



Graphene Oxide Modification of Concrete Containing Recycled PET Fine Aggregate

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Abstract : Recycled polyethylene terephthalate (PET) can be used as a partial replacement for the natural fine aggregate in concrete, although its integration can affect workability, strength, and transport behavior. The present work investigates if small additions of graphene oxide (GO) counteract these effects utilizing seven combination techniques presented in a thesis. The program consisted of a control, 5% and 10% PET substitution by original sand mass, 0.03% and 0.05% GO addition by cement mass, and two selected hybrids of 5% PET with 0.03% GO and 10% PET with 0.05% GO. The nominal water/cement ratio was 0.40. Fresh characteristics, compressive strength at 7, 28, and 56 days, 28-day splitting tensile and flexural strength, water transport, and electrical charge were comparatively described. The 28-day compressive strength reduced from 38.6 MPa of the control to 36.8 and 33.9 MPa of PET-only mixes. GO enhanced the respective hybrid means to 39.7 and 37.5 MPa, respectively, an enhancement of 7.9% and 10.6% over matching PET-only mixes. The lower-dose hybrid also reduced reported absorption from 4.50% to 3.80% and charge passed from 3500 C to 2600 C; slump declined from 76 to 68 mm. The two hybrids were below the research placement target of 75-100 mm. These data are consistent with the descriptive compensation of performance penalties associated with PET, with the lower-dose hybrid presenting a more robust overall profile than the two hybrids tested. They don't provide statistical synergy, continual optimum, or structural-grade acceptance. There are no specimen-level results, the independent replication of batches is unknown, test records are incomplete, and there is unreconciled reproducibility and inference regarding the nominal yield. The results identify candidates for confirmatory testing rather than qualified field mixtures.

IndexTerms - recycled PET; graphene oxide; fine aggregate replacement; concrete strength; sorptivity; workability; transport indicators

1 Introduction

The use of post-consumer plastic in concrete provides a possible outlet for some waste streams and may lower the volume of virgin aggregate specified in a mix. The benefits depend on the polymer, particle geometry, replacement basis, and performance attained. PET particles used as aggregate should be separated from PET fibers because changing part of the granular skeleton is a distinct operation from adding elongated reinforcement. Early PET aggregate studies show the significance of dose and particle properties [1-3]. Therefore, data obtained from fibers, other polymers, or using other replacement conventions cannot be directly translated to the present system.

The specific gravity of PET is far less than that of real sand. Thus, an equal-mass swap adds more solid volume than the volume of sand removed [4-7]. This alters the link between the quantities of nominal mixture, packaging, and actual concrete yield. Reduced density may be advantageous in some applications, but neither low density nor waste incorporation leads to sufficient mechanical performance. A proper assessment should take workability and hardened qualities together and keep a clear separation between recipe quantities and verified contents per unit volume [8-11]. The chemistry and dispersion of GO could affect the reactivity of the cement matrix; hence, GO is studied as a cementitious-material modifier. Published concrete research covers both mechanical characteristics and transport-related measurements [4]. However, a positive GO-only response does not prove that GO will compensate for PET-related alterations under similar production conditions. Product identity, solids concentration, dispersion, carrier water, and compatibility with the admixture continue to be of relevance in the interpretation of a mixed mixture [12]. The research objective is thus: do the described hybrid mixtures recover performance relative to matched PET-only mixtures, and is such recovery followed by an appropriate fresh-state response? The contribution is a clear comparison of seven reported combinations, with consistent denominators and an unambiguous placement screen. The dataset is an incomplete treatment design, designed to discover promising tried combinations and evidence needed for confirmation, rather than to create a general PET-GO interaction law.

Additional primary investigations allow us to distinguish between claims on constituent effects and combined-mixture effects. Akçaözöglu et al. [13] explored shredded PET aggregate, Hannawi et al. [14] examined PET and polycarbonate aggregates in mortar and Rahmani et al. [15] investigated processed PET particles in concrete. Saikia and de Brito [16] extended the mechanical

examination to abrasion and Silva et al. studied the curing conditions and durability related reaction. [17]. These investigations encourage attention to material form, replacement basis, and curing; their results should not be taken as interchangeable quantitative standards for the present recipes.

