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Post-Design Integration of Recycled PET into Hot Mix Asphalt: Preserved Binder Dosage and a Stiffness Gain Independent of Binder Content

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Abstract

Recycled polyethylene terephthalate (PET) improves the stiffness of asphalt mixtures, but nearly all of that evidence was obtained at a fixed binder content, assuming that the optimum binder content does not change with PET dosage. Only a design that varies both factors can test it, since their interaction shows whether the response to binder changes with PET and, with it, whether an existing mix design can be kept. A 4 × 5 full factorial design was adopted, combining four dosages of fine dry-process PET (0, 3, 5, and 7% by weight of aggregate) with five binder contents (4.5 to 6.5%) and three replicate specimens per combination (60 Marshall specimens of dense-graded hot mix asphalt), analyzed with two-factor analysis of variance (ANOVA) and effect size analysis. PET raised stability from 691 to 714 kg, reduced flow from 2.98 to 2.78 mm, and increased stiffness from 232 to 258 kg/mm, with significant differences at 7%, while air voids, voids in mineral aggregate, and voids filled with asphalt were preserved. The interaction was non-significant for all six indicators and explained at most 6% of the variance, and the Marshall optimum binder content of each PET dosage varied by 0.12 percentage points, from 5.49 to 5.37%. Within the tested range, the PET effect is independent of binder content, so PET can be integrated into an existing mix design without re-optimizing the binder, reducing dosing to a single variable.

Keywords: Marshall stability; volumetric behavior; factorial design; effect size; binder re-optimization; plastic waste; flexible pavement

1. Introduction

Driving on a pavement with an International Roughness Index (IRI) of 5 m/km raises vehicle repair costs by 40% for a passenger car and 50% for a heavy truck [1], and delaying the rehabilitation of damaged sections increases the annual cost of maintaining them by about 28% [2]. The predictive maintenance strategies that would reduce that bill require an initial investment that, in several cases, exceeds 10% of the annual maintenance budget and discourages agencies under financial constraints [3]. To that burden is added that of a material with no destination: in 2021, the world consumed 583 billion polyethylene terephthalate (PET) bottles, against 300 billion in 2000 [4], and of the 302 million tonnes of plastic released to the environment in 2015, only 62 million were recycled [5], a mismatch that persists even where management systems are consolidated, since in North America, the bottle recycling rate barely reached 37.8% in 2022 [6].

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In Peru, the two bills overlap on the same territory. Plastic accounts for 6.22% of municipal solid waste [7], and a 10 km Andean corridor assessed in Cusco recorded in 2023 an IRI of 4.04 m/km and surface cracking of 27.9% [8], a value that already raises vehicle repair costs by 10% and that, one meter per kilometer higher, quadruples them [1]. Waste awaiting a destination and a road awaiting intervention thus share the same place and the same clock, and that coincidence has steered research toward solutions capable of addressing both fronts at once.

The route by which PET enters the mixture was fixed by its chemistry. With a melting point close to 250 °C, well above the mixing temperature, it cannot melt into the binder and is incorporated into the hot aggregates before the binder is added, in the so-called dry process [5]. That process admits ten to twenty times more plastic than the wet process [5], requires no special equipment [9], and today offers the most favorable combination of performance and sustainability for the plastic most studied in asphalt mixtures [10]. The earliest work used PET as an aggregate substitute: replacing 20% by volume of the 2.36 to 4.75 mm fraction, 5% of the mixture weight, left stability and the Marshall quotient nearly equal to those of the control with a density 2.8% lower [11], and replacing fine aggregate reduced the stiffness modulus [12]. The line that later consolidated adds it onto the unaltered aggregate, in particles finer than 2.36 mm, so that it retains its semicrystalline state and acts as reinforcement [13,14].

On that basis, there is consensus that PET raises stiffness and resistance to permanent deformation and fatigue, at the expense of moisture resistance [9]. The proposed mechanism is twofold, since the fraction of PET that softens improves adhesion between aggregate and binder while the solid fraction absorbs energy under cyclic loading, and above an optimum, the excess of particles weakens the structure [14,15]. In the Marshall indicators, that optimum is clearly observed: with 4% PET by weight of binder, stability exceeds the control by 11 to 13% and flow reaches its minimum, and beyond that point both reverse [16]; with 0.6% by weight of aggregate, stability rises by 26% and flow drops by 17% [15]; and the resilient modulus grows up to 16% with 6% by weight of bitumen [13].

