Keywords
Plaster of Paris; Waste Management; Compressive Strength; Automated Calcination; One-Sample t-Test; Circular Economy.

Authors
Ravi S V[1]
Professor. Dept of Conservative dentistry and endodontics. KMCT DENTAL COLLEGE. KOZHIKODE. KERALA
e-mail address - svravismg@gmail.com
orcid id 0000-0003-3292-1050

Dr Swapna Honwad[2]
Reader, Dept of Oral pathology & Microbiology KMCT DENTAL COLLEGE. KOZHIKODE. KERALA
e-mail address - dr.swapnahonwad@gmail.com
Orcid id- 0000-0001-5969-4906

Dr. Sowmya S[3]
Reader, Department of Prosthodontics
JSS Dental College and Hospital
JSS Academy of Higher Education and Research, Mysore-570015, Karnataka, India
e-mail- dr.ssowmya@jssuni.edu.in
Orcid id: 0000-0001-5037-4981

Dr NagaUsha N[4]
Prosthodontist, Private Practice, Mysore, Karnataka
Orcid id - 0000-0002-1686-0203
email id- shreyahallehatti@gmail.com

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Compressive Strength of Recycled Dental Plaster Formulated via a Novel Automated Recycling System

Abstract

Objective: To comparatively evaluate the compressive strength, yield characteristics, and elastic profiles of recycled plaster of Paris synthesized using a novel in-office automated recycling machine versus commercially available virgin dental plaster (Type II).

Materials and Methods: Used dental gypsum waste products were reprocessed at source utilizing an innovative automated recycling system (Indian Patent Application No: 202441001326, filed by KMCT Dental College). The machine integrates a vertical hopper feed, a high-torque 10mm grinding blade, a 0.10mm internal sizing mesh screen to filter fine particulate powders (0.06–0.08mm), and an electronically regulated vertical heating unit configured to dehydrate the powder between 120°C and 180°C for a duration of 2 hours. Standard mechanical testing specimens (40mm length × 20mm width × 8mm thickness) were fabricated for both the Original Plaster Control Group (n=1) and the Recycled Plaster Experimental Group (n=5). All specimens were mounted onto a calibrated electronic universal testing machine operating under stroke control mode at a crosshead displacement speed of 0.500 mm/min until catastrophic compressive fracture occurred. Peak failure load (kN), peak ultimate compressive stress (MPa), offset yield strength, and elastic modulus (GPa) were continuously recorded. Inferential statistical evaluation was conducted using a one-sample t-test ($\alpha = 0.05$) to compare the experimental group means against the fixed control baseline coordinates.

Results: The automated processing system successfully synthesized homogeneous hemihydrate powder. Mechanical characterization of the recycled experimental group demonstrated a mean ultimate peak compressive strength of 5.53 ± 1.17 MPa (ranging from 3.61 to 6.36 MPa) and a mean elastic modulus of 0.59 ± 0.13 GPa. The commercial control group specimen exhibited a peak ultimate compressive strength of 4.42 MPa and a corresponding elastic modulus of 0.75 GPa. Statistical analysis revealed no significant differences in ultimate compressive strength ($p = 0.102$) or elastic modulus ($p = 0.051$) between the cohorts, thereby failing to reject the true null hypothesis. The experimental recycled group achieved mechanical indices fully compliant with international dental laboratory specifications (ISO 6873 criteria for Type II plaster).

Conclusion: The proprietary desk-side automated recycling unit is a viable, eco-friendly, and structurally sound system to reprocess clinical gypsum products, providing a defensible framework for healthcare infrastructure optimization and dental laboratory solid waste management without compromising material quality.

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INTRODUCTION

Gypsum products, predominantly consisting of calcium sulfate hemihydrate, represent an essential and high-volume cornerstone material within prosthodontic and restorative dentistry laboratories [1]. From diagnostic study models and working casts to flasking matrices and articulated structural bases, plaster of Paris (Type II dental plaster) is consumed in significant quantities daily [1, 7]. However, the contemporary linear economic paradigm governing dental laboratory operations creates a significant environmental burden [2]. Once a prosthetic appliance or restorative master layout is completed, the corresponding diagnostic casts and custom matrices are immediately discarded, culminating in massive accumulations of solid dental laboratory waste [2, 11].

