

Optimisation of Mine Dust, Clay and Recycled Polyethylene Proportions for Improved Mechanical and Physical Properties of Lightweight Construction Composites

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Abstract

Mine dust from dimension-stone quarrying and expansive clay excavated during construction accumulate as unmanaged by-products in peri-urban Kenya, while post-consumer polyethylene continues to burden landfills. This study determined the proportions of mine dust, clay and recycled polyethylene that give the best combined mechanical and physical performance in a ternary composite intended for lightweight, non-load-bearing partitions. Nine formulations were prepared for each polymer type following a Taguchi L9 orthogonal array with three control factors, recycled polymer, clay and mine dust, at three levels each. Composites were produced by melt intercalation at 170°C for high-density polyethylene (HDPE) and 140°C for low-density polyethylene (LDPE), and then evaluated for compressive strength (ASTM D695-15), surface roughness (ISO 4287) and water absorption (ASTM D570-98). Signal-to-noise ratios, analysis of variance and linear regression were used to identify the optimal proportions and to quantify the contribution of each constituent. The optimal formulations were 400 g polymer, 10 g clay and 80 g mine dust for HDPE, equivalent to 82%, 2% and 16% by mass, and 200 g polymer, 10 g clay and 80 g mine dust for LDPE, equivalent to 69%, 3% and 28% by mass. The polymer fraction governed HDPE behaviour, contributing 81.92% to compressive strength, 91.20% to surface roughness and 95.09% to water absorption, whereas mine dust governed LDPE behaviour, contributing 93.98%, 88.81% and 85.71% respectively. Regression models reproduced the measured responses with coefficients of determination above 0.9. Confirmation specimens produced at the

optimal settings reached compressive strengths of 1.63 MPa (HDPE) and 2.48 MPa (LDPE) and gained no more than 0.002 g after immersion, indicating adequate strength and dimensional stability for partitions and facade infill panels.

Keywords

Mine Dust, Recycled Polyethylene, Clay, Taguchi Optimisation, Lightweight Composite

1. Introduction

Polymers are used across almost every manufacturing sector because they are cheap, easy to form and light [1] [2]. Their spread through textiles, construction, medicine and electronics [3] has produced waste volumes that municipal systems in most developing economies cannot absorb [4]. Converting that waste into construction materials is one of the few disposal routes that retains value rather than destroying it [5]. Recycled polymers combined with mineral reinforcement yield composites whose mechanical and physical properties can be tuned for specific building elements [6], and lightweight partition systems are a particularly good fit because they carry no vertical load and therefore tolerate modest strength while benefiting greatly from low self-weight.

Kenya generates two mineral waste streams that suit this purpose. Dimension-stone quarrying around Joska, Machakos County, produces large volumes of fine particulate rock dust that degrades air quality and sterilises productive land. Separately, expansive clay excavated during building and road works is dumped indiscriminately, blocking natural and constructed drainage and contributing to localised flooding in the rainy season. Neither material is suitable for conventional construction on its own, the first because it is unbound and the second because of its swelling potential and structural instability, yet both are abundant, free and chemically stable.

Earlier work on recycled plastics for building materials has concentrated on agricultural and industrial additives, such as fly ash [7], coconut shell powder [8] and hybrid clay-fibre systems [9], which perform competitively against synthetic reinforcement [10]. Mineral fillers have proved equally effective: Linz-Donawitz slag [11], red mud [12], granite powder [13], aluminium powder [14] and blast furnace slag [15] all raise stiffness and durability when dispersed in a polymer matrix. Working with the same quarry waste stream used here, Shagwira *et al.* [16] showed that quarry dust in HDPE and polypropylene increases Shore D hardness monotonically with filler content, reaching a value of 82 at 80 wt% dust, but that water absorption rises sharply beyond 60 wt% and impact strength exceeds that of the pure polymer only at low loading. That result frames the problem addressed here: filler content improves some properties and degrades others, so the useful question is not whether mineral waste can be used but in what proportion.

The answer depends on more than filler fraction alone. Composite performance is set by the quality of the filler-matrix interfacial bond, the uniformity of particle dispersion, the porosity of the consolidated matrix and the rheology of the melt during processing [17] [18]. Stiffness generally rises with reinforcement content [19], but only while the matrix can still wet and encapsulate the particles; beyond that point agglomeration and voids reverse the trend [20] [21]. In melt intercalation, the loading conditions, shear rate, mixing time and temperature, govern how far the clay layers exfoliate, and viscous polyethylenes need enough shear and heat to achieve intercalation without thermally degrading the organic constituents [22]. Residence time, mixing geometry and the choice of compatibiliser further complicate the picture [23] [24]. Because these variables interact, changing one constituent shifts the response of the others, and single-factor experimentation is both slow and misleading.

The Taguchi design of experiments addresses exactly this situation. It uses orthogonal arrays to explore a multi-factor space with a small number of runs, ranks factor influence through signal-to-noise ratios and identifies robust settings that hold up against process noise [25]. It has been applied widely to polymer processing, including shrinkage and warpage control in thin-wall mouldings [26] [27] and the optimisation of mechanical properties in recycled plastic products [28], and it is well suited to a formulation problem in which the responses of interest, strength, surface quality and moisture resistance, pull in different directions.

Despite this body of work, the ternary combination of mine dust as filler, expansive clay as reinforcement and recycled polyethylene as matrix has not been systematically proportioned. This paper reports that optimisation. The objective was to determine the compositions of mine dust, clay and recycled polymer that give improved mechanical and physical properties, using compressive strength, surface roughness and water absorption as the response variables and covering both high-density and low-density recycled polyethylene.

2. Materials and Methods

2.1. Materials

Recycled high-density polyethylene (HDPE) and low-density polyethylene (LDPE) were obtained in pellet form from Polymer Recycling Industries, Kariobangi, Nairobi. Recycled and virgin polyethylene blends differ in degree rather than in kind: recycled material shows lower crystallinity and melting temperature because of chain scission and imperfect crystal formation, and slightly reduced modulus and yield strength, while crystallisation temperature, storage modulus and phase compatibility remain comparable to virgin material [29]. The reduction in stiffness is therefore predictable and does not preclude structural use at the modest stress levels required of partitions.

