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Mechanical and Transport Properties of Concrete Containing Recycled PET and Graphene Oxide

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ABSTRACT: This study presents a test-wise assessment of concrete containing recycled polyethylene terephthalate (PET) fine aggregate and graphene oxide (GO), with particular attention to splitting tensile strength. The attached manuscript reports seven mixtures comprising a control, 5% and 10% PET replacement, and four hybrids containing 0.03% or 0.05% GO by cement mass. Slump, 28-day compressive strength, splitting tensile strength, flexural strength, 28-day water absorption, and 56-day rapid chloride penetration test charge were examined. The manuscript's numerical tables were used consistently where its original figures and text disagreed. Splitting tensile strength declined from 4.12 MPa for the control to 3.87 and 3.63 MPa for 5% and 10% PET mixtures. The addition of 0.05% GO increased the corresponding values to 4.58 and 4.37 MPa, representing matched gains of 18.3% and 20.4%. The 5% PET plus 0.05% GO mixture also recorded 50.6 MPa compressive strength and 6.24 MPa flexural strength, compared with 44.2 and 5.55 MPa for 5% PET alone. Its reported water absorption and electrical charge were 3.55% and 1520 C, respectively. However, slump decreased to 69 mm, below the 75 mm reference line used in the source figure. The results indicate descriptive recovery of PET-associated strength and transport penalties in the reported dataset. Original specimen observations, independent batch counts, and ANOVA outputs were unavailable; consequently, statistical significance, synergy, grade acceptance, and field suitability are not established. Differences between the attached manuscript and the earlier thesis dataset require author verification before submission.

KEYWORDS: PET aggregate; graphene oxide; splitting tensile strength; compressive strength; flexural strength; water absorption; RCPT.

I. INTRODUCTION

Recycled PET particles have been investigated as partial substitutes for natural aggregate in concrete [1–3]. Their response depends on particle geometry, replacement level, matrix composition, and the replacement basis. PET aggregate should be distinguished from PET fibres, since their structural roles and reinforcement mechanisms differ. Studies on shredded PET, PET-containing mortars, and processed PET concrete provide relevant experimental context [13–16]. Curing conditions also influence durability-related measurements in plastic aggregate concrete [17].

GO has been investigated for modifying cementitious matrices and concrete performance [4,18]. Experimental studies address early-age hydration and electrical resistivity [19], agglomeration and workability [20], sorptivity and splitting strength [21], and the effect of dispersed versus re-agglomerated material [22]. Other cement-composite and mortar experiments link GO incorporation with mechanical and microstructural changes under their specific conditions [23–25]. These mechanisms require verification in the concrete being studied; improved strength alone does not demonstrate pore refinement or crack bridging.

Dispersion depends on the liquid medium and material condition. Solvent-dispersion studies [26] cannot establish dispersion quality in cement pore solution. Similarly, PET–graphene nanoplatelet concrete [27] is relevant to combined-material research but differs from the present PET–GO system in both nanomaterial identity and aggregate application [28–32]. This paper evaluates the reported results test by test, expands the splitting tensile procedure and comparisons, and distinguishes measured-response summaries from mechanistic and statistical interpretation [34–38].

II. MATERIALS AND EXPERIMENTAL PROGRAMME

2.1 Dataset and mixture identification

The numerical dataset in this revision is taken from the attached paper, not substituted from the earlier thesis. Its mechanical and durability tables define the seven mixture values. Where embedded figures disagree with these tables, the tables are followed and the figures are redrawn. The original durability aliases M0–M6 are mapped to the row order of the source mechanical table and its optimum-mixture description: CM, PW5, PW10, PW5–GO0.03, PW10–GO0.03, PW5–GO0.05, and PW10–GO0.05. This editorial mapping requires confirmation against the original specimen records [39–40].

The source describes OPC 53-grade cement, river sand, 20 mm crushed coarse aggregate, shredded PET, GO, PCE superplasticizer, and potable water. Supplier certificates, material lot records, actual GO dry-solids delivery, and particle-characterization records were not supplied with the paper. The attached material table lists PET specific gravity as 1.32 and particle size as 2–4.75 mm, whereas its narrative uses 2–5 mm. The tabulated characterization values should therefore be treated as reported inputs pending source verification.