Volumetrics respond in the opposite direction and with a consistent explanation. At a fixed binder content, air voids and voids in mineral aggregate (VMA) rise with PET and voids filled with asphalt (VFA) fall, because part of the binder is consumed coating the particles and because PET recovers elastically after compaction [16]; in that study, air voids went from 4.15 to 4.80% and VMA from 13.3 to 14.6% between 0 and 10% PET. With PET fiber, air voids rose from 4.82 to 6.30% [17], and compactability suffers above 4% by weight of mixture [5]. When binder content varies at the same time, however, it is the binder that governs air voids, from 6.49 to 2.96% between 5 and 7% binder, and PET barely moves them [18]; and with 0.6% PET, density, VMA, and VFA turned out practically identical to those of the control [15].

What remains unresolved is the dosage. Published optima range from 0.18 to 0.41% by weight of aggregate [18,19], 0.6% [15], 4 to 6% by weight of bitumen [13,16], and 16.7% by weight of aggregate and filler [20], expressed on different bases that prevent comparing them [20]. The reviews acknowledge it: the optimum exists but must be identified case by case [9], and there are no standardized protocols for dosage, particle size, or compatibility with the binder [10]. Behind that dispersion lies a shared design decision. One-factor studies fix the binder content, either at the optimum of the control [11] or under the assumption that the optimum does not change with PET, verified only through air voids [16], and they do so precisely to isolate the effect of the additive [17]; in nearly all of them, the analysis is limited to averages of three replicates. Factorial design with analysis of variance entered the field by crossing PET with stress and temperature [19], and a single study crossed PET with binder content, between 0 and 1% and between 5 and 7%, through a thirteen-run central

composite design aimed at finding the optimum, which resulted in 5.88% binder and 0.18% PET; in it, the interaction was non-significant for air voids and VMA, but significant for stability [18].

In Latin America, the line is more recent and keeps the decision to fix the binder. In Chile, coarse PET of 5 to 10 mm added by the dry process at 6 to 22% by weight of bitumen, with bitumen fixed at 5.3%, produced a maximum of stability and Marshall quotient near 14% and a flow that grows with PET until it leaves the specification at 18 and 22%, with air voids that remained between 4 and 6% up to 18% [21]; the same group showed that a mixed plastic waste, added by the dry process, can replace 10% of the bitumen removed in a one-to-one ratio without it being advisable to exceed it [22]. In Brazil, micro-PET replacing sand up to 8% by volume did not alter the optimum binder content; it raised air voids at fixed bitumen, reduced stiffness, and improved moisture resistance, with a tensile strength ratio that went from 92.6 to 101.5% [23]. In Argentina, recycled polyethylene from silo bags added by the dry process raised stability and flow and strongly reduced rutting [24], and in Trinidad and Tobago, the research line moved from the binder, where 2% PET optimized fatigue and rutting [25], to the mixture, where 6% raised the Marshall quotient by 21 to 22% [26]. It is this Latin American line that the systematic review of Mexican authorship proposes adapting to low-resource contexts [10], and in all of its studies, the binder was fixed or reduced beforehand, and the waste was analyzed as a single factor.

In Peru, there is no indexed study that incorporates PET into hot mix asphalt and reports its Marshall properties with its own data. The available evidence is a documentary review of theses and articles reporting stability variations between −8.7 and +108.9% and air void variations between −46.0 and +59.0% depending on the work consulted [27], and an exploratory trial in Arequipa that combined PET at 1 to 3% of the fine aggregate with reclaimed asphalt pavement (RAP) at 15 to 25%, without separating the two effects and with air voids outside the specification [28]. Local capacity for this type of study, by contrast, has been demonstrated with other types of waste: textile fibers in stone mastic asphalt (SMA) with bitumen fixed at 6% [29], styrene-butadiene-styrene (SBS) and an adhesion additive with an optimum binder content of 5.7% [30], and tire rubber in a two-factor design, size by percentage with analysis of variance and interaction, also at constant binder [31]. Factorial design exists in the country; PET and binder as factors do not.

