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ELAEIS SOFT CELLS COMPATIBILITY WITH GYPSUM MATRIX FOR CIRCULAR INDUSTRIAL SYMBIOSIS

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Abstract:

Palm fruit bunch soft components with nanofunctional properties, TRX-cells®, demonstrate yet another unique role in enhancing the flexural durability of recycled gypsum. Incorporation of foreign cells of uniform size into the interior gypsum panel-making residues was found to boost flexural strength by 224% despite a drop in compressive strength. Understanding the quantum-mechanical interactions between the constituents of TRX-cells® and gypsum in soft reinforcement provides insights into profitable use, enabling informed decisions in waste handling. The resource synergy symbolizing symbiosis is a promising approach to mitigate emission risks from unattended residue degradation. Cross-sectoral circularity will foster profitable waste management, harmonizing people and the planet in sustainable industrialization.

Keywords:

Nano Functional Cells, Soft Minerals, Silica, Circularity, Gypsum Plasterboard Waste, Xylan, Quantum Mechanical Interaction

Introduction

Soft biomass cells, such as oil palm (*Elaeis guineensis*) milling residues (EMR), offer unique properties and impacts. To avoid unattended degradation, loss of rescuable commodities, and the ensuing emissions, EMR residues are routed to specific uses, entitling them to a commodity price tag. The effort resonates with circularity principles, which call for design optimization to enable reuse, recycling, and repurposing (Pena et al., 2020; Ghazali & Zbiec, 2022; Puerto et

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al.,2024; Poolsawad et al., 2024).Now quantifiable (Poolsawad et al., 2024), circularity with an embedded lexicon for zero waste, thus signifies resource efficiency. As the circular economy gains a foothold as the prioritised area for research and industrial practices, the'extract-produce-dispose'(Puerto et al., 2024) counterpart, known as the linear system, is gradually being transformed by the management of side products in a more profitable way.Such a process emerges with extreme complexity and can tax a high environmental and economic risks, prompting social(Velenturf & Jensen, 2016), geographic(Chrysikopoulos et al., 2024), and scientific practicality, such as that associated with waste rerouting(Aui, Wang & Wba-Wright, 2021;Halis, Ghazali& Zakaria, 2024), as assessment criteria in circular counterpart.

Biomass-based product innovation resonates with the move to prevent the depletion of fossil-based resources for green transition and ultimately, planetary sustainability. Where EMR is concerned, Indonesia has ingeniously maximized the oil palm trunk for consumer sugar production(Siswati,Insusanty and Susi, 2018;Kurniawan et al., 2018) despite the established sugar as a derived feedstock for the bioenergy (Dirkes, Neubauer &Rabenhorst,2021; Yamada et al, 2010; Kuniawan et al, 2018) sector. Despite its abundance only at the time of felling, or once every 20 years during its lifespan(Kurniawan et al.,2018), sugar from Elaeis guineensis is one of the promising complementary sugars for Indonesia to achieve self-sufficiency in sugar by 2023 (ISO, 2023).The step ingeniously resolves the sweet commodity management issue by sustainably rerouting consumer demand, filling the demand-and-supply gap for sugar, while sealing the circularity loop for oil palm trunk soft polymer management.

Consisting less of consumable sugars,the oil palm empty fruit bunches (EFB) are capitalised for their fibrous structure.While numerous researchers have successfully produced paper using various methods with EFB, commercialising the process has proven challenging, and pulps such as APMP are unrecyclable. Despite the compatibility of wood-based paper recycling with the older notion of recycling as a strategic step towards sustainability,paper recycling has been shown to be incompatible with the circular materials balance in global sustainable production and consumption (Van Ewijk, Stegemann & Ekins, 2017). Paper recycling accounts for 1.3% of global greenhouse emissions(Ewijk, Stegemann & Ekins, 2021), thus, a staggering contributor to the 2°C warming. Such an effect should be avoided, given the already concerning uncontrolled warming(Adetunji,2025), which is projected to repeat the disaster that occurred millions of years ago.

One of the commodities in Elaeis' EMR is the functional cells from the unrecyclable alkaline peroxide paper fibres. Soft cells containing nano fibrils embedded in xylan and dearomatised lignin can be cascaded by deminuting the fibres obtained after a rapid perhydroxyl reaction with EFB(Ghazali et al., 2024). Registered as TRX-cell,the cells possessing nanoscale dimensions in the y-axis were delaminated by the decoupling effect of alkaline peroxide-triggered perhydroxyl radicals on the lignified oil palm empty fruit bunch vascular bundles (Ghazali et al., 2024). As a paper coat,the cells improved inkjet printability by nearly 2-fold due to the surface's precise affinity to the programmed printing pattern(Ghazali et al., 2021a). In functionalising food grains,not only do TRX-cells allow the chromophilic uniformity of delphinidin coat, but also an extended shelf life for the cured grains (Ghazali et al 2021b). TRX-cells-soft mineral compatibility is here scrutinised to possibly actualize the downstream construction-and-food industrial symbiosis via TRX-modified gypsum waste.