Pan et al. [18] analyzed the mechanical characteristics and microstructure of GO–cement at the cementitious-matrix scale. Li et al. [19] studied early hydration and electrical resistivity, Li et al. [20] was on agglomeration and workability, and Li et al. [21] on aggregate-scale GO impacts on sorptivity and tensile splitting. Long et al. [22] compared directly dispersed and re-agglomerated GO pastes. The microstructural and mechanical behaviors of mortar with mineral admixtures were studied by Lv et al. [23, 24] and Liu et al. [25]. The trials showed the importance of considering dispersion and matrix composition in the recording, and that not all performance variations can be attributed to the nominal GO dose. Konios et al. [26] investigated dispersions of GO and reduced GO in organic solvents. This work demonstrates the importance of the liquid-medium environment but does not demonstrate the dispersion in the alkaline cement pore solution. Ghani et al. [27] studied concrete with PET as coarse aggregate and PET mixed with graphene nanoplatelets (GNPs). This is a valid combined-material comparison. But GNPs are different from GO, and coarse-aggregate substitution is different from the present fine-aggregate intervention. The present study therefore keeps material-specific conclusions.

2 Materials and methods

2.1 Study design and evidence basis

The source is the supplied six-chapter thesis entitled Study and Analysis of Concrete Properties by Using Plastic Waste and Graphene Oxide. Seven combinations were reported: a control, two PET-only mixtures, two GO-only mixtures, and two hybrids. The combinations containing 5% PET with 0.05% GO and 10% PET with 0.03% GO were not tested. The experiment therefore does not provide all nine cells of a three-by-three treatment arrangement. Three specimens per mixture and age are stated for the mechanical tests, but the original specimen inventory, individual observations, and number of independent production batches are unavailable in the thesis record. The analysis retains the reported means without constructing artificial replicates, standard deviations, or confidence intervals. No randomization, blinding, or independent batch replication is assumed. The manuscript presents a descriptive analysis of the documented program; procedural details that remain unverified are identified explicitly.

2.2 Constituents and mixture quantities

The thesis reports OPC 53-grade cement, Zone II river sand, angular crushed coarse aggregate with a nominal maximum size of 20 mm, potable water, a polycarboxylate ether superplasticizer, post-consumer PET, and GO. The reported fine- and coarse-aggregate supplier was Bansal Construction Company in the Raisen–Bhopal region. Reported aggregate specific gravities were 2.64 and 2.72, with absorptions of 1.25% and 0.62%, respectively. The fine-aggregate fineness modulus was 2.71. Original grading sheets, lot identifiers, and moisture records were not available.

PET was described as beverage-bottle waste collected in Bhopal, segregated, washed, dried, and mechanically shredded into approximately 2–5 mm particles. Its reported specific gravity was approximately 1.30. The historical washing conditions, drying endpoint, particle distribution, and contamination-control records were unavailable. GO supplier, product code, physical form, and certified dry-solids concentration were not established. Unverified GO thickness and surface-area values are therefore excluded from this manuscript.

Table 1 Reported mixture quantities on the nominal recipe basis

Mixture	PET %	GO %	Sand kg	PET kg	GO kg
Control	0	0	680	0	0
PW-1	5	0	646	34	0
PW-2	10	0	612	68	0
GO-1	0	0.03	680	0	0.12
GO-2	0	0.05	680	0	0.2
PW-GO-1	5	0.03	646	34	0.12
PW-GO-2	10	0.05	612	68	0.2

Common nominal quantities used were 400 kg of cement, 160 kg of specified water, 1180 kg of coarse aggregate, and 4 kg of PCE. PET percentages are based on original sand mass; GO percentages are based on cement mass. These are recipe quantities, not confirmed kg/m³ values. The nominal values are $m_{PET} = r m_{FA,0}$ and $m_{FA} = (1 - r)m_{FA,0}$ for the initial sand mass $m_{FA,0}$ and the replacement fraction r . GO dry addition is $m_{GO} = (G/100)m_C$, where G is its percentage of cement mass. The water-to-cement ratio specified is $160/400 = 0.40$. The effective ratio could not be independently determined, as the total moisture, admixture water, and any GO carrier water were not appropriately reported. The reported specific gravities are used to calculate the PET fraction of PET-plus-sand solid volume $\phi_{PET} = (r/SPET)/[(r/SPET) + (1 - r)/SFA]$. The 5% and 10% substitutions in mass amount to about 9.7% and 18.4%, respectively, of this solid volume. They are not percentages of the entire volume of concrete. The total volume of cement, water, sand, PET, and coarse aggregate for control, 5% PET, and 10% PET are 0.97838 m³, 0.99166 m³, and 1.00493 m³, respectively, before GO, PCE, and air. The last subtotal shows an unsolved discrepancy between the recipe and the yield; it can neither be taken as the measured yield nor rectified retrospectively by assuming an air content.

