3 and 3:1 ratios) showed proportionate improvement in both parameters, confirming the significant influence of mixing ratio on the physical properties of Type III dental stone.

Table 1: Comparison of compressive strength among the study groups

Groups	Mean	Std. Deviation	F value	p value
Control	51.7415	0.89678	6345.07	0.000*
Recycled dental stone	14.3985	0.72980		
Recycled: standard stone 1:1	24.4810	0.71444		
Standard stone: recycled 2:3	34.6045	0.92251		
Standard stone: recycled 3:1	41.3195	0.78479		

One-way ANOVA, p < 0.05 significant

Table 2: Multiple comparison using Post-Hoc Tukey test for compressive strength

Groups	Mean Difference	Sig.
Control vs Recycled dental stone	37.34300*	0.000*
Control vs Recycled: standard stone 1:1	27.26050*	0.000*
Control vs Standard stone: recycled 2:3	17.13700*	0.000*
Control vs Standard stone: recycled 3:1	10.42200*	0.000*
Recycled dental stone vs Recycled: standard stone 1:1	-10.08250*	0.000*
Recycled dental stone vs Standard stone: recycled 2:3	-20.20600*	0.000*
Recycled dental stone vs Standard stone: recycled 3:1	-26.92100*	0.000*
Recycled: standard stone 1:1 vs Standard stone: recycled 2:3	-10.12350*	0.000*

Recycled: standard stone 1:1 vs Standard stone: recycled 3:1	-16.83850*	0.000*
Standard stone: recycled 2:3 vs Standard stone: recycled 3:1	-6.71500*	0.000*
Post Hoc Tukey, p < 0.05 significant; NS: not significant		

Table 3: Comparison of dimensional change among the study groups

Groups	Mean	Std. Deviation	F value	p value
Control	0.3300	0.03866	533.4	0.000*
Recycled dental stone	0.0240	0.02010		
Recycled: standard stone 1:1	0.0440	0.01231		
Standard stone: recycled 2:3	0.0740	0.01465		
Standard stone: recycled 3:1	0.1740	0.02683		
One-way ANOVA, p < 0.05 significant				

Table 4: Multiple comparison of dimensional stability using Post-Hoc Tukey test

Groups Compared	Mean Difference	Sig.
Control vs Recycled dental stone	0.30600*	0.000*
Control vs Recycled: standard stone 1:1	0.28600*	0.000*
Control vs Standard stone: recycled 2:3	0.25600*	0.000*
Control vs Standard stone: recycled 3:1	0.15600*	0.000*
Recycled dental stone vs Recycled: standard stone 1:1	-0.02000	0.081 (NS)
Recycled dental stone vs Standard stone: recycled 2:3	-0.05000*	0.000*
Recycled dental stone vs Standard stone: recycled 3:1	-0.15000*	0.000*
Recycled: standard stone 1:1 vs Standard stone: recycled 2:3	-0.03000*	0.002*
Recycled: standard stone 1:1 vs Standard stone: recycled 3:1	-0.13000*	0.000*
Standard stone: recycled 2:3 vs Standard stone: recycled 3:1	-0.10000*	0.000*
Post Hoc Tukey, p < 0.05 significant; NS: not significant		

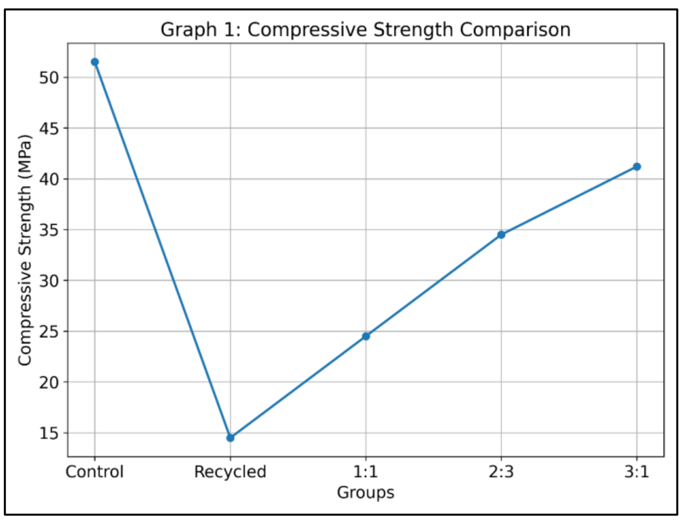

Figure 1: Comparison of compressive strength among different groups. Compressive strength increased progressively with higher proportions of standard dental stone. The control group showed the highest values, while recycled dental stone showed the lowest.

Discussion:

The findings of the present study demonstrated a significant difference in both compressive strength and dimensional stability between recycled and standard Type III dental stone, with the latter consistently showing superior performance. These results align with previous research that has explored the influence of material composition, water quality, calcination parameters and recycling methods on the physical properties of gypsum-based products. The quality of water used in the preparation of gypsum has been reported to significantly affect its setting characteristics and mechanical properties. Taqa and Zuhair **[6]** found that different types of water—such as distilled, tap and slurry water—altered the water–powder ratio, directly impacting the setting expansion and compressive strength of gypsum materials. Inconsistent water purity introduces ions that can either accelerate or retard the crystallization process, influencing the strength and dimensional accuracy of the final cast. This observation is particularly relevant in recycled gypsum, where impurities or residual dihydrate content from previous usage may further compromise material homogeneity and setting behavior. Recycling gypsum for dental applications has gained considerable attention in recent years due to its environmental and economic benefits. Wahyuni *et al.* **[7]** compared the compressive strength and dimensional stability of recycled and commercially available Type III gypsum and found that recycled materials exhibited lower strength and dimensional accuracy. The authors attributed this reduction to incomplete dehydration and altered crystal morphology during calcination. Similarly, Dulaimi and Kanaan **[8]** reported that drying techniques, such as microwave oven drying, can significantly influence the compressive strength of dental stones, emphasizing that heat distribution and exposure time during dehydration play a pivotal role in determining the reactivity and strength of the resulting hemihydrate. Further supporting this, Hasan and Mohammad **[9]** observed that different drying methods affected the crystal structure of gypsum, which in turn influenced its compressive strength. Controlled drying techniques that prevent over-dehydration are essential to maintain the integrity of the material, as overheating can cause the formation of anhydrite, which has reduced rehydration potential and leads to poor mechanical performance. Tang *et al.* **[10]** elucidated the dehydration and rehydration mechanisms of gypsum, demonstrating that the pathway and phase transitions from dihydrate to hemihydrate and back to dihydrate significantly determine the microstructure and, consequently, the strength of the material. Calcination, when carefully controlled, enables the recyclability of gypsum without compromising its mechanical properties. Zakiyuddin *et al.* **[11]** investigated the recyclability of dental gypsum through calcination and concluded that proper temperature and duration can restore its usability effectively. Their study suggested that maintaining calcination within the optimal range prevents over-dehydration and ensures that the reconstituted material achieves adequate strength and dimensional stability for dental applications. Shiny *et al.* **[12]** similarly emphasized that recycling plaster of Paris through thermal treatment can be both sustainable and practical, provided that calcination parameters are optimized to preserve chemical composition and crystal structure.

Beyond technical considerations, the integration of sustainable practices in dental materials has become increasingly significant. Angolan and Portent **[13]** examined the use of slurry water mixed with Type III gypsum and reported that partial replacement did not significantly compromise setting time or dimensional stability, suggesting that certain recycling approaches can maintain acceptable performance levels. This finding highlights the potential of adopting eco-friendly modifications in dental laboratories without sacrificing clinical reliability. The concept of sustainability in prosthodontics has been comprehensively reviewed by Twaddle *et al.* **[14]**, who outlined various recycling methods for gypsum products. They concluded that calcination remains the most effective process, but attention must be given to the number of recycling cycles, as repeated processing can lead to progressive degradation of material properties. Similarly, Chides *et al.* **[15]** stressed the importance of "up-cycling" dental waste through controlled processes to ensure both environmental responsibility and material safety. Their review advocates for the standardization of recycling protocols to minimize waste generation while maintaining clinical efficacy. Furthermore, Shinkai *et al.* **[16]** emphasized that environmental sustainability in prosthodontics is not limited to recycling but extends to minimizing the carbon footprint associated with material production and disposal. They argued that reusing and recycling dental materials such as gypsum can significantly reduce the environmental burden of prosthetic fabrication, aligning dentistry with global sustainability goals. Incorporating these practices into routine laboratory procedures could help balance ecological responsibility with clinical performance. The current study's results reinforce these findings by demonstrating that although recycled Type III dental stone alone exhibits inferior mechanical and dimensional properties, blending it with standard gypsum in controlled proportions can significantly improve its performance. The progressive increase in both compressive strength and dimensional stability with higher ratios of standard dental stone suggests that partial recycling may be a viable and sustainable approach. This observation is consistent with previous reports indicating that hybrid mixtures can maintain acceptable accuracy and strength while reducing material waste. However, the diminished performance of fully recycled gypsum observed in this study can be attributed to microstructural irregularities and incomplete reformation of hemihydrate crystals after calcination. These alterations reduce the number of interlocking needle-like crystals formed during setting, leading to weaker and less dense structures. Similar mechanisms were described by Wayne *et al.* **[7]** and Zakiyuddin *et al.* **[11]**, confirming that repeated thermal cycling may lead to structural degradation and reduced reactivity of recycled gypsum. While the full replacement of standard Type III gypsum with recycled material may not yet be feasible for high-precision prosthodontic applications, partial substitution presents a promising balance between material performance and environmental sustainability. Continued research focusing on optimizing calcination conditions, hydration kinetics and recycling cycles is essential to further enhance the clinical applicability of recycled gypsum in dental practice. The findings of the present study demonstrated that incorporation of standard dental stone into recycled Type III dental stone significantly improved compressive strength and dimensional stability. Similar improvements in mechanical behavior of dental materials have been reported in previous *in vitro* studies evaluating composite resins and prosthodontic acrylics. Evaluation of compressive strength among different dental materials showed that material composition plays a critical role in determining final mechanical properties and durability. Likewise, Szymlet *et al.* and Bilal and Hamafaraj reported that fabrication technique and material modification can markedly influence the mechanical performance of prosthodontic dental acrylics, supporting the concept that optimized material mixtures may enhance clinical applicability and strength characteristics **[17, 18].**

Conclusion:

Recycled Type III dental stone shows lower compressive strength and stability. Mixing recycled material with fresh stone significantly improves these essential physical properties. Optimized calcination ensures partial recycling offers a sustainable alternative for prosthodontic applications.

Advancement to knowledge:

This study provides new evidence on the feasibility of recycling Type III dental stone for clinical use. It demonstrates that completely recycled gypsum shows significantly reduced compressive strength and dimensional stability. However, mixing recycled gypsum with fresh dental stone in controlled ratios improves both mechanical and dimensional properties. The study establishes that partial replacement can achieve acceptable performance without major compromise in quality. It also highlights the importance of calcination and processing methods in determining the final properties of recycled gypsum.

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