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Modification of gypsum waste from gypsum-based production lines could reroute gypsum wastes from the landfill and rule out the potential gaseous emissions like H2S (Guna *et al*., 2021) through oxidation of $CaSO_4$ to CaS, microbial (Kazemian *et al.,* 2019), particulate matter (USEPA, 2024; Sekhavati & Yengejeh, 2023), and other emissions from gypsum neglect. Gypsum recycling could reduce the carbon footprint of freshly produced gypsum by an additional 140.7 kgCO2/t (Fort & Cerny, 2018; Jafari & Sadeghian, 2024), provided that distance is met for circularity principles (Weimann *et al*., 2021). Conversion of waste into commodities will not only contribute to the circular economy of the construction industry (Puerto *et al*., 2024) but also reduce health risks associated with construction and building materials. We examined the extent of the positive effects of combining the generated soft nano cells with the soft inorganic gypsum waste on the set admixture durability and mapped the results to an appropriate application. The foreseen symbiosis between CDW and OMR is the way forward for a simple, cheaper, and doable circular bioeconomy of the construction and food (palm oil milling) industries.

Materials & Methods

Soft Materials

The soft biopolymer from the oil palm empty fruit bunches vascular bundles (EFBVB) and the soft on the Mohs-Hardness scale, industrial gypsum waste were pre-processed upon acquisition. While EFB was reacted with the dioxydanyl radicals for delamination of the fibrous cell walls, gypsum waste from the gypsum-based product manufacturer, Saint-Gobain (M) Pte Ltd, was segregated by their particle size using Retsch AS 200 sieve-and-shaker. The lowest-mesh waste, consisting predominantly of paper strips, was discarded. The particles passing the 1000-micrometre (18-mesh) screen (P18), denoted GyP18, were collected, with an appropriate proportion reserved for analysis. The outcome of blending the soft nano cells (TRX-cells®) with the soft inorganic gypsum (GyP18) was examined via mixed quantitative-qualitative methodology. We discuss the results and rationalise the desired enhancement with sound theoretical considerations.

Soft Nano Cells Production and Characterisation

Alkaline peroxide was premixed to generate perhydroxyl radicals for the dearomatization of lignin in the middle lamella of the oil palm empty fruit bunch vascular bundles. The pulp, containing macro-, microfibres, and fibre bundles, was refined by applying 0.7 to 17 MWhr/mt refining energies. The nano cell mass generated by the varying energies was made into webs, while a portion was refrigerated as the never-dried cells.

In 2 L of distilled water, 0.05 g of TRX-cells® in fibre admixture was stirred to yield a homogenous colloidal suspension. The layer of TRX-cells® was decanted as a clear solution with 0.04% nano cells. A scheduled Transmission Electron Microscopy (TEM) examination was performed to verify the presence. The suspension of nano cells was refrigerated in portions sufficient for GyP18 augmentation, pigment immobilization, non-food product coating, and other applications.

Cell Network Tear and Optical Traits Predicting Descent Rigidity

Webs of cells derived from varying levels of refining energy were tested for tear resistance per TAPPI Test Method T414 om-98. Samples were conditioned at the standard conditioning temperature and humidity before analysis with the L&W Tearing Tester at the ISO17025

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laboratory. Analysis was run on the web, prepared in replicates ($4 < n < 6$), and further analysis for derivative values was based on the average indices. The predictor of "softness" is based on the percentage change in the tear resistance. TAPPI Test Method T425 was adopted for cell web opacity assessment. The parameters for the web of cells refined at a specific energy are the average values of four to six replicates ($4 < n < 6$).

Cellular Electron Microscopy
The web strips from the Thwing-Albert Elmendorf test were analysed using a Leo Supra 50 VP Carl Zeiss Scanning Electron Microscope. The samples were mounted on conducting carbon tape and gold-coated for 10 minutes using a Polaron Equipment Limited E500, applying 1.2kV and 20 Pa for 10 minutes.