2.3 Testing and Preparation

GO was distributed in a portion of the mixing water by ultrasonication for 30 min prior to concrete preparation. The power, frequency, volume of suspension, temperature, and energy delivered by the sonicator were not accessible, so dispersion quality depends on more than just time. Mixing, casting, compaction, demoulding, and curing were characterized as common procedures, but the operational histories were not recorded well enough to be reproduced independently. New measurements included slump, density, and compaction factors. The specified placement aim was 75–100 mm slump. Consistency, density, preparation of specimens, and curing are as per IS 1199 [5–7], and hardened strength is as per IS 516 [8]. To cite a method does not of itself prove that it was historically complied with. Compressive tests on 150 mm cubes at 7, 28, and 56 days; splitting tensile tests on

150 mm diameter by 300 mm cylinders at 28 days; and flexural testing on 100 x 100 x 500 mm beams at 28 days were reported. There was no data on support span, loading arrangement, loading rates, machine calibration, or individual failure loads.

Absorption, sorptivity, water-penetration depth, and quick chloride permeability test charge were the indicators used. Absorption is represented as a percentage, sorptivity in mm/ $\sqrt{\text{min}}$, penetration depth in mm, and charge in coulombs. ASTM C1585 and C1202 [9, 10] refer to the relevant transport and electrical measurements. Conditioning histories, sorptivity mass-time series, penetration pressure and duration, and RCPT current-time data were not accessible. Hence, the numerical comparisons do not result in verified values of permeability coefficients, chloride diffusion coefficients, or service life forecasts. Results of chemical exposure were removed from the major analysis due to insufficient definitions of exposure and records of reference strength.

2.4 Descriptive comparisons and criteria for decision.

Changes relative to the control were determined as $\Delta \text{ control} = 100(Y \text{ mix} - Y \text{ control})/Y \text{ control}$. Matched hybrid modifications employed the equivalent PET-only denominator: $\Delta \text{ matched} = 100(Y \text{ hybrid} - Y \text{ PET}) / Y \text{ PET}$. Positive numbers are favorable for strength. Negative values are favorable for absorption, sorptivity, penetration depth, and charge. Percentages were derived from reported rounded means and rounded to one decimal place for presentation. No significant tests were employed, as there was no within-mixture variation and no independent batch replication.

Candidate selection is done in the specified slump period before hardened performance evaluation. Such criterion is not fulfilled by a mixture with satisfactory technical profile when the reported droop is outside the range of 75-100 mm. Also the desired M40 designation is not reached: the control mean is 38.6MPa and neither a single reported mean nor a mean close to 40MPa gives the necessary evidence of production and acceptance. There is no claim of proven concrete M40.

3 Results

Table 2 Reported fresh properties and compressive strength

Mixture	Slump mm	Density kg/m ³	Compaction factor	7 d MPa	28 d MPa	56 d MPa
Control	82	2385	0.93	25.8	38.6	42.7
PW-1	76	2340	0.91	24.5	36.8	40.4
PW-2	69	2295	0.89	22.4	33.9	37.3
GO-1	74	2390	0.91	27.8	40.9	45.2
GO-2	67	2395	0.89	28.6	42.3	46.8
PW-GO-1	68	2355	0.89	26.9	39.7	43.9
PW-GO-2	58	2310	0.86	25.2	37.5	41.6

3.1 Fresh response

Slump decreased from 82 mm for the control to 76 and 69 mm with 5% and 10% PET replacements, respectively. GO-only mixtures recorded 74 and 67 mm. The hybrids produced 68 and 58 mm, the lowest values in the programme. Relative to matched PET-only mixtures, GO addition reduced slump by a further 8 and 11 mm. Only the control and PW-1 met the stated 75–100 mm interval; neither hybrid passed this screen.