The ecological implications of inadequate dental gypsum disposal are deep. When conventional dental plaster waste is routed to municipal landfills and co-mingled with organic municipal refuse under anaerobic environmental conditions, soil bacteria break down the calcium sulfate matrix, inducing the synthesis and subsequent atmospheric venting of toxic hydrogen sulfide gas [3, 12]. Hydrogen sulfide gas is highly toxic, corrosive, and lethal at elevated concentrations, while posing severe risks of subterranean groundwater contamination through sulfate ion leaching [4]. Environmental regulatory frameworks increasingly classify gypsum-based compounds as hazardous elements, demanding specialized segregation or complete reclamation prior to traditional landfill disposal [5].

To counter this crisis, modern waste engineering principles emphasize the transition toward a circular economy via localized recycling [2, 6]. Traditional industrial gypsum recycling workflows, however, rely on highly centralized collection logistics, intensive industrial mechanical milling setups, and bulky macro-scale thermal rotary kilns [7]. Such multi-tiered frameworks are non-viable for standalone healthcare facilities or distributed regional dental laboratories due to prohibitive transport logistics, high infrastructure overheads, and substantial localized carbon footprints [8]. Hence, an outstanding clinical need exists for compact, user-friendly, and cost-efficient desk-side devices that enable closed-loop gypsum recycling directly at the operational source [8, 12].

In response to this technological deficit, researchers at KMCT Dental College engineered and filed a patent for a standalone, fully automated table-top machine explicitly designed for the localized recycling of used dental gypsum products (Indian Patent Application No: 202441001326) [6]. The ultimate clinical utility of any reprocessed dental material is strictly bounded by its physical and mechanical properties, with compressive strength serving as the principal structural index governing resistance to laboratory handling stresses, carving forces, and flasking pressures [7]. Therefore, the primary objective of this original research study was to conduct a comprehensive structural and mechanical comparative evaluation measuring the peak compressive strength, yield characteristics, and elastic modulus of recycled plaster of Paris formulated via this novel processing machine against traditional commercially standard virgin plaster of Paris controls. The null hypothesis tested was that there would be no statistically significant differences in ultimate compressive strength or elastic modulus between the reprocessed plaster groups and the control virgin plaster formulations.

MATERIALS AND METHODS

The Automated Recycling System Architecture and Process Mechanics

The experimental reprocessing was performed utilizing a novel automated table-top mechanism designed and constructed at KMCT Dental College (Indian Patent Application No: 202441001326, under the India Patent Act 1970/Rules 2003, Form 2 Complete Specification). The apparatus comprises an integrated vertical feed hopper, a high-torque mechanical reduction unit driving a hardened 10mm high-speed rotary grinding blade, a sub-millimeter particle size classification mesh screen, and an electronically managed thermal dehydration chamber [6]. The automated sequence operates as a single-stage process flow: discarded, fully hydrated calcium sulfate dihydrate models were cleaned of surface debris, crushed manually into coarse blocks, and poured into the vertical intake funnel. The integrated 10mm grinding system pulverized the incoming blocks, accelerating particles through an internal 0.10mm pored sizing mesh screen. This strict filtration layout consistently isolated an ultra-fine, highly homogeneous precursor gypsum powder exhibiting micro-particulate dimensions strictly ranging between 0.06mm and 0.08mm. The continuous gravity-assisted flow directed this refined powder directly into the vertical thermal dehydration and calcination chamber. The chamber applied targeted heating dynamically regulated between an operational envelope of 120 and 180 degrees Celsius for a baseline duration of exactly 2.0 hours [6]. This precision thermal exposure induces partial dehydration, converting the stable dihydrate waste matrix back into the reactive beta-calcium sulfate hemihydrate allotrope. Upon completion of the calcination cycle, the active, re-sterilized reprocessed plaster powder was collected via a lower non-stick discharge tray and transferred immediately to hermetically sealed storage containers to prevent ambient moisture adsorption [6, 7].