Table 1 Reported mixture design and adopted identifiers

Mixture	PET replacement %	GO addition %	Reported table w/c	PCE %
CM	0	0	.45	1.0
PW5	5	0	.45	1.0
PW10	10	0	.45	1.0
PW5–GO0.03	5	0.03	.45	1.0
PW10–GO0.03	10	0.03	.45	1.0
PW5–GO0.05	5	0.05	.45	1.0
PW10–GO0.05	10	0.05	.45	1.0

PET replacement is described relative to fine aggregate and GO relative to cement mass. The attached prose specifies w/c = 0.40, whereas its mixture table specifies 0.45 for every mixture. Table 1 reproduces the latter without resolving this conflict. No effective water-to-cement ratio is assigned in this revision until original batching and moisture records are checked. M40 is retained only as the intended design grade; reported strength means alone do not demonstrate production acceptance under the design and specification framework [11,12].

2.2 Preparation and testing schedule

The source reports 30 minutes of GO ultrasonication, dry mixing of constituents, subsequent wet mixing, vibration, demoulding after 24 hours, and water curing at $27 \pm 2^\circ\text{C}$. These are manuscript-reported procedures; equipment identity, delivered sonication energy, moisture correction, batch logs, and curing histories were not available. The preparation framework is related to the fresh-concrete methods cited in [5–7]. Compliance cannot be independently established from a procedure description alone.

Table 2 Test wise specimen and reporting schedule

Test	Reported specimen	Reported age	Available result
Slump	Slump cone	Fresh	Seven graphical means and reported SDs
Compression	150 mm cube	7, 28, 56 days planned	28-day means and SDs only
Splitting tension	150 mm diameter × 300 mm cylinder	28 days	Means and SDs for seven mixtures
Flexure	100 × 100 × 500 mm beam	28 days	Means and SDs; span unconfirmed
Water absorption	100 mm cube	28 days	Means and SDs
RCPT	100 mm diameter × 50 mm disc	56 days	Charge means and SDs

Three specimens per mixture are stated in the attachment. Their identities, individual readings, and independent batch counts are unavailable. The $\pm$ values are retained as manuscript-reported standard deviations, not independently verified measurement uncertainty. No additional 7-day or 56-day compressive values, direct tensile measurements, or replicate records have been generated.

2.3 Splitting tensile test procedure and formula

The tensile assessment is the splitting tensile test, an indirect tensile-strength measurement on a concrete cylinder. The source cites IS 5816:1999; the combined hardened-strength reference is given in [8]. A 150 mm diameter by 300 mm long cylinder is placed horizontally so that opposing bearing strips transfer compression along two diametrically opposite generators. Diametral loading induces transverse tension, and the maximum applied load at splitting failure is used to calculate the strength. This describes the test principle; actual strip dimensions, loading rate, machine calibration, measured cylinder dimensions, and failure observations require the laboratory record.

$$f_{st} = 2P_{max} / (\pi LD)$$

Here, f_{st} is splitting tensile strength in MPa, P_{max} is maximum applied load in N, L is cylinder length in mm, and D is cylinder diameter in mm. When the recorded load is expressed in kN:

$$f_{st} = 2000P_{max,kN} / (\pi LD)$$

For nominal dimensions $L = 300$ mm and $D = 150$ mm, the expression becomes $f_{st} = 2000P_{max,kN} / (\pi \times 300 \times 150)$. Measured specimen dimensions should replace nominal values where required by the adopted method. Individual cylinder strengths should be calculated before their mean and SD are determined. Neither a direct tensile strength nor fracture energy can be inferred from this test.

2.4 Other tests and descriptive calculations

Compressive strength is calculated as $f_c = P_{max}/A$, where load is in N and loaded area in mm^2 , giving MPa. Flexural strength depends on the actual loading arrangement and fracture position; under third-point loading with a valid central fracture, $f_r = P_{max}\ell/(bd^2)$, where ℓ is support span and b and d are the beam width and depth. The beam length is not the support span. Span and fixture records were not supplied, so no failure load is reconstructed from flexural means.