Fresh density decreased from 2385 kg/m³ to 2340 and 2295 kg/m³ for PET-only mixtures. The hybrid densities were 2355 and 2310 kg/m³, each 15 kg/m³ above its matched PET-only value. Compaction factors decreased from 0.93 for the control to 0.89 and 0.86 for the hybrids. These observations identify a fresh-state penalty, but they do not quantify entrapped air, placement adequacy, or hardened lightweight classification.

3.2 Mechanical response

At 28 days, PW-1 and PW-2 reached 36.8 and 33.9 MPa, representing reductions of 4.7% and 12.2% relative to the control. GO-1 and GO-2 reached 40.9 and 42.3 MPa, respectively, corresponding to increases of 6.0% and 9.6%. The lower-dose hybrid reached 39.7 MPa, 2.8% above the control and 7.9% above PW-1. The higher-dose hybrid reached 37.5 MPa, 10.6% above PW-2 but 2.8% below the control. Thus, recovery relative to PET-only concrete did not always restore the control strength.

Strength increased with age for every reported mixture. At 56 days, PW-GO-1 reached 43.9 MPa compared with 42.7 MPa for the control and 40.4 MPa for PW-1. PW-GO-2 reached 41.6 MPa compared with 37.3 MPa for PW-2. The GO-only mixtures remained the highest at 45.2 and 46.8 MPa. These are descriptive age trends; without individual results, differences between mixtures cannot be assigned statistical confidence.

Table 3 Reported tensile flexural and transport indicators

Mixture	Split MPa	Flexural MPa	Absorption %	Sorptivity mm/ $\sqrt{\text{min}}$	Depth mm	Charge C
Control	3.25	4.62	4.2	0.118	24	3200
PW-1	3.12	4.48	4.5	0.128	27	3500
PW-2	2.92	4.21	5	0.142	31	3900
GO-1	3.45	4.95	3.7	0.092	20	2500
GO-2	3.58	5.18	3.5	0.084	18	2200
PW-GO-1	3.39	4.89	3.8	0.096	21	2600
PW-GO-2	3.18	4.56	4.1	0.107	24	3000

Splitting and flexural strengths are reported at 28 days. Transport-test conditioning and age require verification against original records. The lower-dose hybrid achieved splitting tensile and flexural strengths of 3.39 and 4.89 MPa, compared with 3.25 and 4.62 MPa for the control. Against PW-1, the gains were 8.7% and 9.2%. The higher-dose hybrid recorded 3.18 and 4.56 MPa: above PW-2 by 8.9% and 8.3%, respectively, but slightly below the control. GO-2 gave the highest reported values, 3.58 and 5.18 MPa. These tests do not establish toughness, fracture energy, or post-cracking ductility.

3.3 Water transport and electrical response

PET-only mixtures showed higher absorption, sorptivity, penetration depth, and charge than the control. At 10% PET, the respective values were 5.00%, 0.142 mm/ $\sqrt{\text{min}}$, 31 mm, and 3900 C. GO-only mixtures showed lower values across these indicators, with GO-2 recording 3.50%, 0.084 mm/ $\sqrt{\text{min}}$, 18 mm, and 2200 C. The direction of the reported changes was therefore consistent across the four indicators, although their physical meanings differ. The lower-dose hybrid reduced absorption from 4.50% for PW-1 to 3.80%, sorptivity from 0.128 to 0.096 mm/ $\sqrt{\text{min}}$, penetration from 27 to 21 mm, and charge from 3500 to 2600 C. These correspond to matched reductions of 15.6%, 25.0%, 22.2%, and 25.7%. Against the control, the same hybrid showed reductions of 9.5%, 18.6%, 12.5%, and 18.8%.