Mine dust was collected from dimension-stone quarrying operations in Joska, Machakos County (1°17'3"S, 37°5'51"E). Expansive clay was recovered from construction spoil disposal sites in the same area. Both minerals were dried, ground and sieved to a uniform particle size of 45 µm, a size range that promotes uniform

dispersion and effective interfacial bonding in polymer-clay systems [30]. The four constituents are shown in their prepared state in **Figure 1**. Elemental composition was determined by X-ray fluorescence spectroscopy and is given in **Table 1**. Both materials are silica-dominated, but they differ in a way that matters for composite behaviour: the mine dust is the more siliceous of the two at 71.41% SiO₂ with negligible magnesia, whereas the clay carries 21.12% CaO, roughly nine times the calcium content of the dust. The alumina contents are similar, at 11.69% and 12.65% respectively.

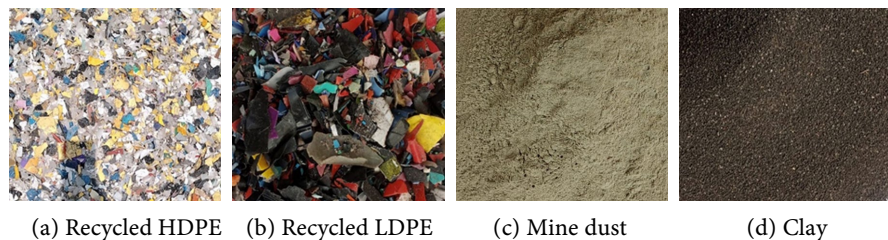


Figure 1. Constituent materials used in the composite formulations.

Table 1. Chemical composition of the mine dust and clay determined by X-ray fluorescence spectroscopy (mass %).

Material	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	S	Cl	K ₂ O	CaO	Ti	Fe
Mine dust	2.967	11.694	71.410	0.044	0.226	0.168	5.969	2.388	0.336	4.431
Clay	0.000	12.649	55.502	0.210	0.615	0.615	4.155	21.123	0.580	4.690

2.2. Design of Experiments

Three control factors, polymer, clay and mine dust, were each investigated at three levels (**Table 2**). The number of runs required follows from the degrees of freedom, Equation (1).

Table 2. Control factors and their levels.

Factor	Unit	Symbol	Level 1	Level 2	Level 3
Polymer	g	P	200	300	400
Clay	g	C	10	25	40
Mine dust	g	M	20	50	80

$$\text{DOF} = 1 + \sum (L_i - 1) \quad (1)$$

where DOF is the degrees of freedom, L_i is the number of levels of factor i and the summation runs over the number of independent variables. For three factors at three levels this gives seven degrees of freedom, which the L9 orthogonal array satisfies with nine runs (**Table 3**) instead of the twenty-seven a full factorial would demand. All factors vary simultaneously between runs according to the array rather than one at a time. The design and the subsequent statistical analysis were carried out in Minitab.

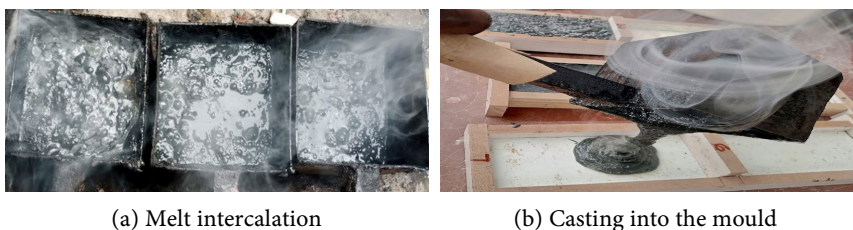
Table 3. Taguchi L₉ orthogonal array used for the nine formulations.

Run	Polymer (g)	Clay (g)	Mine dust (g)
1	200	10	20
2	200	25	50
3	200	40	80
4	300	10	50
5	300	25	80
6	300	40	20
7	400	10	80
8	400	25	20
9	400	40	50

One consequence of this design should be stated at the outset. The three constituent masses were varied independently rather than within a fixed total, so the total batch mass ranges from 230 g to 490 g across the array. Constituent proportion and total mass processed are therefore confounded, and the effects reported below are effects of the constituent masses as charged, not of composition at constant batch size. The conclusions are accordingly limited to the batch masses tested. A fixed-total mixture design would separate the two and is recommended for subsequent work.

2.3. Composite Preparation

Recycled polymer was charged into a preheated steel mould measuring 100 mm × 100 mm × 100 mm and held until fully molten (**Figure 2(a)**). The premixed mine dust and clay were then introduced gradually into the melt and the mixture was stirred manually for approximately ten minutes. Elevated temperature combined with shear drives polymer chains into the pores and surface irregularities of the mineral particles, which improves polymer-filler adhesion, promotes exfoliation of the clay platelets and produces a uniform particle distribution through the matrix [31]. Mixing temperature was held at 170°C for HDPE and 140°C for LDPE to prevent thermal degradation while keeping melt viscosity low enough for wetting. The molten composite was poured into moulds and left to cool and solidify at room temperature (**Figure 2(b)**), after which specimens were demoulded and sectioned to the dimensions required for each test.

**Figure 2.** Preparation of the mine dust-clay-recycled polyethylene composite.

2.4. Property Evaluation

Compression testing followed ASTM D695-15. Prismatic specimens measuring 12 mm × 12 mm × 25 mm were cut from the cast blocks on a Struers Accutom-50 precision cutting machine to obtain smooth, parallel and dimensionally consistent faces, surface irregularity on a compression specimen being a source of stress concentration that depresses the recorded strength. Specimens were conditioned at 23°C and ambient laboratory humidity for at least 40 h before testing, as required by the standard. Load was applied along the 25 mm axis on a GUNT WP 300 materials testing machine of 20 kN capacity (**Figure 3(a)**) at the crosshead rate of 1.3 mm/min specified in ASTM D695-15, with the specimen seated centrally between hardened platens (**Figure 3(b)**). One specimen was tested for each of the nine screening formulations, and the values in **Table 4** and **Table 5** are therefore individual measurements rather than means; four replicate specimens were tested at each of the two optimal settings and are reported in Section 3.6. Failure was consistently brittle: specimens split along planes parallel to the loading axis and separated into angular fragments rather than deforming plastically (**Figure 3(c)** and **Figure 3(d)**), which is the response expected of a highly filled polyethylene matrix in which the mineral phase carries a large share of the load.