From that trajectory follows the question the field left unanswered. All the evidence on the PET effect rests on a design assumption: that the optimum binder content does not change with the PET dosage and that, therefore, fixing it at that of the control suffices to isolate the effect of the additive [16,17,21]. That assumption is not established; it is in dispute. It was confirmed once, at a single PET level and through mix redesign, when micro-PET at 8% by volume did not alter the optimum [23]; it was contradicted when the replacement of aggregate by PET slightly raised the optimum [32]; and the only study that crossed both factors with analysis of variance found the interaction non-significant for volumetrics but significant for stability, over nine distinct combinations, with a single replicate outside the center point and without effect size [18]. If that interaction were general, dosing PET would require re-optimizing the binder at every construction site; if it were not, PET could be added onto the existing mix design. The distinction has practical consequences in the field and has not been tested where it matters: in dense-graded hot mix asphalt, in the dosage range of the dry process, with a replicated full factorial design that allows the variance to be decomposed into components associated with each factor and with their interaction and expressed as effect size. In Peru, where the factorial design has already been used with rubber but never with PET nor with the binder as a factor, the question has not even been posed.

This study poses it and answers it with the design the question demands: a replicated full factorial design that crosses four PET dosages, from 0 to 7% by weight of aggregate, with five asphalt cement contents, in a dense-graded hot mix asphalt with Peruvian materials. Three decisions are made to address the gap instead of conforming to the custom of the field. PET is added by the dry process onto the unaltered aggregate, which is the situation of a plant that incorporates the waste into an already approved mix design and not that of a laboratory that redesigns the mix. The dosage range, which reaches 6.2% by weight of mixture and 123% by weight of binder (7% by weight of aggregate), goes beyond the compactability threshold that the literature places near 4% by weight of mixture, so that the test can show whether the decline that this threshold announces appears inside the tested range; it is the same logic with which the valorization of other Peruvian waste types in construction materials has been studied, where prickly pear cactus ash in concrete showed an optimum at 1.5% and a decline at 2% [33]. And the binder enters the analysis as a factor and not as a constant, so that the variance of each indicator can be decomposed into components associated with PET, the binder, and their interaction, and expressed as effect size through eta squared (η^2) in its partial and total forms, which distinguish whether the PET effect exists from how much it weighs against that of the binder [34,35], interpreted with Cohen's thresholds [36]. The materials, tests, and statistical procedure are detailed in Section 4, after the results and their discussion.

With that design, the problem ceases to be a question of existence and becomes one of attribution: how much of the change in the mechanical performance of the mixture corresponds to the PET dosage once binder content is accounted for, and whether that effect depends on the binder with which it is combined. Answering it is the objective of the study: to determine the effect of PET dosage on the mechanical performance of hot mix asphalt, in its two dimensions, Marshall stiffness, measured by stability, flow, and stiffness, and volumetric behavior, measured by air voids, VMA, and VFA, separating its contribution from that of binder content and verifying whether the two factors interact. From that objective follow three hypotheses, which the results test one by one: the general hypothesis (GH) holds that PET dosage influences the mechanical performance of flexible pavement; the first specific hypothesis (SH1) holds that it influences Marshall stiffness; and the second (SH2) holds that it does not significantly influence volumetric behavior.

Answering them has a scope that exceeds the laboratory. A dosing rule that allows PET to be incorporated into an existing mix design, without re-optimizing the binder, contributes to Sustainable Development Goal 9, industry, innovation, and infrastructure, because it lowers the cost of adopting a recycled material in road infrastructure; it also contributes to Goal 11, sustainable cities and communities, because it removes from the municipal waste stream a material that today has no destination; and to Goal 12, responsible consumption and production, because it turns a single-use container into an input for a long-lived product. In Peru, that contribution plays out at the subnational scale, where the evidence on mining canon transfers shows that progress toward the goals depends more on the stability of resources than on their volume [37]; in that context, adding PET into an approved mix design, without redesigning it, removes one of the barriers between the laboratory and the field.