The higher-dose hybrid reduced the corresponding PW-2 values to 4.10%, 0.107 mm/ $\sqrt{\text{min}}$, 24 mm, and 3000 C. Matched reductions were 18.0%, 24.6%, 22.6%, and 23.1%. Its penetration depth equalled the control, while absorption and charge were only 2.4% and 6.3% lower. Reported recovery is therefore stronger relative to PET-only concrete than relative to the reference mixture. Charge remains an electrical indicator and cannot be converted into a chloride diffusion coefficient from these summaries.

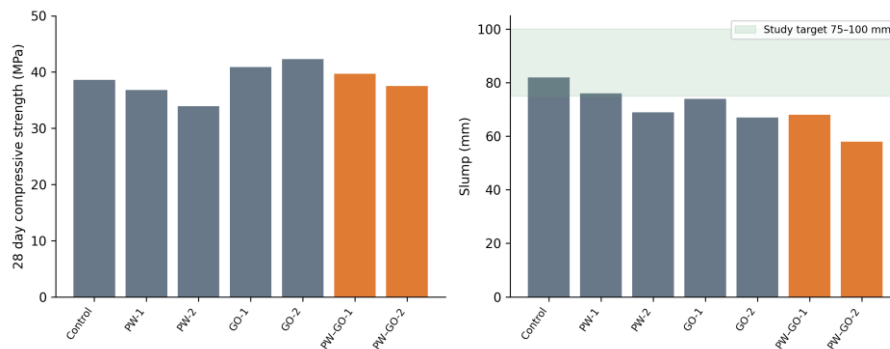


Figure 1 Strength recovery and the associated workability tradeoff. Bars represent thesis-reported means. No uncertainty bars are shown because replicate-level observations were unavailable. The shaded interval is the study placement target.

Figure 2 displays the reported strength progression without fitting a hydration model. The lines connect tested ages only and do not imply observations between those ages. Figure 3 separates the four transport indicators to preserve their units. Figure 4 and Table 4 use matched PET-only denominators so that recovery is not confused with comparison against the control.

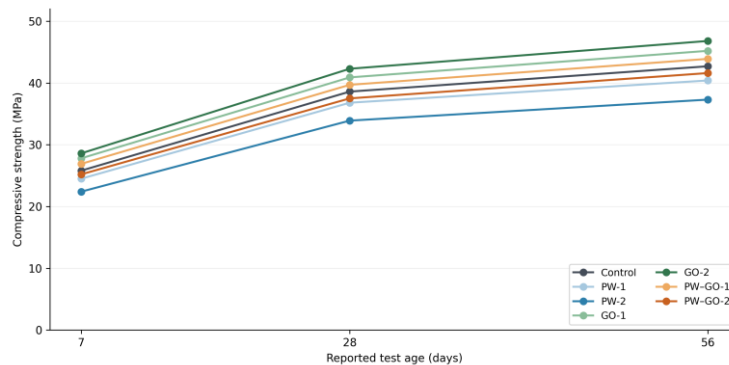


Figure 2 Compressive strength development at 7, 28, and 56 days. Lines join reported mixture means; replicate variability and batch uncertainty were unavailable.