Table 4. Measured responses for the HDPE composite formulations.

Run	Polymer (g)	Clay (g)	Mine dust (g)	Compressive strength (MPa)	Surface roughness Ra (μm)	Water absorption (g)	Water absorption (%)
1	200	10	20	0.582	8.680	0.035	0.94
2	200	25	50	0.703	7.250	0.032	0.77
3	200	40	80	0.956	7.980	0.030	0.67
4	300	10	50	1.195	4.850	0.020	0.52
5	300	25	80	1.262	5.860	0.020	0.49
6	300	40	20	0.983	5.740	0.025	0.65
7	400	10	80	1.626	3.950	0.011	0.28
8	400	25	20	1.349	4.270	0.013	0.36
9	400	40	50	1.384	3.850	0.012	0.31

Table 5. Measured responses for the LDPE composite formulations.

Run	Polymer (g)	Clay (g)	Mine dust (g)	Compressive strength (MPa)	Surface roughness Ra (μm)	Water absorption (g)	Water absorption (%)
1	200	10	20	0.895	6.250	0.050	1.38
2	200	25	50	1.627	3.705	0.030	0.75
3	200	40	80	2.180	2.567	0.020	0.46

Continued

4	300	10	50	1.363	3.898	0.040	1.08
5	300	25	80	2.281	1.806	0.020	0.50
6	300	40	20	0.520	7.852	0.070	1.89
7	400	10	80	2.484	2.242	0.010	0.27
8	400	25	20	0.428	5.562	0.050	1.41
9	400	40	50	1.189	4.265	0.040	1.06



(a) GUNT WP 300 testing machine



(b) Specimen between the platens



(c) Failed specimen on the lower platen



(d) Fragments recovered after compression

Figure 3. Compression testing arrangement and the condition of specimens after loading.

Surface roughness was measured with a confocal laser scanning microscope (LEXT OLS5100, Olympus) following ISO 4287:1997, giving the arithmetic mean roughness R_a , the root mean square roughness R_q and the maximum peak-to-valley height R_z [32]. R_a is reported here as the response variable.

Water absorption followed ASTM D570-98 on specimens measuring 60 mm × 60 mm × 1 mm. Specimens were dried for 24 h at 50 °C, cooled in a desiccator and weighed to obtain the dry mass before immersion in distilled water at 23 °C [33], following the conditioning procedure of the standard. Specimens were weighed on a balance of 0.001 g resolution after 4, 8, 12, 16 and 20 hours and after 1 day, 1 week, 2 weeks and 4 weeks, and the four-week value is reported. Uptake is given both as an absolute mass change and as a percentage of the dry mass. Because the specimens differ in density with composition, from 0.985 to 1.250 g/cm³ across the array, their dry masses differ from 3.54 g to 4.50 g for a common specimen

volume of 3.6 cm³, and the percentage basis is the one on which formulations can properly be compared. The dry mass used for each formulation is the product of that volume and the composite density calculated by rule of mixtures from the constituent volume fractions. Absolute gains at the optimised settings approach the resolution of the balance, so those values support an order-of-magnitude comparison against the screening formulations rather than precise ranking among themselves.

2.5. Statistical Analysis

Compressive strength is a larger-the-better characteristic, so its signal-to-noise ratio was computed from Equation (2).

$$S/N \text{ (larger-the-better)} = -10 \log \left[(1/n) \sum (1/y_{ij}^2) \right] \quad (2)$$

Surface roughness and water absorption are smaller-the-better characteristics, evaluated using Equation (3).

$$S/N \text{ (smaller-the-better)} = -10 \log \left[(1/n) \sum y_{ij}^2 \right] \quad (3)$$

In both expressions y_{ij} is the measured response, n is the number of observations in the factor-level combination, i runs over observations and j over factor levels. A higher signal-to-noise ratio always indicates better quality, so the optimal level of each factor is the one with the highest ratio regardless of the direction of the underlying characteristic. Analysis of variance was then used to apportion the total variation among the three constituents, and linear regression was used to express each response as a function of the three constituent masses.

The three constituents were entered into the analysis of variance as continuous linear predictors expressed in grams rather than as categorical three-level factors, which is why each carries a single degree of freedom in the analysis reported in Section 3.3. Only linear main effects were fitted; no quadratic terms and no two-factor interactions were included. Any curvature in the response across the three levels tested is therefore not captured by the model and is absorbed into the residual.

One specimen was tested for each of the nine screening runs, so $n = 1$ in both expressions. The signal-to-noise ratio is therefore a monotonic transformation of a single response rather than a measure of within-condition variability, and it ranks the factor levels without demonstrating robustness against replicate scatter. For the same reason the residual term in the analysis of variance represents the portion of the between-run variation not accounted for by the three linear main effects, rather than an independent estimate of pure experimental error. Replication was instead concentrated at the two optimal settings, where four specimens were tested for each system. This limitation is restated in Section 3.8.

3. Results and Discussion

3.1. Measured Responses

Table 4 and **Table 5** give the compressive strength, surface roughness and four-

week water absorption for the nine HDPE and nine LDPE formulations. The two polymer systems behave differently enough to be worth separating. In the HDPE composites the three responses move together and track the polymer content almost monotonically: compressive strength climbs from 0.582 MPa at 200 g polymer to 1.626 MPa at 400 g, roughness falls from 8.680 μm to 3.950 μm and water absorption drops from 0.035 g to 0.011 g. Filler content produces only second-order shifts within each polymer level.