2. Results

2.1. Descriptive Analysis

Sixty Marshall specimens were tested, corresponding to the four PET dosages evaluated (0%, 3%, 5%, and 7% by weight of aggregate), combined with five asphalt cement contents and three replicates per combination, following the procedure described in Section 4. The

descriptive analysis of these results allows a first look at how each mechanical property of the mixture behaves as the proportion of PET increases.

The characterization is organized around the two dimensions that define the mechanical performance of the asphalt mixture, Marshall stiffness and volumetric behavior. Table 1 gathers, for each indicator, the mean value and its standard deviation at each dosage level, while the subsequent figures illustrate the distribution of the most representative properties. The extended characterization, with the median, the extreme values, and the coefficient of variation of each indicator, is provided in Table S1 of Supplementary S1. The data describe a coherent behavior, in which the incorporation of PET tends to reinforce and stiffen the mixture without appreciably altering its internal void structure.

Table 1. Descriptive statistics of mechanical performance by PET dosage.

Indicator	PET 0%	PET 3%	PET 5%	PET 7%
Marshall stiffness				
Stability (kg)	691 ± 120	700 ± 120	708 ± 120	714 ± 120
Flow (mm)	2.98 ± 0.34	3.00 ± 0.29	2.93 ± 0.32	2.78 ± 0.38
Stiffness (kg/mm)	232 ± 28	233 ± 28	241 ± 29	258 ± 35
Volumetric behavior				
Air voids (%)	4.28 ± 0.75	4.40 ± 0.73	4.18 ± 0.70	4.18 ± 0.70
VMA (%)	15.6 ± 1.18	15.7 ± 1.07	15.8 ± 1.08	15.8 ± 1.08
VFA (%)	72.6 ± 4.54	72.1 ± 4.15	73.5 ± 4.07	73.5 ± 4.07

Note. PET = polyethylene terephthalate; VMA = voids in mineral aggregate; VFA = voids filled with asphalt. Values are expressed as mean ± standard deviation. n = 15 specimens per PET level, with no missing data.

Regarding Marshall stiffness, stability showed a sustained upward trend as PET dosage increased, going from 691 kg in the control mixture to 714 kg at the 7% dosage. This progressive increase suggests that PET contributes to a greater capacity of the mixture to bear loads without deforming. Complementarily, flow decreased toward the highest dosages, falling to 2.78 mm at 7%, which indicates a firmer mixture under the Marshall load.

The combination of these two behaviors, that is, greater stability accompanied by lower flow, translated into the most relevant result of this dimension. Stiffness, understood as the ratio between the two parameters and equivalent to the Marshall quotient of the literature, increased from 232 kg/mm in the control mixture to 258 kg/mm at the 7% dosage, evidencing a progressive hardening of the mixture. This trend is clearly seen in Figure 1, where the distribution of stiffness shifts upward as PET dosage increases, reaching its highest concentration of values at 7%. From the perspective of pavement performance, this increase is relevant, since Marshall stiffness is associated with resistance to rutting, which is the main form of deterioration of flexible pavement subjected to heavy traffic.

The behavior of stability, the parameter that largely underlies the increase in stiffness, is illustrated in Figure 2. It shows how the median stability rises gradually between the control mixture and the 7% dosage, which visually confirms the trend described and reinforces the idea that PET provides greater load-bearing capacity to the asphalt mixture.

In contrast with the marked effect observed on the strength properties, the volumetric behavior of the mixture remained practically stable with the incorporation of PET. Air voids were preserved at around 4.2% at all dosages, while VMA and VFA showed marginal variations, with no appreciable differences among the PET levels. This finding has a favorable meaning for the research, since it shows that the improvement in stiffness and stability is achieved without compromising the internal void structure of the mixture, which is an indispensable condition for ensuring its durability and its adequate behavior against moisture.