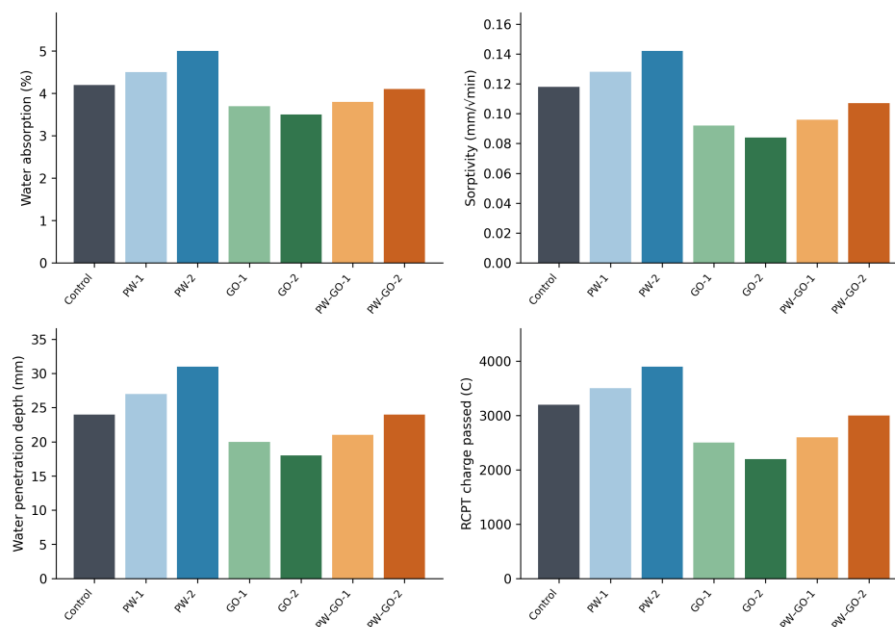


Figure 3 Reported water absorption, sorptivity, water penetration, and electrical charge. Each panel retains its own unit and zero-based scale. Lower values are favourable within the reported comparisons; conditioning and protocol verification remain incomplete.

Table 4 Matched changes from PET only to PET plus GO

Indicator	5% PET pair	Change %	10% PET pair	Change %
Compressive strength	36.8 → 39.7	+7.9	33.9 → 37.5	+10.6
Splitting tensile strength	3.12 → 3.39	+8.7	2.92 → 3.18	+8.9
Flexural strength	4.48 → 4.89	+9.2	4.21 → 4.56	+8.3
Water absorption	4.5 → 3.8	-15.6	5 → 4.1	-18.0
Sorptivity	0.128 → 0.096	-25.0	0.142 → 0.107	-24.6
Water penetration	27 → 21	-22.2	31 → 24	-22.6
RCPT charge	3500 → 2600	-25.7	3900 → 3000	-23.1
Slump	76 → 68	-10.5	69 → 58	-15.9

4 Discussion

4.1 Compensation and the boundaries of a claim to synergy

The mechanical and transport indices reported were better in both the hybrids than in their corresponding PET-only blends. This supports the limited conclusion that under the tested conditions, the addition of GO was associated with compensatory effects. It's not synergistic. A claim of synergy must possess a defined contrast of interaction, an acceptable model, and a defensible estimate of uncertainty. Replicate observations are not available for an error-based test of interaction, and missing treatment combinations impede the estimate of a saturated categorical three-by-three interaction. The simultaneous adjustments in the dosages of PET and GO also make it difficult to compare the two hybrids. PW-GO-1 had better performance than PW-GO-2 in slump, mechanical strengths, and all four transport indicators, even if that ordering cannot isolate the effect of either dosage. The enhanced response of 0.05% GO compared to 0.03% GO in GO-only mixes also defines the better of two tested levels, not finding a continuous optimum or showing that rising GO is helpful at higher dosages.

4.2 Interpretation of the material

The PET-only trend is consistent with the literature, which shows that the behavior of recycled plastic aggregate depends on particle characteristics and replacement amount [1–3]. Lower particle stiffness, changing packing, and interfacial factors can plausibly explain lower strength and variable transport response. Their relative contributions were not measured in this study. The dataset does not have any validated outputs from microscopy, phase analysis, or pore structure to determine the operative mechanism. Moreover, the GO-linked enhancements may be consistent with matrix change mentioned in concrete studies [4], but better strength and reduced absorption alone are not enough to prove nucleation, crack bridging, and pore refinement. Alternative influences are changes in water balance, compaction, dispersion of product, and conditioning of specimens. The reduction in slump is particularly noteworthy, as the same harsh reactions attributed to GO might be affected by compaction quality. Confirmatory work should document fresh air content, mixing energy, dispersion conditions, and moisture corrections in addition to microstructural measures.

4.3 Resource and application implications

The hybrid with the lower dose hybrid has more potential for further mixture development of the two hybrids studied. Its benefit is conditional, with the noted drop of 68 mm being below the specified placement criteria. The efficacy of a modified mixing technique cannot be inferred from the present results but may be examined. If water is added to bring the mix to the required slump, the water-cement ratio is altered and the mix must be retested for performance. On the basis of the current ranking, no field recommendation can be made. The proposed M40 grade raises a new qualification issue. The mean of control is 38.6 MPa, which is less than 40 MPa, and the mean of hybrid is 39.7 MPa, which does not lead to grade acceptance. Here, the design and specification framework [11, 12] would require production variability, target mean strength, trial mixtures, and acceptance records. A satisfactory transport indication or a high comparison score does not substitute for grade verification.