Water absorption is expressed as $WA = 100(msat - mdry)/mdry$, using the masses and conditioning states defined by the adopted ASTM C642 procedure. RCPT charge is $Q = \int I(t)dt$, with current in A and time in s, giving C. Its result is an electrical indication of resistance to chloride-ion penetration [10]; it is not a direct diffusion coefficient. Raw conditioning, mass, and current–time records were unavailable.

$$\Delta_{control} (\%) = 100(Y_{mix} - Y_{control})/Y_{control}$$

$$\Delta_{PET} (\%) = 100(Y_{hybrid} - Y_{PET})/Y_{PET}$$

The matched denominator is PW5 for a 5% PET hybrid and PW10 for a 10% PET hybrid. Positive changes are favourable for strengths; negative changes are favourable for water absorption and charge. CV is calculated separately for a test as $CV = 100s/\bar{y}$, where s is its reported SD and $\bar{y}$ its mean. The source's single CV column is not reused

because it does not agree with the property-specific SD/mean ratios. ANOVA and Tukey significance claims are omitted because original observations, batch structure, and analysis outputs were not supplied.

III. TEST WISE RESULTS AND DISCUSSION

3.1 Slump test

Table 3 Reported fresh concrete slump

Mixture	Slump mean $\pm$ SD mm	Change vs control %	At least 75 mm
CM	82 ± 2	—	Yes
PW5	76 ± 2	-7.3	Yes
PW10	70 ± 2	-14.6	No
PW5-GO0.03	73 ± 2	-11.0	No
PW10-GO0.03	68 ± 2	-17.1	No
PW5-GO0.05	69 ± 2	-15.9	No
PW10-GO0.05	64 ± 2	-22.0	No

The source slump chart reports 82 ± 2 mm for CM, 76 ± 2 mm for PW5, and 70 ± 2 mm for PW10. The four hybrids recorded 73, 68, 69, and 64 mm in the order used here. These graphical values are reproduced because the paper has no numerical slump table. Their assignment follows the chart's explicit PET-GO labels, not the conflicting M aliases used elsewhere. Only CM and PW5 reached the 75 mm reference threshold drawn in that figure. This threshold is used as the source study screen and is not presented as a universal minimum for structural concrete.

PW5-GO0.05 recorded 69 mm, 9.2% below PW5 and 15.9% below CM. Its favourable hardened-property profile therefore accompanies a measurable slump reduction. The source assertion that all mixtures met its reference workability threshold is inconsistent with the plotted data. Without air, rheology, or compaction records, the decline cannot be assigned exclusively to a particular particle or GO mechanism.

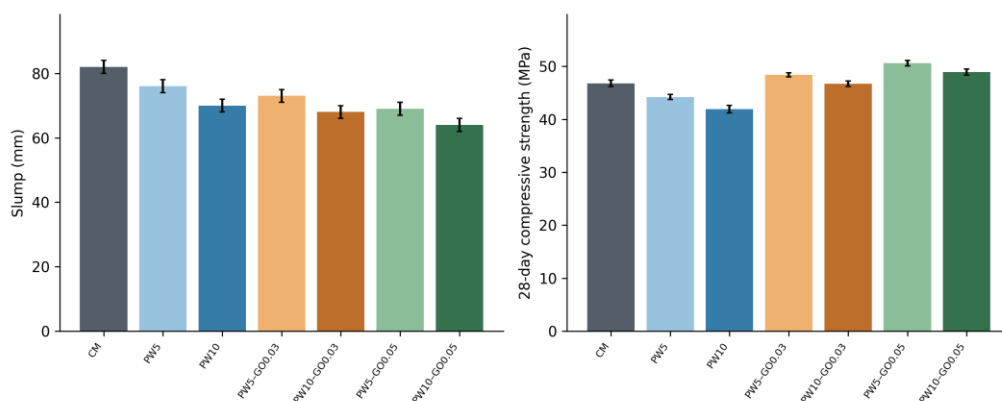


Figure 1 Slump and 28-day compressive strength. Slump values follow the source chart labels; compressive values follow the source numerical table. Error bars reproduce reported SDs and do not establish independent batch uncertainty.