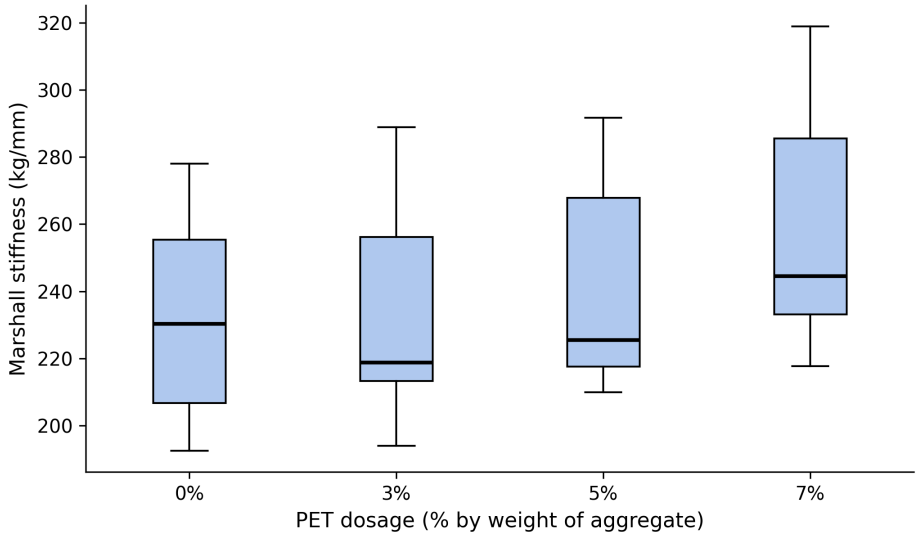


Figure 1. Distribution of Marshall stiffness by PET dosage. Note. Box plots of the 15 specimens per PET level (median, quartiles, and whiskers at 1.5 times the interquartile range), prepared by the authors from the study data.

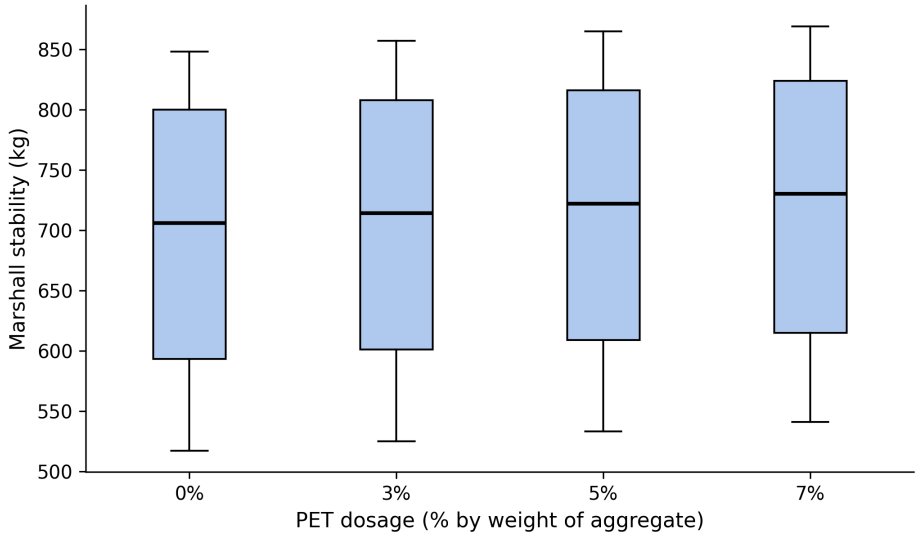


Figure 2. Distribution of Marshall stability by PET dosage. Note. No outliers were identified in any of the indicators evaluated, which supports the consistency of the measurements.

The description of the data thus anticipates that PET dosage exerts a positive influence on the mechanical performance of the asphalt mixture, concentrated mainly in its stiffness and stability, and without adverse effects on its volumetric behavior. Nevertheless, these descriptive trends need to be tested through the inferential analysis, whose results are presented in the following sections and will determine whether the observed differences are statistically significant.

2.2. Verification of Assumptions

Before applying the inferential tests, it was necessary to check whether the data met the conditions that guarantee the validity of the analysis of variance (ANOVA). Every comparison of means through ANOVA rests on two fundamental assumptions: that the model residuals are normally distributed and that the dispersion of the results is comparable

among the groups evaluated. Verifying these conditions determines whether parametric tests should be used or whether, on the contrary, nonparametric alternatives must be resorted to for any of the indicators.