Gypsum Characterization
GyP18 was analysed at the Centre of Archaeological Global Research's Earth Mineral Characterisation Laboratory (EMCL) of Universiti Sains Malaysia. X-ray Diffraction spectroscopic data were acquired with Bruker D8 Advance accessory. DIFFRAC.EVA Ver. 1.4 and the ICDD PDF-2 software with more than 200,000 spectral database was used to characterise the sample.

The Bruker M4 TORNADO XRF (X-ray Fluorescence) spectrometer, integrated with fused-glass bead calibration tools, enabled elemental analysis of GyP18. Trace elemental data (µg/g) was extracted by the Omnian method using a pressed powder pellet. EMCL ignition facility also provided GyP18's Loss on Ignition (L.O.I.) by ignition at 500-1100°C temperature range. Gravimetric analysis of GyP18 ash determined the percentages of mineral oxides using TAPPI Test Method T266 to quantify the organic and non-volatile inorganic components ignited during the L.O.I. investigation.

P18 Gypsum (GyP18) Brick Augmentation
The inorganic residues were thoroughly mixed for homogeneity. Four sets of bricks of 210 g GyP18 were formed with and without TRX-cells® in accordance with the dimensional recommendation in British Standards. Table 1 summarizes the samples prepared and examined for GyP18 augmentation.

Table 1. Gypsum Waste, Gyp18, Samples Prepared in Triplicate.

CODE	SAMPLE DESCRIPTION
GyP18	Gypsum waste passing 18-mesh screen.
GyP18-TRX	GyP18 mixed with 0.04% TRX-cells®
GyP18-µF	GyP18 mixed with the microfibre (TRX-cells® production Feedstock)
GyP18-µF-TRX	GyP18 mixed with microfibre and TRX-cells®

The mixing procedures and brick preparation adhered to the BS EN 13279-2:2014. Gypsum-water admixture was stirred for 60 seconds and poured immediately into the rectangular mold (40 mm x 40 mm x 160 mm). The samples were left to stand at 23±2°C and 50% relative

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humidity for 7 days before drying at 40°C to a constant weight. Post-conditioning, samples were tested for flexural (3-point bending test) and compressive strengths using an INSTRON UTM 5582 to investigate quantum-mechanical interactions (Hassan, Verma & Ganguly, 2012) between TRX-cells® and gypsum.

Results & Discussion

Elemental Analysis of the Soft Inorganics

The mixed waste of fibrous organics and inorganics was apparently in the proportion described by Wiemann *et al.* (2021). X-ray Diffraction indicates the presence of crystalline inorganics constituting orthorhombic $CaSO_4.0.5H_2O$ bassanites with traces of SiO_2 (Figure 1). While the fused Glass Bead calibration in the elemental analysis using X-ray Fluorescence spectroscopy (Table 2) confirms the predominance of calcium sulfate hemihydrate (bassinite, $CaSO_4.0.5H_2O$), GyP18 was 79.7% gypsum ($CaO+SO_3$, Table 2), with 4% SiO_2, occupying the 74% of the inorganics.