The LDPE composites show the opposite pattern. Compressive strength is governed by mine dust content, rising from 0.428 MPa to 2.484 MPa, and the three runs with 20 g of mine dust are the three weakest in the set regardless of polymer level. Run 6 (300 g polymer, 40 g clay, 20 g mine dust) and run 8 (400 g polymer, 25 g clay, 20 g mine dust) return the lowest strengths, 0.520 MPa and 0.428 MPa, together with the roughest surfaces and the highest water uptake, while the highest-strength runs are those combining 80 g of mine dust with low clay. The physical explanation is straightforward: LDPE is the less viscous and less crystalline matrix, so it contributes little intrinsic stiffness and the rigid mineral phase has to carry the load transfer.

3.2. Signal-to-Noise Analysis and Optimal Proportions

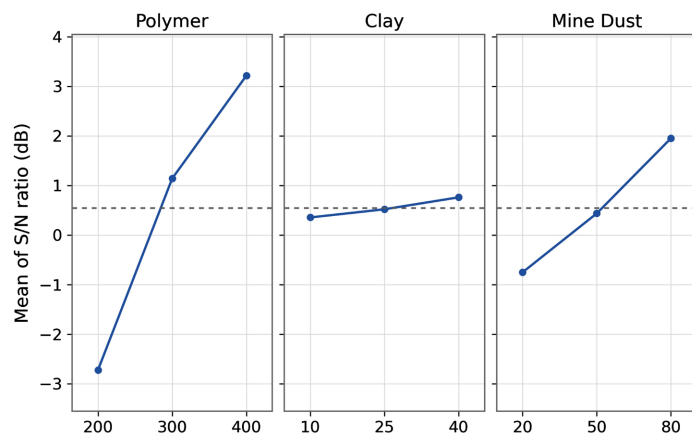
Table 6 and **Table 7** give the mean signal-to-noise ratio at each factor level, together with the delta value, the range between the highest and lowest level means, and the resulting rank. **Figure 4** and **Figure 5** show the corresponding main effects plots.

Table 6. Signal-to-noise response table for the HDPE composite (dB).

Response	Level	Polymer	Clay	Mine dust
Compressive strength	1	−2.7178	0.3554	−0.7501
	2	1.1399	0.5202	0.4364
	3	3.2144	0.7610	1.9502
	Delta	5.9322	0.4056	2.7003
	Rank	1	3	2
Surface roughness	1	−18.01	−14.81	−15.52
	2	−14.75	−15.06	−14.21
	3	−12.08	−14.98	−15.11
	Delta	5.92	0.25	1.31
	Rank	1	3	2
Water absorption	1	29.82	34.09	32.96
	2	33.33	33.87	34.10
	3	38.44	33.64	34.54
	Delta	8.61	0.45	1.58
	Rank	1	3	2

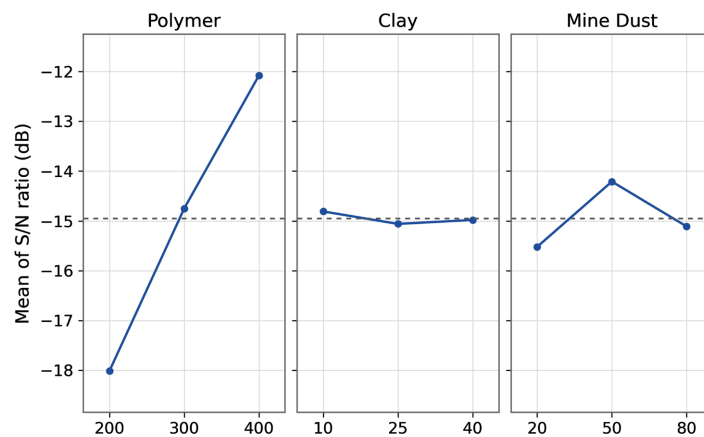
Table 7. Signal-to-noise response table for the LDPE composite (dB).

Response	Level	Polymer	Clay	Mine dust
Compressive strength	1	3.3439	3.2096	-4.6683
	2	1.3934	1.3419	2.8080
	3	0.6809	0.8667	7.2785
	Delta	2.6630	2.3429	11.9468
	Rank	2	3	1
Surface roughness	1	-11.828	-11.582	-16.240
	2	-11.617	-10.472	-11.933
	3	-11.508	-12.899	-6.780
	Delta	0.319	2.427	9.461
	Rank	3	2	1
Water absorption	1	30.15	31.33	25.05
	2	28.35	30.15	28.79
	3	31.33	28.35	35.99
	Delta	2.98	2.98	10.94
	Rank	2.5	2.5	1