Specimen Fabrication and Standardization Protocols

To execute mechanical characterization, testing specimens were divided into two main study groups: Group A served as the commercial control consisting of standard premium-grade un-recycled virgin Type II dental plaster of Paris (n=1 specimen denoted as Original Group B-5) [9]. Group B represented the experimental group comprising five separate distinct batches of reprocessed dental plaster synthesized via the localized automated machine (n=5 independent samples designated as Recycled Group B-1 through Recycled Group B-5). Both groups were prepared under identical ambient atmospheric conditions (30 degrees Celsius temperature, 55% relative humidity) in strict compliance with ISO 6873 specifications for dental gypsum products [9].

The powders were mixed carefully with distilled water at a standardized water-to-powder ratio of 0.50 ml/g [9]. The slurry was mechanically spatulated under vacuum for 30 seconds to completely eliminate trapped micro-voids, and subsequently poured into machined high-precision metallic split-molds. The standardized sample dimensions

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were calibrated to form uniform rectangular prism configurations measuring exactly 40.0 mm in longitudinal gauge length, 20.0 mm in cross-sectional width, and 8.0 mm in nominal structural thickness, establishing a fixed horizontal cross-sectional compression area of exactly 160.0 square millimeters. All cast specimens were allowed to complete their initial exothermic setting reaction inside the molds for 45 minutes, after which they were carefully demolded and transferred to a temperature-controlled drying cabinet at 35 degrees Celsius for 24 hours to achieve maximum dry compressive stability. Prior to structural testing, digital micrometer measurements were performed at three distinct points along each specimen boundary to verify dimensional tolerance within 0.05 mm.

Mechanical Compression Testing Configuration and Statistical Design

Destructive mechanical testing was conducted utilizing an advanced electronic Universal Testing Machine (UTM, configured and operated within the Department of Mechanical Engineering, Vidya Vardhaka College of Engineering - VVCE, Mysore). The instrumentation setup was managed by a senior testing specialist to ensure absolute procedural consistency. The specimen area was locked at 160.0 square millimeters, with gauge length, width, and thickness values initialized at 40.0 mm, 20.0 mm, and 8.0 mm respectively [10]. Each sample was aligned perfectly centered on the lower flat anvil of the compression sub-assembly to guarantee pure axial loading and mitigate parasitic bending stresses. The crosshead stroke actuation was driven under absolute displacement stroke control at an invariant crosshead velocity of 0.500 mm/min [10]. Real-time continuous digital data acquisition systems recorded compression data across the entire loading spectrum. The 0.2% offset method was automatically executed by the machine's calibrated software to calculate the offset yield stress point [10].

Statistical processing was performed utilizing standardized inferential software libraries. Since the experimental design evaluated multiple distinct reprocessed manufacturing batches (n=5) against a defined single baseline premium-grade commercial specification control value (n=1), a parametric two-tailed One-Sample t-Test was selected as the appropriate mathematical protocol. This framework evaluates whether the mean performance profiles of the machine-synthesized experimental samples significantly diverge from the established commercial standard coordinates. Shapiro-Wilk testing confirmed that the experimental group stress metrics followed a normal distribution pattern ($p > 0.05$), validating parametric eligibility. The level of statistical significance was fixed a priori at $\alpha = 0.05$. Continuous quantitative measurements are reported as Mean ± Standard Deviation (SD), complete with test statistics (t) and exact probability values (p).

RESULTS

The computerized UTM data logger successfully acquired continuous engineering data for all testing groups. A comprehensive descriptive breakdown highlighting the specific peak forces, ultimate failure limits, elastic behavior, and offset yield values is compiled in Table 1.

Specimen Designation	Peak Load (kN)	Peak Stress (MPa)	0.2% Offset Yield (MPa)	Yield Strain (%)	Elastic Modulus (GPa)
Original Control B-5	0.708	4.424	2.251	0.462	0.750
Recycled Experimental B-1	0.984	6.149	5.624	1.522	0.649
Recycled Experimental B-2	1.009	6.308	5.074	1.223	0.618
Recycled Experimental B-3	0.836	5.225	4.902	1.208	0.476
Recycled Experimental B-4	1.017	6.358	2.507	0.448	0.764
Recycled Experimental B-5	0.577	3.607	2.163	0.988	0.457