3.2 Compressive strength test

Table 4 Compressive strength results at 28 days

Mixture	Mean $\pm$ SD MPa	Vs control %	Vs matched PET %
CM	46.8 $\pm$ 0.6	—	—
PW5	44.2 $\pm$ 0.5	-5.6	—
PW10	41.9 $\pm$ 0.7	-10.5	—
PW5-GO0.03	48.4 $\pm$ 0.4	+3.4	+9.5
PW10-GO0.03	46.7 $\pm$ 0.5	-0.2	+11.5
PW5-GO0.05	50.6 $\pm$ 0.5	+8.1	+14.5
PW10-GO0.05	48.9 $\pm$ 0.6	+4.5	+16.7

CM reached 46.8 MPa. PET replacement reduced the reported mean to 44.2 MPa at 5% and 41.9 MPa at 10%, decreases of 5.6% and 10.5%. At 0.03% GO, the matched hybrid means rose to 48.4 and 46.7 MPa, gains of 9.5% and 11.5% over the respective PET-only mixtures. At 0.05% GO, the corresponding values were 50.6 and 48.9 MPa, gains of 14.5% and 16.7%.

PW5-GO0.05 had the highest reported compressive mean, 8.1% above CM. PW10-GO0.03 remained approximately equal to CM at -0.2%. These comparisons support descriptive recovery under the attached dataset. Although 7- and 56-day testing is mentioned in the programme, their numerical compression results are not supplied; age-development conclusions cannot be added.

3.3 Splitting tensile strength test

Table 5 Splitting tensile strength results at 28 days

Mixture	Mean $\pm$ SD MPa	Vs control %	Vs matched PET %	Calculated CV %
CM	4.12 $\pm$ 0.05	—	—	1.21
PW5	3.87 $\pm$ 0.04	-6.1	—	1.03
PW10	3.63 $\pm$ 0.05	-11.9	—	1.38
PW5-GO0.03	4.31 $\pm$ 0.04	+4.6	+11.4	0.93
PW10-GO0.03	4.11 $\pm$ 0.05	-0.2	+13.2	1.22
PW5-GO0.05	4.58 $\pm$ 0.04	+11.2	+18.3	0.87
PW10-GO0.05	4.37 $\pm$ 0.05	+6.1	+20.4	1.14

CM recorded 4.12 $\pm$ 0.05 MPa. PW5 and PW10 recorded 3.87 $\pm$ 0.04 and 3.63 $\pm$ 0.05 MPa, respectively, representing losses of 6.1% and 11.9% relative to CM. The PET-only trend is consistent with the concurrent compression and flexure reductions, but does not by itself identify the controlling interface or crack-initiation process.

Adding 0.03% GO increased splitting tensile means to 4.31 $\pm$ 0.04 MPa for PW5-GO0.03 and 4.11 $\pm$ 0.05 MPa for PW10-GO0.03. These are gains of 11.4% and 13.2% relative to their matching PET-only mixtures. Relative to CM, the changes were +4.6% and -0.2%; thus, improvement relative to PET-only concrete did not always exceed the control.

At 0.05% GO, splitting tensile strength reached 4.58 $\pm$ 0.04 MPa for the 5% PET hybrid and 4.37 $\pm$ 0.05 MPa for the 10% PET hybrid. The corresponding gains over PET-only concrete were 18.3% and 20.4%, and gains over CM were 11.2% and 6.1%. PW5-GO0.05 gave the highest absolute mean, whereas PW10-GO0.05 gave the larger percentage recovery because its PET-only baseline was lower. These are distinct comparisons and should not be interchanged.

Calculated tensile CVs range from 0.87% to 1.38%, using the reported SDs and rounded means. These values describe the dispersion claimed in the attachment; they do not verify batch-to-batch repeatability. GO-related changes in cement-matrix response are plausible in light of experiments [18,20–25], but crack bridging, pore refinement, and ITZ

improvement were not measured on these specimens. No direct tensile test, stress–strain response, fracture-energy result, or verified significance level is available.