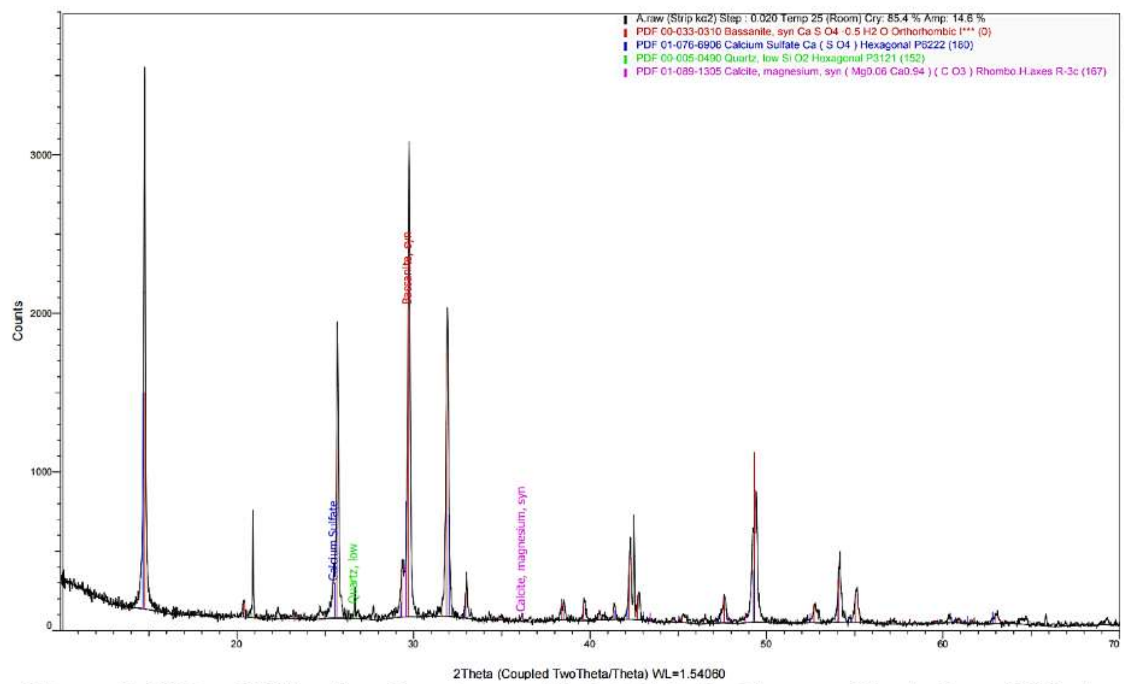

Figure 1. X-Ray Diffraction Spectrum of Saint-Gobain Gypsum Plasterboard Waste Screened to Yield Particles Passing the 18-Mesh, Marking the Sample Gyp18.

Based on 74% ash, the figure approximates 6% of minerals volatilising above 500 °C, confirming the hemihydrate form of Plaster of Paris and indicating the high purity of Saint-Gobain gypsum waste. The L.O.I. below 21% (L.O.I. = 9%, Table 2) suggests that the waste has a high mineral-to-hydrocarbon ratio, with approximately 500 ppb Sr (Table 2), which adds to the stability of other minerals' point of ignition. The obtained Gyp18 L.O.I. value resembles that of fly ash reported by Javed and co-workers (2024).

Among GyP18's 26% augmenting elements intended to add the desired functionality of the plasterboard were cellulose ethers, which were commonly added to provide a smoother gypsum

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surface while improving workability, resisting permeability, controlling moisture, and reducing cracking (Meng *et al.,* 2021).

Table 2. Elements of Gypsum Plasterboard Waste and the Associated L.O.I.

Elements	Trace Elements (ug/g)	Major Elements (wt %)[1]	Ash (wt %)
Cl	384-772	-	
Sr	489-538	-	
Cu	47	-	
Zn	22-35	-	
TiO_2	-	0.05±0.00	
Al_2O_3	-	0.72±0.01	
Fe_2O_3	-	0.45±0.05	
MgO	-	0.27±0.01	
Na_2O	-	0.03±0.01	
K_2O	-	0.18±0.00	74%
P_2O_5	-	0.03±0.00	
SO_3	-	46.57±0.33	
CaO	-	33.14±0.09	
SiO_2	-	3.60±0.30	
L.O.I (550-1000°C)	-	9.30±0.34	

[1] Fused glass beads calibration.

In the construction and building industry, gypsum is the retarder to the key concrete component, the metal-free, cement admixture. As a retarder, gypsum lowers the activation energy for cement hardening by reducing the temperature required for hardening (Cateno *et al*., 2024).

Nanomodified Gypsum - Flexural Durability

An attempt to improve the flexural durability of P18-gypsum (GyP18) by mixing with soft nanocells from EFB resulted in increased flexural strength of 224% and 147% with and without thermos-effect, respectively. when subject to thermo-effects (TRX cf. Pure Gypsum, Figure 2).

While the sediments of the decanted TRX-cell® allowed the bricks to resist an additional 0.7709 MPa pressure, resulting in 137% flexural strength enhancement, as opposed to 17% enhancement without heat treatment (TRX-µFibres cf. Pure Gypsum, Figure 2). Adding varying filler sizes results in a 60% drop in flexural strength (TRX cf. µfibre, Figure 2).

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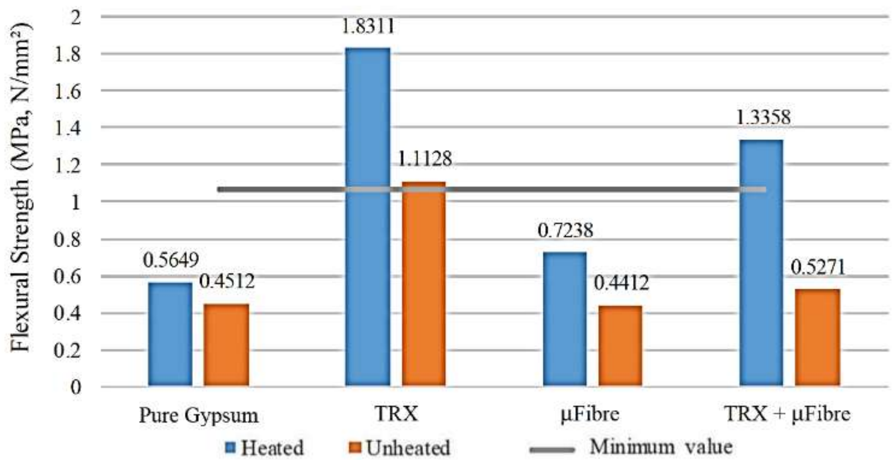