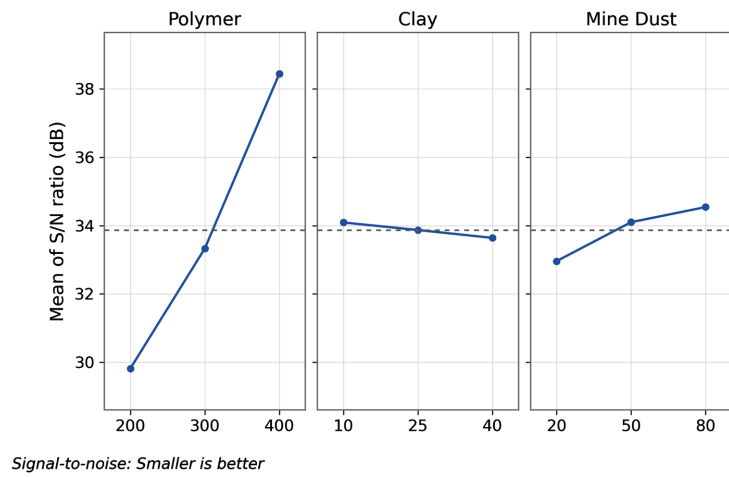
Signal-to-noise: Larger is better

(a) Compressive strength

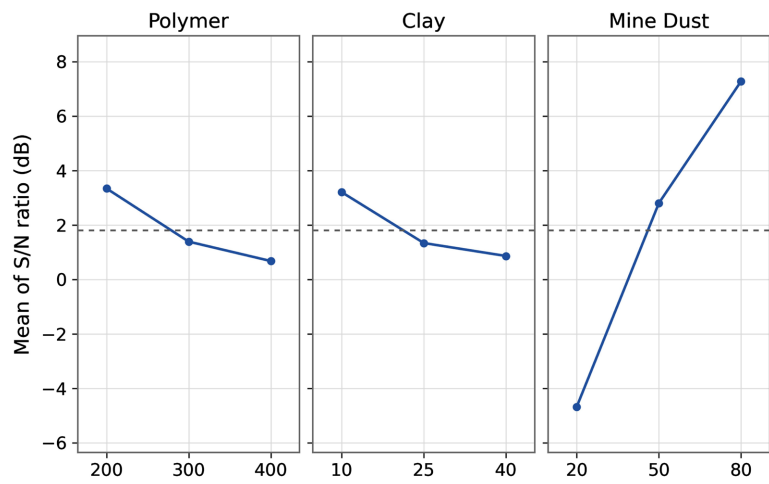


Signal-to-noise: Smaller is better

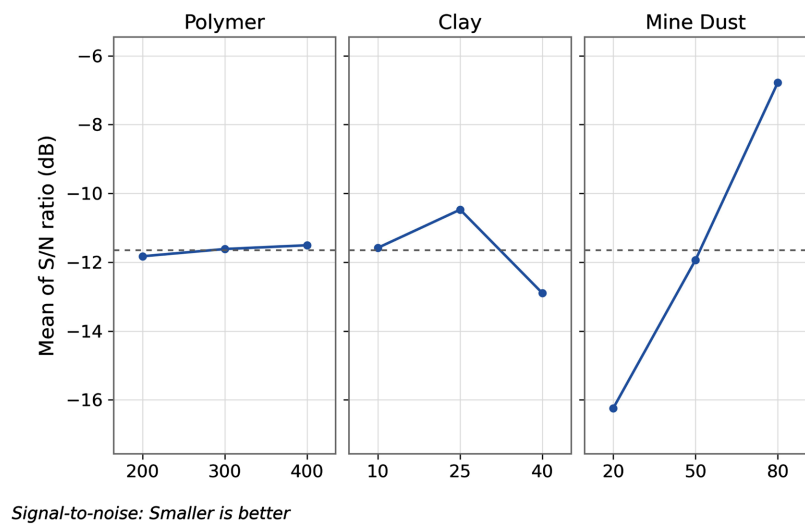
(b) Surface roughness



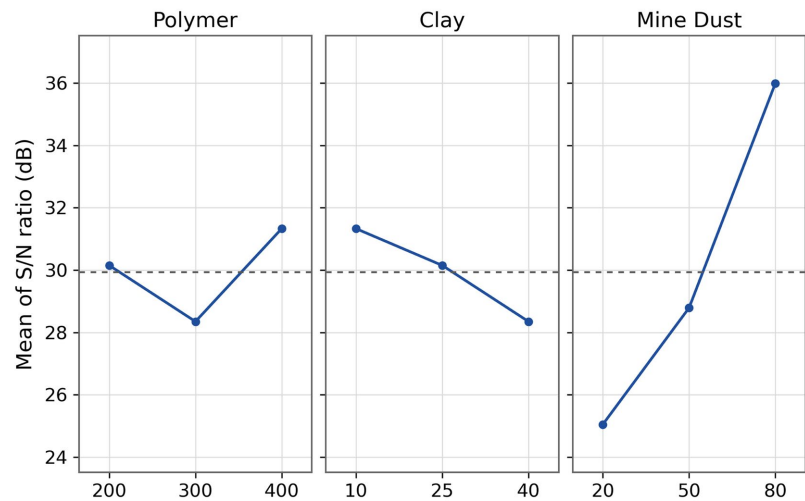
(c) Water absorption

Figure 4. Main effects plots of the signal-to-noise ratios for the HDPE composite.

(a) Compressive strength



(b) Surface roughness



Signal-to-noise: Smaller is better

(c) Water absorption

Figure 5. Main effects plots of the signal-to-noise ratios for the LDPE composite.

For the HDPE composites the polymer is ranked first for all three responses, with deltas of 5.93, 5.92 and 8.61 for compressive strength, surface roughness and water absorption respectively. Mine dust is consistently second and clay a distant third, its delta never exceeding 0.45. For the LDPE composites the ranking inverts: mine dust leads on every response with deltas of 11.95, 9.46 and 10.94, while polymer and clay are close to each other and far behind.

Each response taken individually points to a slightly different combination, which is the usual outcome of a multi-response Taguchi study. Because the intended application is a partition element whose primary structural requirement is resistance to compression, maximum compressive strength was adopted as the governing criterion. On that basis the optimal proportions are 400 g polymer, 10 g clay and 80 g mine dust for HDPE, and 200 g polymer, 10 g clay and 80 g mine dust for LDPE. Expressed as mass fractions these correspond to 82% polymer, 2% clay and 16% mine dust for the high-density system, and 69% polymer, 3% clay and 28% mine dust for the low-density system. Both optima select the lowest clay level, which is consistent with the small deltas recorded for clay throughout and indicates that at these particle sizes the clay is acting more as an inert extender than as a reinforcing phase.

3.3. Factor Contributions

Analysis of variance quantifies what the signal-to-noise ranking indicates qualitatively. **Table 8** and **Table 9** give the degrees of freedom, adjusted sums of squares and mean squares, F and P values and percentage contribution for each constituent. A factor is taken to be significant where F exceeds 5 and P is below 0.05; a P value above 0.05 indicates that the observed variation is more plausibly experimental error than a real effect of the factor.

Table 8. Analysis of variance for the HDPE composite.