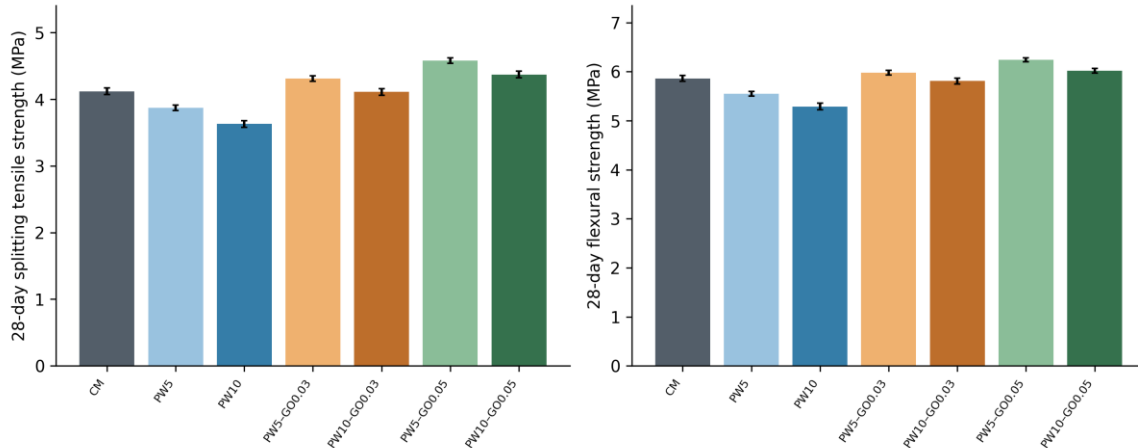


Figure 2 Separate splitting tensile and flexural results from the numerical mechanical table. Bars show reported means $\pm$ SD; no significance letters are assigned.

3.4 Flexural strength test

Table 6 Flexural strength results at 28 days

Mixture	Mean $\pm$ SD MPa	Vs control %	Vs matched PET %
CM	5.86 $\pm$ 0.06	—	—
PW5	5.55 $\pm$ 0.05	-5.3	—
PW10	5.29 $\pm$ 0.07	-9.7	—
PW5-GO0.03	5.98 $\pm$ 0.05	+2.0	+7.7
PW10-GO0.03	5.81 $\pm$ 0.06	-0.9	+9.8
PW5-GO0.05	6.24 $\pm$ 0.04	+6.5	+12.4
PW10-GO0.05	6.02 $\pm$ 0.05	+2.7	+13.8

The flexural mean decreased from 5.86 MPa for CM to 5.55 MPa for PW5 and 5.29 MPa for PW10, losses of 5.3% and 9.7%. The 0.03% GO hybrids reached 5.98 and 5.81 MPa, increases of 7.7% and 9.8% over their respective PET-only mixtures. The 0.05% GO hybrids reached 6.24 and 6.02 MPa, gains of 12.4% and 13.8%.

PW5-GO0.05 exceeded CM by 6.5% and gave the highest reported flexural mean. The overall ordering supports the same descriptive candidate as the tensile and compression tests. However, missing support-span and loading records limit method verification, and flexural strength alone does not establish toughness or post-cracking performance.

3.5 Water absorption test

Table 7 Water absorption results at 28 days

Mixture	Mean $\pm$ SD %	Vs control %	Vs matched PET %
CM	4.18 $\pm$ 0.08	—	—
PW5	4.46 $\pm$ 0.09	+6.7	—
PW10	4.73 $\pm$ 0.10	+13.2	—
PW5-GO0.03	3.82 $\pm$ 0.07	-8.6	-14.3
PW10-GO0.03	3.95 $\pm$ 0.08	-5.5	-16.5
PW5-GO0.05	3.55 $\pm$ 0.06	-15.1	-20.4
PW10-GO0.05	3.69 $\pm$ 0.07	-11.7	-22.0

Absorption rose from 4.18% for CM to 4.46% for PW5 and 4.73% for PW10, increases of 6.7% and 13.2%. At 0.03% GO, the hybrids recorded 3.82% and 3.95%, reductions of 14.3% and 16.5% relative to their matching PET-only mixtures. At 0.05% GO, the values were 3.55% and 3.69%, matched reductions of 20.4% and 22.0%.