Figure 2. Flexural Strength of the Nanomodified Gypsum Matrix Marked as 'TRX'.

The 224% flexural improvement is the highest and demonstrates the potential of the nano cells for P18 gypsum waste from the gypsum-based production line. The importance of additive uniformity is apparent from the 27% to 60% drop in flexural values relative to the nano TRX-cells gypsum composite.

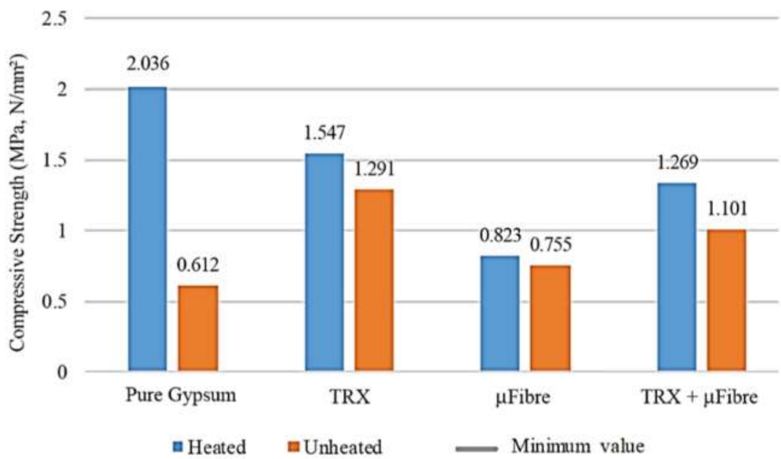

Figure 3. Compressive Strength of the Modified Recycled Gypsum.

TRX-GyP18, µFibre-GyP18, and TRX-µfibre-GyP18 exhibit a similar range of compressive durability (Figure 3). Relative to the unheated samples, however, the TRX-containing gypsum matrix shows a 111% higher compressive strength relative to the unheated pure gypsum. A similar effect is observed with GyP18+µFibre and GyP18+TRX+µFibre, showing 23% and 80%, respectively, suggesting the augmentation effects of matrices when blended with TRX-cells®.

Overall, adding organic entities, such as micro- and nanolignocellulosic fibres, reduced the cementitious phase of the gypsum block. The organic-inorganic phases also aggravated the fibre-gypsum micro gaps (Bentgeri *et al*., 2024). These resulted in only the GyP18 pressure resistance meeting the bare minimum (2-10 MPa) requirements set by the construction and building industry. The phenomenon may be attributed to deterioration and contamination with

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microelements during processing (waste packing, transportation, homogenization, and size screening).

GyP18 samples improved in flexural strength (Figure 2) by 25% upon thermo-effects during brick conditioning. A significant 65% enhancement in flexural stability was observed with the GyP18 reinforced with TRX cells and microfibres when thermo-effects were applied during conditioning. A bizarre 153% flexural strength enhancement was achieved in gypsum with a blend of microfibres and TRX cells, reflecting the enormous water retention when the cells were blended with their parent fibres. The phenomenon is attributable to the increase in the hydrophilic moiety discussed in the next section. Thermo-effects boosted the flexural strength as water was liberated from the matrix. GyP18 block durability improved by 65% following thermo-effect, resulting in an overall 153% leap in flexural strength. Results not only indicate the thermo-effects on the flexural strength of the bricks but also the profound effect of uniform filler size.

An opposite trend was observed in compressive strength development (Figure 3), where pure GyP18 showed a 233% increase, while its softened counterparts showed an average of only 18% increase upon heat treatment. Recycled gypsum matrices, with and without soft cell blending, all met the minimum industrial requirement for flexural strength. Overall, the thermal effects of gypsum bricks with and without soft cell blending improved both flexural and compressive strengths, except for pure GyP18 compressive resistance, which met the minimum 2 MPa pressure resistance.