Response	Factor	DF	Adj SS	Adj MS	F	P	Contribution (%)
Compressive strength	Polymer	1	0.747372	0.747372	187.59	0.000	81.92
	Clay	1	0.001056	0.001056	0.27	0.629	0.12
	Mine dust	1	0.144026	0.144026	36.15	0.002	15.79
	Error	5	0.019920	0.003984			2.18
	<i>Total</i>	<i>8</i>	<i>0.912374</i>				<i>100.00</i>
Surface roughness	Polymer	1	23.3643	23.3643	55.15	0.001	91.20
	Clay	1	0.0014	0.0014	0.00	0.957	0.01
	Mine dust	1	0.1350	0.1350	0.32	0.597	0.53
	Error	5	2.1184	0.4237			8.27
	<i>Total</i>	<i>8</i>	<i>25.6190</i>				<i>100.00</i>
Water absorption	Polymer	1	0.000620	0.000620	404.46	0.000	95.09
	Clay	1	0.000000	0.000000	0.11	0.755	0.00
	Mine dust	1	0.000024	0.000024	15.65	0.011	3.68
	Error	5	0.000008	0.000002			1.23
	<i>Total</i>	<i>8</i>	<i>0.000652</i>				<i>100.00</i>

Table 9. Analysis of variance for the LDPE composite.

Response	Factor	DF	Adj SS	Adj MS	F	P	Contribution (%)
Compressive strength	Polymer	1	0.05998	0.05998	3.10	0.138	1.30
	Clay	1	0.12121	0.12121	6.27	0.054	2.63
	Mine dust	1	4.33806	4.33806	224.44	0.000	93.98
	Error	5	0.09664	0.01933			2.09
	<i>Total</i>	<i>8</i>	<i>4.61589</i>				<i>100.00</i>
Surface roughness	Polymer	1	0.0336	0.0336	0.06	0.812	0.11
	Clay	1	0.8809	0.8809	1.66	0.255	2.76
	Mine dust	1	28.3751	28.3751	53.32	0.001	88.81
	Error	5	2.6608	0.5322			8.33
	<i>Total</i>	<i>8</i>	<i>31.9504</i>				<i>100.00</i>
Water absorption	Polymer	1	0.00000	0.00000	0.00	1.000	0.00
	Clay	1	0.00015	0.00015	3.00	0.144	5.36
	Mine dust	1	0.00240	0.00240	48.00	0.001	85.71
	Error	5	0.00025	0.00005			8.93
	<i>Total</i>	<i>8</i>	<i>0.00280</i>				<i>100.00</i>

In the HDPE composites the polymer content accounts for 81.92% of the variation in compressive strength ($F = 187.59$, $P = 0.000$), 91.20% of the variation in surface roughness ($F = 55.15$, $P = 0.001$) and 95.09% of the variation in water absorption ($F = 404.46$, $P = 0.000$). Mine dust is significant only for compressive strength and water absorption, contributing 15.79% and 3.68%, and clay is not significant for any response, contributing at most 0.12%. The rheological and interfacial behaviour of the matrix therefore sets the achievable strength, the quality of the surface finish, the residual porosity and the resulting moisture response, while the mineral phase contributes stiffness and dimensional stability rather than primary load capacity.

In the LDPE composites mine dust accounts for 93.98% of the variation in compressive strength ($F = 224.44$, $P = 0.000$), 88.81% of the variation in surface roughness ($F = 53.32$, $P = 0.001$) and 85.71% of the variation in water absorption ($F = 48.00$, $P = 0.001$). Polymer content is not significant for any response and contributes essentially nothing to water absorption. In a matrix this compliant the rigidity, packing density and pore-filling capacity of the mine dust determine how stress is transferred between particles, how smooth the consolidated surface becomes and how far water can penetrate.

Taken together the two analyses show that the same three constituents can be governed by different mechanisms depending on which polyethylene is used, and that a formulation optimised for one matrix should not be transferred to the other without re-optimisation.

3.4. Regression Models

Linear regression was used to express each response as a function of the constituent masses, where A is the polymer mass in grams, B the clay mass and C the mine dust mass. Equations (4) to (6) apply to the HDPE composites and Equations (7) to (9) to the LDPE composites.

$$\text{Compressive strength} = -0.179 + 0.003529A - 0.00088B + 0.005164C \quad (4)$$

$$\text{Surface roughness} = 11.97 - 0.01973A + 0.0010B - 0.00500C \quad (5)$$

$$\text{Water absorption} = 0.05556 - 0.000102A + 0.000011B - 0.000067C \quad (6)$$

$$\text{Compressive strength} = 0.561 - 0.001000A - 0.00948B + 0.02834C \quad (7)$$

$$\text{Surface roughness} = 7.45 - 0.00075A + 0.0255B - 0.07249C \quad (8)$$

$$\text{Water absorption} = 0.0617 + 0.000000A + 0.000333B - 0.000667C \quad (9)$$

The signs of the coefficients reproduce the analysis of variance. For HDPE the polymer term dominates every expression and carries the expected sign, positive for strength and negative for both roughness and water uptake. For LDPE the mine dust term dominates, with a coefficient on compressive strength (0.02834) an order of magnitude larger than the polymer term, and the polymer coefficient for water absorption falls to zero. Coefficients of determination exceeded 0.9 for all six models, so the predicted and measured responses agree closely and the models can be used to interpolate compositions between the tested levels.