Normality was assessed on the model residuals through the Shapiro–Wilk test, as the most appropriate test for moderate-sized samples such as that of the present study. Homogeneity of variance was examined with Bartlett's test, appropriate when normality of the data is confirmed. This test was applied first over the four PET dosage levels and then over the twenty cells of the factorial model, where Levene's test, centered on the mean and on the median (Brown–Forsythe), served as a complement (Table S15 of Supplementary S1). The residuals of each model were also inspected against the fitted values and in normal quantile plots (Figure S1 of Supplementary S1). In every case, a probability value above 0.05 indicates that the assumption is met. Table 2 gathers the results obtained for the six mechanical performance indicators over the PET dosage levels and the twenty cells.

Table 2. Verification of the normality and homogeneity of variance assumptions.

Indicator	Shapiro–Wilk (p)	Bartlett, PET Levels (p)	Levene, 20 Cells (p)	Brown–Forsythe, 20 Cells (p)	Decision
Stability (kg)	0.139	0.999	0.819	0.955	Two-factor ANOVA
Flow (mm)	0.031	0.806	<0.001	0.929	Two-factor ANOVA with permutation support
Stiffness (kg/mm)	0.124	0.825	0.012	0.708	Two-factor ANOVA with permutation support
Air voids (%)	0.014	0.994	0.767	0.991	ANOVA (robustness)
VMA (%)	0.011	0.982	0.792	0.992	ANOVA (robustness)
VFA (%)	0.020	0.973	0.697	0.989	ANOVA (robustness)

Note. The Shapiro–Wilk p value was computed on the residuals of the two-factor model. The assumption is considered met when $p > 0.05$. Bartlett's test was computed over the four PET dosage levels, with fifteen observations each. Levene's test, centered on the mean, and Brown–Forsythe test, which centers it on the median, were computed over the twenty cells of the factorial model, with three specimens each (Table S15 of Supplementary S1).

The results allow three situations to be distinguished. First, stability, a central indicator of the mechanical dimension, meets both assumptions in every check, so its analysis proceeds through two-factor ANOVA without any restriction. Second, the volumetric indicators, that is, air voids, VMA, and VFA, show normality slightly below the threshold, though with practically perfect homogeneity of variance. Since ANOVA is robust to slight departures from normality when groups are of equal size and variances are homogeneous, and these conditions were met in this study with fifteen specimens per PET level, their analysis is also performed through two-factor ANOVA, with this consideration placed on record.

Finally, flow and stiffness are particular cases, and both receive an additional check. Flow has a normality slightly below the threshold, a behavior explained by the fact that this property takes a reduced number of discrete values derived from the flow meter reading, which gives it a quasi-stepped character. Homogeneity of variance among the four PET dosage levels, by contrast, is met with ample margin ($p = 0.806$). Over the twenty cells, Levene's test centered on the mean flags unequal variance ($p < 0.001$) while the test centered on the median does not (Brown–Forsythe $p = 0.929$), which is a difference consistent with the repeated readings that the 0.254 mm steps of the flow meter leave within each cell (Table S15 of Supplementary S1).

Stiffness, obtained as stability divided by flow, follows a similar path. Its variance is homogeneous among the four PET dosage levels ($p = 0.825$), yet over the twenty cells, Levene's test centered on the mean flags unequal variance ($p = 0.012$) while the test centered on the median does not (Brown–Forsythe $p = 0.708$), and its residuals spread out as the fitted value rises (Figure S1 of Supplementary S1). With equal variances supported by the PET levels and by the median-centered test, both indicators are analyzed through two-factor ANOVA, and their conclusions are subjected to a permutation test blocked by binder content

that does not require normality in order to confirm that the results do not depend on those assumptions (Table S16 of Supplementary S1 for stiffness).

In this way, the verification of assumptions does not only validate the inferential procedure but it also guides the selection of the most appropriate test for each indicator, ensuring that the conclusions on the influence of PET rest on correctly applied statistical tools. The complete statistics are detailed in Supplementary S1, which gathers the Shapiro–Wilk W value and the Levene contrast over the PET levels (Table S2), the checks over the twenty cells (Table S15 and Figure S1), and the permutation tests for flow and stiffness (Tables S13 and S16).