Without meeting the industrial standard of 3-10 MPa (or 20-50 MPa for engineering bricks) (BIA, 1999; Marshalls, 1999) for compressive strength as a sturdy construction material, gypsum waste is better suited to non-construction applications. Soft interior design paste for the trending luxurious gypsum art may offer an economic advantage, especially with TRX-cells® admixture, which adds aesthetic value through precise colour affinity. Such formulation has to undergo a comprehensive Transaction Cost Economics (Zainudin, Mustapa & Minsan, 2022) and other viability studies to assess the product and process economics. The modification would ultimately be an integral part of an ecologically friendly interior design with the elements of a circular economy, essential for global sustainability. The softer GyP18-TRX is a promising material for innovative bubble houses (Ban et al., 2018; Geraldo *et al*., 2017; Saez-Perez *et al*., 2021) interior ceiling structures apart from other soft-load panel products.

The high flexural and altered hydration kinetics provide optimum workability for creative drywall sculpting. Given the characteristics of TRX-cells®, the GyP18-TRX also suits precision painting with adaptability to both organic and inorganic pigments.

Softness in Retrospection of Pressure Sensitivity

The non-compliant compressive strength (Figure 3) and the superior flexural (Figure 2) durability of the nanomodified gypsum bricks prompted a softness analysis of TRX-cells®. The cue for softness, depicted as translucence, is captured from web opacity relative to web density and morphological transition (Figure 4). Tear resistance was reported to be inversely proportional to tensile strength, similar to the negative correlation between tensile and softness reported by Morais *et al*. (2019), and the correlation between the delaminated fibre structure and softness was tested on the refined fibrous mass. The found association between xylan and an increase in carboxylic (Salam *et al.,* 2011; Rebola, Ferreira & Evtuvin, 2020), in addition to

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the inherent hydrogen bonding (H-bonds) amongst cell mass, predicts an inclination of softness on account of the subtler H-bonds afforded by the branching polysaccharide cf. cellulose H-bonds.

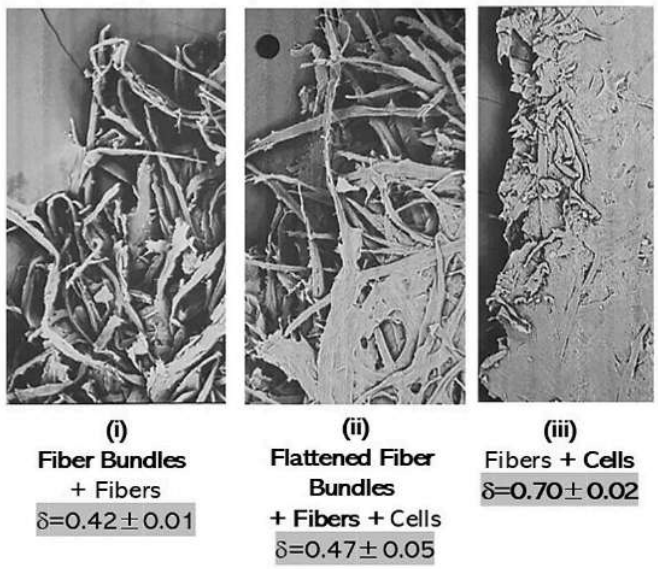

Figure 4. Transitional Optical and Physical Properties with Images of the Torn 60 GSM Web Strip-Edges for µfibre (i), µfibre+TRX Mix (ii), and TRX (with Parent Fibre (iii)).

The 26% xylan (Ghazali *et al*., 2024) exposure also increases the hydrogen bonding among the cells, resulting in compaction ($\delta=0.07\pm0.02$, Figure 4) and the reduction in inter-fibre space by 34%, given by the difference in the mechanical tearing index (Equation 1):

$$\text{Tear Indices Difference (\%)} = [(Tear_{TRX} - Tear_{\mu Fibre}) / (Tear_{TRX} + Tear_{\mu Fibre})/2)] \times 100 \quad \ldots(1)$$

From a compositional standpoint, the y-axis nanoscale layers of the delaminated cells, open or partially folded, gave rise to pseudo cellulose-cellulose, as the cellulosic microfibrils are still held by the hemicellulose to form a web. Unlike cellulose-cellulose hydrogen bonding prevalence in pure micro-fibre web, xylan-cellulose, and xylan-xylan hydrogen bonding predominate in the formed web of nano cells (Figure 4(iii)) but scarcely affected the water content (L.O.I. 9%, Table 2) when blended in GyP18. As more xylan moieties were exposed, cell softness increased by 29%, as evidenced by the tearing resistance profile (Table 3).