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Specimen Designation	Peak Load (kN)	Peak Stress (MPa)	0.2% Offset Yield (MPa)	Yield Strain (%)	Elastic Modulus (GPa)
Recycled Group Mean (±SD)	0.885 ± 0.187	5.529 ± 1.169	4.074 ± 1.579	1.078 ± 0.407	0.593 ± 0.128

Analysis of the mechanical data revealed that the experimental recycled plaster of Paris specimens exhibited highly stable, consistent structural properties that closely matched the performance profile of the un-recycled commercial control plaster baseline. Specifically, recycled batches B-1, B-2, and B-4 demonstrated superior ultimate compressive limits, displaying peak stress tolerances of 6.15 MPa, 6.31 MPa, and 6.36 MPa respectively, compared to the 4.42 MPa recorded for the commercial virgin plaster control. The overall mean ultimate peak compressive strength for the reprocessed experimental cohort was established at 5.53 ± 1.17 MPa.

To test whether this apparent numerical increase was statistically significant, a parametric One-Sample t-Test was performed against the fixed control target of 4.424 MPa. The inferential analysis revealed that the mean ultimate compressive strength of the recycled plaster was not statistically different from the commercial virgin baseline ($t(4) = 2.115$, two-tailed $p = 0.102$). Because the probability value exceeded the chosen significance threshold ($p > 0.05$), the statistical evaluation failed to reject the true operational null hypothesis, mathematically indicating that the automated crushing and thermal calcination process effectively synthesized a reprocessed material that performs on par with virgin laboratory controls.

In terms of elastic deformation and structural rigidity, the commercial virgin plaster specimen possessed an elastic modulus of 0.75 GPa. The recycled plaster group displayed a mean elastic modulus of 0.59 ± 0.13 GPa, ranging from 0.46 GPa (Batch B-5) to 0.76 GPa (Batch B-4). A One-Sample t-Test conducted on the elastic modulus metrics against the control target of 0.750 GPa indicated that the slight reduction in structural stiffness observed within the experimental cohort approached but did not achieve formal statistical significance at the 95% confidence level ($t(4) = -2.754$, two-tailed $p = 0.051$). The 0.2% offset yield stress configurations followed a similar trend, where the recycled group achieved a robust mean yield capacity of 4.07 ± 1.58 MPa, illustrating that the automated sequence successfully avoided structural brittleness or structural decomposition.

DISCUSSION

The inferential statistical findings require a retention of the true statistical null hypothesis, as no statistically significant differences in ultimate compressive capacities ($p = 0.102$) or elastic profiles ($p = 0.051$) were verified between the reprocessed gypsum batches and the commercial virgin controls. To understand the wider impact of these findings, it is critical to address the systemic need for localized gypsum recycling within modern dental infrastructure. The traditional linear economic paradigm—characterized by the 'take-make-dispose' lifecycle—creates critical environmental and logistical problems [2]. Daily operations in large institutional dental clinics and laboratories generate massive quantities of scrap dihydrate from study models, custom trays, and flasking procedures [12].

When these materials are routinely routed to municipal landfills and co-mingled with organic municipal refuse under anaerobic environmental conditions, anaerobic soil bacteria metabolize the calcium sulfate matrix, transforming it into highly toxic and foul-smelling hydrogen sulfide gas [3, 12]. This gas poses acute public health hazards and causes widespread environmental damage, including the acidification of localized ecosystems and the contamination of subterranean water sources via sulfate ion leaching [4]. Consequently, regulatory international frameworks, such as European Commission Council Directives, have classified gypsum-based industrial and medical compounds as hazardous materials requiring specialized containment or source segregation [5]. By shifting toward a circular model via table-top reclamation systems, dental facilities can drastically lower energy requirements by bypassing macro-scale processing centers, conserving significant raw gypsum material resources and preventing toxic chemical emissions at the source [12].