3.5. Multiple-Response Prediction

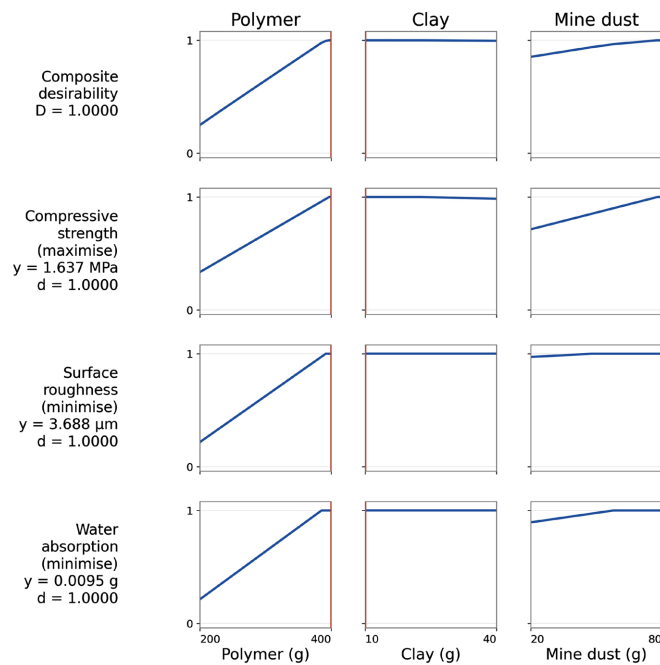
Because the three responses are optimised in different directions, a composite desirability analysis was run to confirm that a single formulation can satisfy all three simultaneously. **Table 10** gives the predicted fits at the optimal settings with their standard errors and the 95% confidence and prediction intervals, and **Figure 6** shows the corresponding optimisation plots, in which each response and the composite desirability are traced across the range of one constituent while the other two are held at their optimal values. The HDPE setting achieved a composite desirability of 1.000 and the LDPE setting 0.9907, so neither optimum requires a meaningful trade-off between the three characteristics. **Figure 6** also shows why the two systems differ: for HDPE the desirability rises steeply with polymer content and is nearly flat in clay, whereas for LDPE it is mine dust that drives the composite desirability while polymer and clay are comparatively flat. All fitted values fall within their prediction intervals. Two of the LDPE intervals extend below zero: the prediction interval for surface roughness, -0.624 to 4.136 μm , and both the confidence and the prediction intervals for water absorption, -0.0025 to 0.0259 g and -0.0114 to 0.0347 g respectively. The corresponding intervals for LDPE compressive strength, 2.254 to 2.813 MPa and 2.080 to 2.987 MPa, remain above zero throughout. The intervals that cross zero reflect the wider scatter in those two responses rather than a failure of the model, and the negative limits have no physical meaning since neither roughness nor mass gain can be negative. The confidence interval bounds the mean response at the optimal setting, whereas the wider prediction interval bounds a single future observation at that setting.

Table 10. Predicted responses at the optimal settings with 95% confidence and prediction intervals.

System	Response	Fit	SE fit	95% CI	95% PI
HDPE	Compressive strength (MPa)	1.6366	0.0493	(1.5098, 1.7635)	(1.4307, 1.8426)
	Surface roughness Ra (μm)	3.6870	0.5090	(2.379, 4.995)	(1.563, 5.811)
	Water absorption (g)	0.0097	0.0010	(0.0072, 0.0122)	(0.0056, 0.0137)
LDPE	Compressive strength (MPa)	2.5330	0.1090	(2.254, 2.813)	(2.080, 2.987)
	Surface roughness Ra (μm)	1.7560	0.5700	(0.290, 3.222)	(-0.624 , 4.136)
	Water absorption (g)	0.0117	0.0055	(-0.0025 , 0.0259)	(-0.0114 , 0.0347)

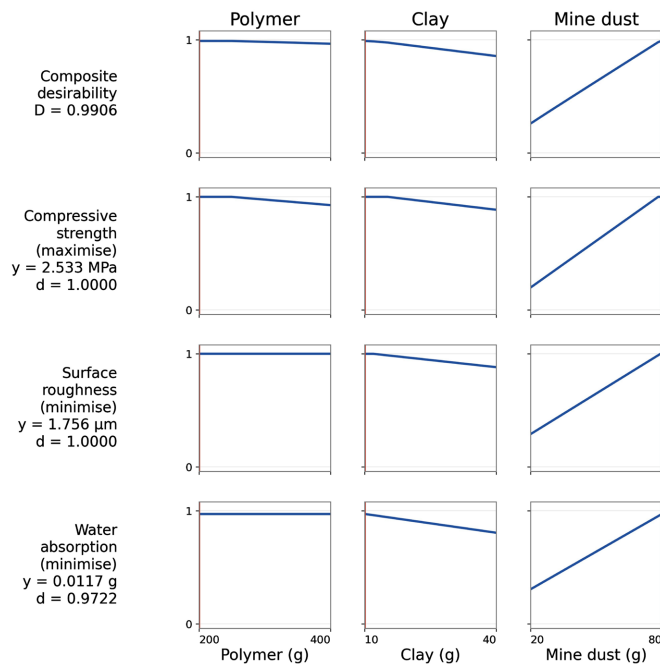
Settings: HDPE, polymer 400 g, clay 10 g, mine dust 80 g; LDPE, polymer 200 g, clay 10 g, mine dust 80 g.

HDPE · optimum 400 / 10 / 80 g



(a) HDPE composite

LDPE · optimum 200 / 10 / 80 g



(b) LDPE composite

Figure 6. Multiple-response optimisation plots for the two composite systems. Each cell traces the individual desirability of one response, or the composite desirability, across the range of one constituent with the other two held at their optimal values; the vertical line marks the optimal setting. Computed from the regression models of Section 3.4 using the Derringer-Suich desirability transform with bounds taken from the observed response ranges.

3.6. Confirmation Tests

Confirmation specimens were produced and tested to verify the predicted performance. The composites reached compressive strengths of 1.63 MPa for HDPE and 2.48 MPa for LDPE, against predicted values of 1.637 MPa and 2.533 MPa. Both measurements fall inside the 95% prediction intervals of **Table 10**, 1.431 to 1.843 MPa and 2.080 to 2.987 MPa respectively, so the optimisation is confirmed for both systems. The composition of the LDPE confirmation batches given in the submitted version of **Table 11** was a transcription error and has been corrected to the optimal setting of 200 g polymer, 10 g clay and 80 g mine dust. The correction is supported by the model: evaluating the LDPE regression at the erroneous entry of 392 g, 10 g and 64 g returns 1.888 MPa, which is inconsistent with the 2.48 MPa measured, whereas evaluation at 200 g, 10 g and 80 g returns 2.533 MPa, which the measurement matches. Expressed as mass fractions the corrected confirmation composition is 69.0% polymer, 3.4% clay and 27.6% mine dust. **Table 11** gives the mass change recorded for four replicate specimens of each system after immersion. Uptake did not exceed 0.026% of dry mass for the HDPE specimens or 0.048% for the LDPE specimens, against ranges of 0.28% to 0.94% for the HDPE screening runs and 0.27% to 1.89% for the LDPE screening runs. The optimised formulations therefore absorb roughly an order of magnitude less water than the screening formulations.