PW5-GO0.05 gave the lowest reported absorption, 15.1% below CM. Absorption is an indicator dependent on specimen conditioning and accessible water uptake. These values do not directly measure intrinsic permeability, pore-size distribution, or field water ingress. The conditioning histories must be recovered before the physical interpretation can be strengthened.

3.6 Rapid chloride penetration test

Table 8 RCPT electrical charge results at 56 days

Mixture	Mean $\pm$ SD C	Vs control %	Vs matched PET %
CM	1920 $\pm$ 28	—	—
PW5	2140 $\pm$ 35	+11.5	—
PW10	2360 $\pm$ 38	+22.9	—
PW5-GO0.03	1690 $\pm$ 26	-12.0	-21.0
PW10-GO0.03	1780 $\pm$ 29	-7.3	-24.6
PW5-GO0.05	1520 $\pm$ 24	-20.8	-29.0
PW10-GO0.05	1605 $\pm$ 27	-16.4	-32.0

CM recorded 1920 C; PW5 and PW10 increased to 2140 and 2360 C, changes of +11.5% and +22.9%. The 0.03% GO hybrids recorded 1690 and 1780 C, reductions of 21.0% and 24.6% relative to their respective PET-only mixtures. The 0.05% GO hybrids recorded 1520 and 1605 C, corresponding matched reductions of 29.0% and 32.0%.

PW5-GO0.05 gave the lowest reported absolute charge and was 20.8% below CM. As with tensile strength, the 10% PET hybrid showed the greater percentage recovery from its poorer PET-only baseline. Charge depends on the electrical response, pore solution, conditioning, and temperature history. It should be described as charge passed or an electrical chloride-penetration indicator, rather than a directly measured chloride diffusion coefficient or demonstrated service life.

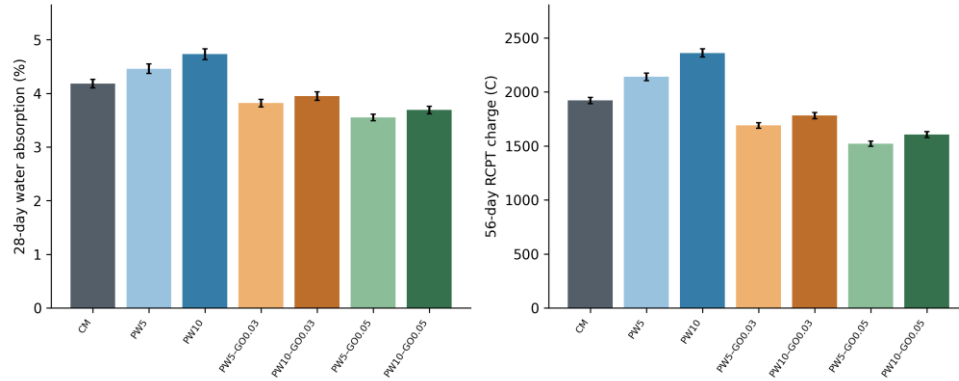


Figure 3 Water absorption and RCPT results from the numerical durability table. The panels use different units and test ages; error bars reproduce manuscript-reported SDs.

3.7 Integrated test wise assessment

Table 9 Summary for the highest strength hybrid PW5–GO0.05

Test	Hybrid mean	Change vs CM %	Change vs PW5 %
Slump mm	69	-15.9	-9.2
Compression MPa	50.6	+8.1	+14.5
Splitting tension MPa	4.58	+11.2	+18.3
Flexure MPa	6.24	+6.5	+12.4
Absorption %	3.55	-15.1	-20.4
RCPT C	1520	-20.8	-29.0

Table 9 shows why candidate selection requires test-specific interpretation. PW5–GO0.05 has the highest reported mechanical strengths and lowest absorption and charge, yet lower slump than both CM and PW5. It is the best-performing reported hardened-property candidate among these mixtures, rather than a validated continuous optimum or a qualified field mixture. The programme lacks GO-only controls and records of independent batch replication, so the descriptive changes do not establish a statistically tested PET–GO interaction.