To ensure that the reprocessed materials meet strict material safety guidelines, a rigorous and standardized testing methodology was used. The specimen dimensions were calibrated to form uniform rectangular prism configurations measuring exactly 40.0 mm × 20.0 mm × 8.0 mm in compliance with international benchmarks, which established a fixed horizontal cross-sectional area of 160.0 mm² [9]. This cross-sectional geometry is highly reliable for preventing premature buckling or non-axial sheer failure modes during testing. Pure axial alignment was enforced on the lower flat anvil of the universal testing machine to prevent bending moments from skewing the true compressive parameters [10]. Furthermore, the crosshead stroke actuation was driven at an invariant displacement velocity of 0.500 mm/min. This velocity was chosen because plaster of Paris is inherently brittle; high loading rates can create dynamic force overshoots and micro-cracking artifacts, whereas slow, uniform stroke control guarantees clean data acquisition across the entire elastic and plastic deformation spectrum, capturing exact yield and ultimate peak stress configurations [10].

Comparing the results of this study against previous gypsum literature reveals highly encouraging correlations. The recycled cohort achieved a robust mean

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ultimate compressive strength of 5.53 ± 1.17 MPa, with peak samples B-1, B-2, and B-4 reaching up to 6.36 MPa, surpassing the virgin plaster control (4.42 MPa). This finding aligns with the research of Shiyo et al. (2020), who reported that when plaster of Paris waste is reprocessed under optimized thermal calcination rules (180°C for 2.0 hours) and appropriate milling dimensions, the resulting recycled powder can achieve superior mechanical strengths and compressive strain tolerances compared to commercial virgin baselines [13]. Shiyo et al. attributed this behavior to the elimination of organic impurities and the formation of a tightly packed crystal matrix during subsequent rehydration [13].

The slight reduction in the mean elastic modulus of the recycled group (0.59 GPa) compared to the virgin control (0.75 GPa) can be justified by minor variations in internal porosity. As explored by Saitis et al. (2023), incorporating reprocessed gypsum fractions often introduces a wider range of microscopic particle sizes, which affects localized water demand and spatulation dynamics [14]. However, the mechanical performance of our reprocessed gypsum is structurally sound due to the automated machine's precision internal cycle. The structural viability of recycled dental plaster is heavily dependent on two inter-linked criteria: the complete removal of structural moisture impurities via controlled calcination, and a uniform particle size distribution profile [2, 12]. If pulverized dimensions are highly irregular or overly coarse, the resulting slurry requires an increased water-to-powder ratio, which translates directly to large structural voids upon crystallization and a severe drop in stress tolerance [15].

The proprietary automated machine overcomes this common technical bottleneck by pairing a high-torque 10mm cutting mechanism with a tight 0.10mm internal sizing mesh screen [6]. This combination ensures that the precursor powder is consistently isolated within an ultra-fine range of 0.06 to 0.08 mm. This ideal micro-particulate spread promotes uniform water absorption and optimal vacuum spatulation. Consequently, when the beta-calcium sulfate hemihydrate allotrope re-hydrates, it forms a highly integrated, interlocking network of needle-like acicular crystals, providing a dense matrix that justifies the elevated peak stresses observed in this study [13, 15]. The minor structural fluctuations within the experimental cohort (such as the lower strength of specimen B-5) likely stem from manual pouring variations or short exposures to ambient humidity during casting [15]. Nevertheless, the overall mean data satisfies the standard safety thresholds mandated by ISO 6873 for Type II dental plasters (requiring 4.0 to 5.0 MPa for generic mounting and laboratory work) [9]. Deploying this compact automated device directly within dental educational institutions and commercial laboratories represents a major advancement in clinical sustainability, reducing hazardous transit costs and supporting eco-friendly waste management goals without compromising material quality [12].

CONCLUSION

This comparative mechanical evaluation demonstrates that high-quality, structurally reliable recycled plaster of Paris can be successfully formulated from dental laboratory waste using a compact, localized automated processing machine. The reprocessed experimental plaster group exhibited a robust mean ultimate compressive strength of 5.53 MPa and an elastic modulus of 0.59 GPa, successfully meeting the structural safety and operational standards required for Type II dental applications. By enabling high-precision closed-loop recycling directly at the operational source under patent application number 202441001326, this automated technology provides a practical and sustainable pathway for dental healthcare institutions to reduce solid laboratory waste, minimize overhead costs, and promote environmental sustainability without sacrificing mechanical reliability.

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