Table 3. Softness Enhancement Signaled by Tearing Durability.

Transition Parameter	Raw Average Tear Index (mNm^2/g)			Resultant Softness
	Micro Mass Network		Nano Mass Network	
Percentage	5.48±0.32 (n=5)	→	3.87±0.38 (n=5)	
Change	-29% (29% softness enhancement)			-34%
Percentage Difference	-34% (34% softness difference)			-41%

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The softness led to the composite's moldability, enhancing flexural performance but hampering compressive performance due to the lower crystallinity of the hydrocarbon filler.

Equation 2 provides quantitative insight into the enhanced softness, which correlated with the compaction of cells forming the 'fused' composite matrix.

$$\text{Change in Tear Indices (\%)} = (Tear_{TRX} - Tear_{\mu Fibre}) / Tear_{\mu Fibre}) \times 100 \quad ..(2)$$

The fibre appearance diminished, and the intermingling xylan-rich structure formed glued cells (Figure 4(iii)) rather than a fibre web (Fig. 4(i)). Within the gypsum matrix, the effects of TRX-cells® soft nano cushioning on GyP18-TRX flexural strength (Figure 2) are superior to those of microfibres and the TRX-parent fibre mix. As the cells were blended and set to harden in the GyP18, a layering and random cushioning around the P18 particles were conceptualised (Figure 5). While the scarce 0.4% (atomic) nano minerals (Ghazali et al 2024) are inadequate to hold GyP18 firmly enough to exert compressive resistance (Figure 3), the hygroscopic binding between GyP18-TRX's xylan and cellulose, plus the prevalent x-direction cushioning, resulted in an immense enhancement of flexural or bending resistance of the composite structure (Figure 2). The reported presence of nano silica may share the positive effects reported by AlTawaiha *et al*. (2023).

Considering the bed joint position of the tested bricks, all GyP18 bricks blended with soft organic fillers met the accepted requirement for engineering-quality concrete bricks for flexural strength (Marshalls, n.d.).

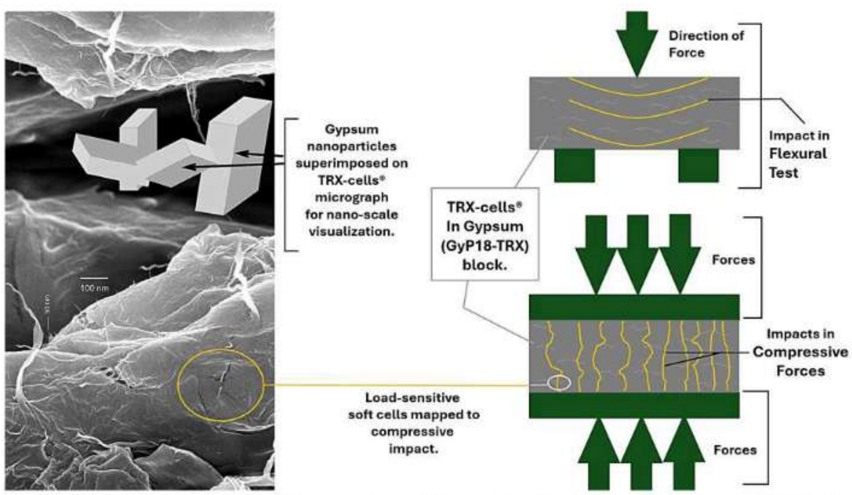

Figure 5. FESEM for y-Axis Dimension Nano Scale Visualization of TRX-Cells® in Gyp18 Structure.

An increase in surface hydroxyl groups arising from the redistribution of nano-organics and xylan within the fibrous structure led to extensive interactions (Figure 5) with $CaSO_4.0.5H_2O$, potentially increasing the hydration of the soft inorganics under certain conditions. Hissein and team (2019) reported a similar enhancement in the flexural durability of high-density calcium-silicate-hydrate (C-S-H) upon reinforcement with cellulose nanocrystals (CNC). Adding natural fibres, however, has repeatedly been shown to adversely affect compressive resistance (Romero-Gómez *et al*., 2022; Capasso *et al.,* 2025). A correlated outcome is evident in Figures 2 and 3. Integration of microfibres in the matrix (μFibre) plausibly acts as the defect

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propagation point against the flexural and compressive impacts (Figures 2 and 3, respectively). The bending durability enhancement at the given compressive strength thus illuminates the promising use of the nanoscale cells to engineer gypsum plasterboard for applications requiring soft-body impact resistance. Future use of artificial intelligence (AI) as a predictive tool (Bentgeri *et al*., 2025) is highly recommended. Mapping GyP18-TRX use to soft, non-load applications, commensurate with the law that forbids gypsum reuse for construction purposes.