2.3. Dimension 1: Marshall Stiffness

Once the assumptions were verified, it was determined whether the trends observed in the descriptive analysis corresponded to statistically significant effects of PET dosage. The three indicators were evaluated through two-factor analysis of variance, which isolates the effect of PET from that exerted by asphalt cement content. For flow and stiffness, the conclusions were additionally contrasted with a permutation test blocked by binder content. Table 3 summarizes the results obtained for the three indicators of this dimension.

Table 3. Inferential results of the PET effect on the Marshall stiffness indicators.

Indicator	Test	Statistic	p	Partial η^2	Total η^2	Decision
Stability (kg)	ANOVA	$F(3, 40) = 6.06$	0.002	0.313	0.006	Significant
Stiffness (kg/mm)	ANOVA	$F(3, 40) = 12.30$	<0.001	0.480	0.116	Significant
Flow (mm)	ANOVA	$F(3, 40) = 6.67$	<0.001	0.333	0.068	Significant

Note. Partial η^2 expresses the proportion of variance explained by PET dosage once binder content is accounted for; total η^2, the proportion over the variance of the whole dataset. The permutation test blocked by binder content, with 5000 resamples, yielded $p = 0.001$ for flow (Table S13 of Supplementary S1) and $p < 0.001$ for stiffness (Table S16 of Supplementary S1). A p value < 0.05 is considered significant.

The effect of PET dosage on stiffness was highly significant, $F(3, 40) = 12.30$, $p < 0.001$, with a substantial effect size once binder content is accounted for (partial $\eta^2 = 0.480$), equivalent to 11.6% of the variance of the whole dataset (total $\eta^2 = 0.116$). This result, confirmed by the permutation test blocked by binder content ($p < 0.001$; Table S16 of Supplementary S1), shows that PET substantially increases the Marshall stiffness of the mixture, an indicator associated with its resistance to permanent deformation. Tukey multiple comparisons pinpointed the origin of this improvement: the 7% dosage showed a stiffness significantly higher than that of the control mixture ($p < 0.001$), as well as those of 3% ($p < 0.001$) and 5% ($p = 0.007$), while the intermediate dosages did not differ from each other or from the control. Within the tested range, 7% was therefore the best-performing dosage and the only one with a statistically supported increase in Marshall stiffness, an indicator associated with resistance to permanent deformation.

Stability likewise showed a significant PET effect, $F(3, 40) = 6.06$, $p = 0.002$, though of reduced magnitude over the whole dataset (partial $\eta^2 = 0.313$, total $\eta^2 = 0.006$). This difference in magnitude is explained by the fact that asphalt cement content governs the stability of the mixture almost entirely, so that the contribution of PET, although real, is secondary to that of the binder. The post hoc analysis revealed that stability improves significantly relative to the control from 5% PET ($p = 0.029$) and is consolidated at 7% ($p = 0.001$). A more gradual progression than that recorded for stiffness is thus observed, consistent with the complementary role that PET plays on this property.

Flow, for its part, decreased significantly as PET dosage increased, $F(3, 40) = 6.67$, $p < 0.001$, partial $\eta^2 = 0.333$; this is a result confirmed by the permutation test blocked by

binder content ($p = 0.001$), detailed in Table S13 of Supplementary S1. Tukey multiple comparisons again located the difference at the highest dosage: 7% showed a flow significantly lower than that of the control mixture ($p = 0.003$), than that of 3% ($p = 0.001$), and than that of 5% ($p = 0.040$), with no differences among the remaining dosages. This effect becomes visible only when binder content is incorporated into the model. When evaluated in isolation, without accounting for the variability associated with the binder, the difference among dosages is masked and the PET effect goes unnoticed, which is a circumstance that clearly illustrates why the factorial design is indispensable for correctly attributing the observed behavior.

The results of this dimension confirm that the incorporation of PET significantly improves the three Marshall stiffness indicators, by raising stability, reducing flow, and increasing the resulting stiffness, with its most pronounced and statistically supported effect at the 7% dosage. The complete analyses of variance tables for the three indicators appear in Tables S3–S5 of Supplementary S1, and the six pairwise comparisons of each, with their mean difference and standard error, appear in Tables S9–S11. These findings support, in regard to Marshall stiffness, the hypothesis that PET dosage favorably influences the mechanical performance of flexible pavement.