On a nominal recipe basis, the hybrids contain 34 or 68 kg PET and replace the same mass of sand. These are the declared substitute figures only. The actual yield is disputed, and the 10% PET absolute-volume subtotal exceeds one cubic meter before mixing and air; therefore, one cannot claim realistic material savings per cubic meter. The study also lacks a life-cycle inventory, implications of producing GO, energy input for processing, transport distances, cost data, and evidence of leaching. Waste incorporation is stated without claiming measurable carbon reduction, economic advantage, or environmental safety. Correspondingly,

4.4 Limitations and Verification Program

The main constraint is resolution of evidence. Mixture implies that arithmetic comparisons can be made but does not permit measurement precision, independent replication, or population-level impacts. The initial step in a confirmatory program should be to recover the original loads, masses, dimensions, casting and testing dates, batch identifiers, material certificates and instrument calibration records. Where the narrative passages and the numerical tables differ, the records should be used to resolve the discrepancies; the tabulated numerical results are followed consistently in this draft. Subsequent trials should fill in missing treatment combinations, independently generate replicate batches, and randomize production and testing whenever possible. Specimen replication should be included in the batch and not counted as an additional independent batch. Measurements to be performed are yield, aggregate moisture, GO solids and carrier water, sonication energy, fresh air, and curing conditions. To bolster durability or exposure claims, verification of the transport methods and companion reference specimens is necessary. Statistical modeling can therefore discriminate between batch variability and mixture effects and evaluate interactions with uncertainty.

4.5 Comparison to primary experimental literature

Table 5 presents a comparison of the current descriptive results with chosen primary experiments. A common study issue is performance modification by recycled polymers or graphene-based additions; however, variances in matrix, nanomaterial identity, treatment, and test conditions preclude numerical transfer. Microstructural observations published so far provide hypotheses for this program but require validation by measurements on its specimens. The full list of supplementary sources [13–27] is discussed in the introduction, which supports the material distinctions utilized here.

Table 5 Experimental literature and relevance to the present study

Study	Material system	Experimental focus	Comparison boundary
Akçaözoglu et al.	Shredded PET aggregate	Lightweight cementitious mixtures	Different aggregate and matrix conditions
Rahmani et al. ; Saikia and de Brito	PET aggregate concrete	Physical and mechanical response; abrasion	Replacement basis and particle form differ
Silva et al.	Plastic aggregate concrete	Curing and durability indicators	Curing histories must be matched
Pan et al.; Lv et al.	GO cement composites	Strength and microstructure	Paste-scale mechanisms need concrete validation
Li et al. ; Long et al.	GO cement pastes	Hydration, dispersion and transport	Dispersion state is not defined by dose alone
Liu et al.	GO mortar with mineral additions	Mechanical and transport response	Binder composition differs
Ghani et al.	PET coarse aggregate and GNP concrete	Combined mechanical and environmental study	GNP is not GO; coarse replacement is different

5 Conclusions

1. Replacing PET at 5 and 10% of the original sand mass resulted in a smaller slump, lower mechanical means, and greater reported water-transport and electrical charge indicators than the control.
2. The GO addition led to increasing the hybrid 28-day compressive averages from 36.8 MPa to 39.7 MPa at 5% PET and from 33.9 MPa to 37.5 MPa at 10% PET. The corresponding increases are 7.9% and 10.6%, respectively, and are not statistically significant.
3. The 5% PET + 0.03% GO hybrid showed the stronger reported profile between two tested hybrids. It had an absorption of 3.80%, a sorptivity of 0.096 mm/ $\sqrt{\text{min}}$ and a charge of 2600 C. This is a candidate for confirmation but not yet a confirmed optimum.
4. The hybrids decreased 68 and 58 mm and both were below the study goal of 75-100 mm. So hardened-property recovery did not solve the placement appropriateness issue.
5. Existing studies do not demonstrate PET-GO synergy, M40 acceptability, field durability, or quantitative environmental benefits. For stronger published claims or practical qualification, original records, validated yield and complete treatment coverage with independent batch replication are necessary.

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