Nanomodified Recycled Gypsum: Pros and Cons of GyP18-TRX

TRX-cells® improved the flexural durability of GyP18 bricks by over 200%. The accounted hydrophilic enhancement is favourable for passive cooling by moisture attraction. The property is beneficial for moisture management in arid areas and thus has potential market appeal in places like the dry tropics and deserts.

The better flexural development in TRX-reinforced GyP18 (cf. GyP18-microfibre) indicates the need for uniform-size fillers in composite reinforcement. Capitalizing on the common low (Capasso *et al.,* 2025) compressive resistance, GyP18-TRX is directed toward aesthetic use, which boils down to luxurious interior design (ID) applications in gypsum drywall murals. Xylan-rich TRX-cells® offer a superb post-curing preservative effect (Curry *et al*., 2024), and their strong colour affinity also calls for research into their prolific applications.

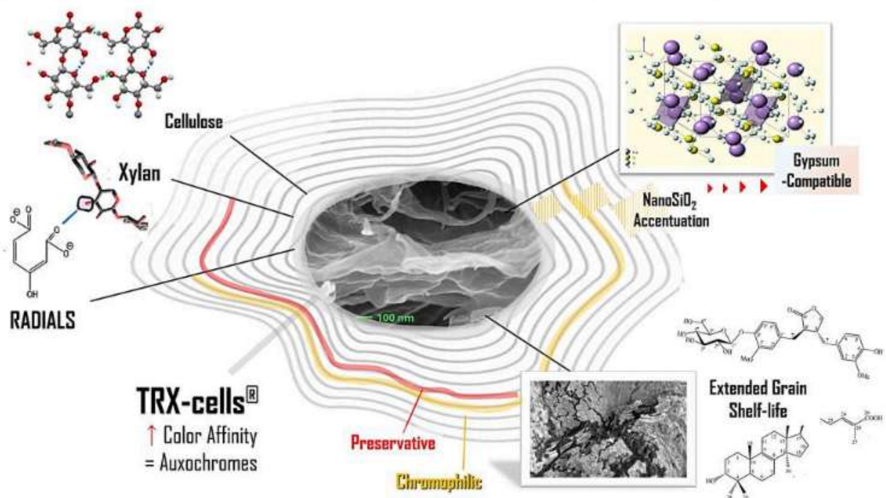

Figure 6. TRX-cells® Components and their Roles in Pigment Immobilization to Harness Gypsum Plaster Styling.

The enhanced flexural resistance of GyP18-TRX, coupled with TRX-cells®' colour-loving properties (Ghazali *et al*., 2021a, Ghazali *et al*., 2021b), creates a link between construction waste and palm oil milling waste. The symbiosis does not oppose but eases law enforcement against gypsum waste dumping at the landfill. Recommended recycling for destinations other than construction attests to the diversified uses of gypsum waste for soft-load items, which withstand soft-body impacts in creative interior decoration. Although subtle, gypsum-inorganic pigment blends enhanced flexural and compressive resistance due to the fibrous organic foreign materials, which were responsible for the reduced LOI. The reported reduction in colour zeal cues for fixing by optimizing nano-minerals, specifically nano-silica coexisting with the radical-altered elements, RADIALS. These nanosilica particles, among other nanominerals, originate from the growth media (Abdul-Malik *et al*., 2025), which later polymerise into

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mineral templates. TRX-cells®' colour-binding property and enhanced flexural resistance suggest its prospective use in ceiling styling to achieve visual comfort, acoustic control, and energy efficiency.

Conclusion

Compositional-driven softness is the principal characteristic of TRX-cells®, enabling curved surface coating with colour enhancement that highlights the use of GyP18-TRX in the trending gypsum art interior design. The nano cells' horizontal soft cushioning provides a comfortable feel when colour paste strikes the gypsum mural, and the bending-resistant nature of the finished panel enables portability. Given the oil-milling waste origin of TRX-cells®, the enhanced flexural strength of GyP18-TRX is a value-added feature that extends the circular resource loop of the construction and demolition sector through symbiosis with the food and interior decoration industries. In essence, the benefits from a socio-enterprise perspective include commoditizing gypsum waste by integrating it with TRX-cells® generated through simple circular nanotechnology within the Construction-Interior Design-Palm Oil Milling industrial symbiosis. Such a venture defines a specific use for construction and demolition waste (CDW), circularising its management.

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