Table 11. Mass change of confirmation specimens after immersion.

Specimen	Polymer (g)	Clay (g)	Mine dust (g)	Nominal dry mass (g)	Mass change (g)	Water absorption (%)
HDPE-1	400	10	80	3.88	0.000	0.000
HDPE-2	400	10	80	3.88	0.000	0.000
HDPE-3	400	10	80	3.88	0.001	0.026
HDPE-4	400	10	80	3.88	0.000	0.000
LDPE-1	200	10	80	4.15	0.002	0.048
LDPE-2	200	10	80	4.15	0.000	0.000
LDPE-3	200	10	80	4.15	0.001	0.024
LDPE-4	200	10	80	4.15	0.000	0.000

a. Confirmation batches were cast at the optimal settings of Section 3.2. Nominal dry mass is the product of the specimen volume, 3.6 cm³, and the composite density calculated by rule of mixtures from the constituent volume fractions, 1.077 g/cm³ for the HDPE composite and 1.153 g/cm³ for the LDPE composite.

The small spread between replicates, from zero to 0.002 g, is nonetheless real and points to sources of variation not captured by the three compositional factors. Shear rate, mixing duration and temperature uniformity during manual stirring are the most likely candidates, and they would need to be brought into the design as additional control factors to close the gap.

The confirmation results also make explicit the inverse relationship between water absorption and compressive strength visible throughout the screening data. Low water uptake is a marker of good polymer-filler compatibility and a well-consolidated matrix: strong interfacial bonding reduces internal porosity and limits the development of continuous moisture transport paths [34] [35]. A denser microstructure transfers load more efficiently, so the same structural feature that resists water also carries stress. The relationship extends to surface quality. Where water uptake is high, moisture migrating through interconnected pores disrupts particle-matrix bonding and causes localised swelling, softening and micro-void formation [36], which manifests as a rougher surface [37] and further depresses compressive strength.

3.7. Suitability for Lightweight Partitions

At 1.63 MPa and 2.48 MPa the optimised composites are well below the strength of masonry or concrete and are not candidates for load-bearing elements. The application considered here is therefore a non-load-bearing one. Partitions and facade infill panels carry only their own weight and incidental lateral loads, and for these the governing requirements are dimensional stability, resistance to moisture-driven deterioration and low self-weight. The present results address the first and third of those directly and the second only through four-week immersion. They are therefore preliminary evidence of suitability rather than qualification for building service, which would additionally require flexural and impact resistance, reaction-to-fire classification, acoustic performance, long-term creep under sustained load and durability under wet-dry and thermal cycling. Subject to that qualification, the practical significance is that both formulations are dominated by waste input, with 16% to 28% mineral waste bound in a matrix that is itself entirely recycled, so the material diverts two waste streams at once.

3.8. Limitations

Four limitations bound the conclusions drawn above. First, the three constituent masses were varied independently rather than within a fixed total, so constituent proportion is confounded with total batch mass and the results apply to the batch masses tested rather than to composition at constant total. Second, a single specimen was tested for each screening run, so the signal-to-noise ratios transform single observations and cannot demonstrate robustness against within-condition variation, and the residual mean square is not an independent estimate of pure experimental error; replication was concentrated at the two optimal settings. Third, the analysis of variance fitted linear main effects only, so curvature across the three levels and any interactions between constituents are not resolved. Fourth, the dry masses underlying the percentage uptake values are nominal, calculated from specimen volume and rule-of-mixtures density rather than weighed individually, and absolute gains at the optimised settings approach the 0.001 g resolution of the balance, so those values support an order-of-magnitude compar-

ison against the screening formulations but not precise ranking among themselves.

4. Conclusions

This study determined the proportions of mine dust, clay and recycled polyethylene that give the best combined mechanical and physical performance in a ternary composite for lightweight partition applications. The following conclusions are drawn.

1) The optimal proportions are 400 g polymer, 10 g clay and 80 g mine dust for the HDPE composite, equivalent to 82% polymer, 2% clay and 16% mine dust by mass, and 200 g polymer, 10 g clay and 80 g mine dust for the LDPE composite, equivalent to 69% polymer, 3% clay and 28% mine dust by mass.

2) The two systems are governed by different constituents. Polymer content controls the HDPE composite, contributing 81.92% to compressive strength, 91.20% to surface roughness and 95.09% to water absorption. Mine dust controls the LDPE composite, contributing 93.98%, 88.81% and 85.71% to the same three responses. Clay was not a statistically significant factor for any response in either system at the particle size and levels tested.

3) Linear regression models relating compressive strength, surface roughness and water absorption to the three constituent masses achieved coefficients of determination above 0.9, and the multiple-response analysis returned composite desirabilities of 1.000 for HDPE and 0.9907 for LDPE, confirming that a single formulation satisfies all three response criteria simultaneously.

4) Confirmation specimens reached 1.63 MPa (HDPE) and 2.48 MPa (LDPE), both inside the 95% prediction intervals of the optimisation, and absorbed no more than 0.05% of their dry mass after four weeks of immersion. These values are preliminary evidence of suitability for non-load-bearing partitions and facade infill rather than qualification for building service, and they exclude any load-bearing function.

5) Residual variation between replicate confirmation specimens indicates that shear rate, mixing time and temperature uniformity also influence the product. A fixed-total mixture design with replicated runs, inclusion of these processing variables as control factors, direct characterisation of the interfacial microstructure, and the service-related testing listed in Section 3.7 are the recommended next steps.

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Author Contributions

Conceptualization, C. O. and J. M.; methodology, C. O., J. M. and F. M.; investigation, C. O. and B. O.; formal analysis, C. O. and B. O.; data curation, C. O.; writing—original draft preparation, C. O.; writing—review and editing, J. M., B. O. and F. M.; visualization, C. O.; supervision, J. M. and F. M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All data generated and analysed during this study are included in this published article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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