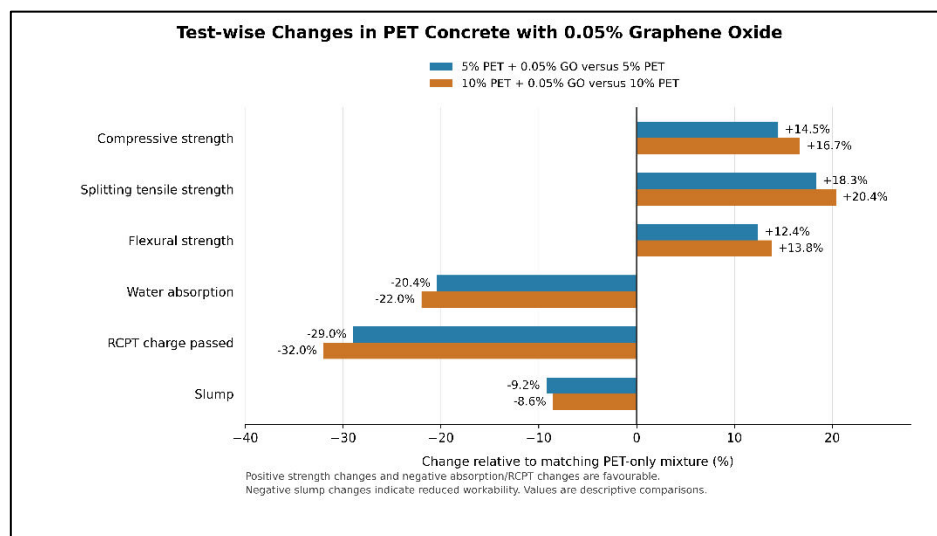


Figure 4 Test wise changes for the two 0.05% GO hybrids. Positive strength changes and negative absorption and charge changes are favourable; a negative slump change represents reduced workability.

IV. LIMITATIONS AND FURTHER VALIDATION

The attached paper differs materially from the earlier thesis dataset in mixture coverage, control strengths, and transport values. This revision preserves the attachment as the requested working source and does not merge the two programmes. The authors must confirm whether the attachment reports a separate experiment or contains values requiring correction. Its figures also disagree with its own tables, and its prose and mixture table disagree on w/c. These issues are documented in the final author note.

The source states $n = 3$ and provides means and SDs but not specimen-level observations, batch identities, failure loads, absorption masses, or RCPT current histories. Statistical letters and p-values from the original illustrations are therefore not reproduced. The revised test-wise comparisons are descriptive. Independent batch replication, raw-data reconciliation, method verification, and material provenance are required before adding significance claims or asserting reproducibility.

Further experiments should include GO-only controls, verified moisture and yield, controlled dispersion energy, calibrated loading records, actual beam spans, and consistent transport conditioning. Microstructural analysis can then test proposed mechanisms. Life-cycle assessment, leaching, costs, and field validation are needed before environmental benefit or suitability for pavements, precast units, retaining structures, or reinforced applications can be established.

V. CONCLUSIONS

1. Splitting tensile results are now reported separately for all seven mixtures. PET-only strengths were 3.87 and 3.63 MPa, compared with 4.12 MPa for CM. The 0.05% GO hybrids reached 4.58 and 4.37 MPa, with matched gains of 18.3% and 20.4%.
2. PW5–GO0.05 recorded the highest mechanical means: 50.6 MPa compression, 4.58 MPa splitting tension, and 6.24 MPa flexure. Relative to PW5, the gains were 14.5%, 18.3%, and 12.4%, respectively.
3. The same hybrid recorded 3.55% absorption and 1520 C charge, reductions of 20.4% and 29.0% relative to PW5. These are test-specific indicators, not demonstrated field durability or service life.
4. Slump was 69 mm for PW5–GO0.05 and 64 mm for PW10–GO0.05. Both fell below the 75 mm reference threshold in the original source figure, indicating a workability constraint despite favourable hardened means.
5. The results identify candidates within the attached dataset. Unresolved source discrepancies and missing raw records prevent a confirmed optimum, statistical synergy, M40 acceptance, or field qualification.

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