2.4. Dimension 2: Volumetric Behavior

The second dimension examines the influence of PET on the internal structure of the mixture, that is, on the distribution of void spaces and asphalt among the aggregate particles. Unlike the previous dimension, where a significant PET effect represents an improvement, in volumetric behavior, the stability of the parameters is the desirable result, since it evidences that mechanical reinforcement is achieved without disrupting the structure of the mixture. Two-factor analysis of variance was applied to the three indicators, as established in the verification of assumptions. Table 4 presents the results obtained.

Table 4. Two-factor ANOVA results for the volumetric behavior indicators.

Indicator	F	p	Partial η^2	Total η^2	Decision
Air voids (%)	1.62	0.199	0.108	0.016	Non-significant
VMA (%)	1.48	0.235	0.100	0.005	Non-significant
VFA (%)	3.38	0.027	0.202	0.023	Significant (weak)

Note. F corresponds to the effect of the PET factor, with degrees of freedom (3, 40). Partial η^2 expresses the proportion of variance explained by PET dosage once binder content is accounted for; total η^2, the proportion over the variance of the whole dataset. A p value < 0.05 is considered significant.

Air voids showed no significant effect of PET dosage, $F(3, 40) = 1.62$, $p = 0.199$, with a small effect size (partial $\eta^2 = 0.108$, total $\eta^2 = 0.016$). Post hoc comparisons identified no differences between any dosages, which confirms that the porosity of the mixture remains stable at around 4.2%, within the optimum design range. In pavement terms, this result is favorable, since it indicates that the incorporation of PET compromises neither the durability nor the moisture resistance of the mixture.

Analogously, VMA showed no significant PET effect, $F(3, 40) = 1.48$, $p = 0.235$, with a practically null effect size (partial $\eta^2 = 0.100$, total $\eta^2 = 0.005$). The post hoc analysis revealed no differences among the dosages either. This shows that the space available among the aggregate particles, indispensable for housing an adequate asphalt film, is preserved unaltered with the addition of PET, ensuring that the mixture becomes neither brittle nor deficient in binder.

VFA, by contrast, was the only volumetric indicator with a significant, though weak, effect, $F(3, 40) = 3.38$, $p = 0.027$, partial $\eta^2 = 0.202$, total $\eta^2 = 0.023$. This result reflects a slight tendency toward an increase in the degree of asphalt filling at the highest dosages.

Nevertheless, Tukey post hoc comparisons identified no significant differences between specific pairs of dosages, with the closest ones lying at the limit of significance (3% versus 7%, $p = 0.056$). This indicates that it is a gentle general trend rather than a jump between specific levels, without relevant practical implications for the behavior of the mixture.

The volumetric behavior of the mixture remained, in essence, stable with the incorporation of PET. Air voids and VMA were not affected, while VFA showed only a significant but weak influence. The complete tables of these three analyses are gathered in Tables S6–S8 of Supplementary S1, and the pairwise comparisons for VFA in Table S12. These findings confirm that the waste reinforces mechanical performance without compromising the volumetric integrity of the mixture, a contrast that is especially valuable: while in Marshall stiffness PET exerts a clear influence, in volumetric behavior its effect is minimal or null, just as expected of an additive that improves strength properties without altering the internal structure of the material.

2.5. Variance Decomposition and the Consistency of the Effect

Having established which indicators respond to PET dosage, it remains to specify the relative magnitude of that response. The factorial design used makes it possible to decompose the variability of each property into the fraction associated with PET, that associated with asphalt cement content, that corresponding to the interaction between the two, and that which remains as experimental error. This decomposition is especially informative because statistical significance indicates only the existence of the effect, not its relative importance within the overall behavior of the mixture. Table 5 presents that decomposition.

Table 5. Decomposition of the variance of mechanical performance among its sources.

Indicator	PET (%)	AC Content (%)	Interaction (%)	Residual (%)
Stability (kg)	0.6	98.2	0.0	1.2
Flow (mm)	6.8	73.7	5.9	13.6
Stiffness (kg/mm)	11.6	70.3	5.5	12.6
Air voids (%)	1.6	84.5	0.5	13.4
VMA (%)	0.5	94.9	0.3	4.4
VFA (%)	2.3	87.7	0.8	9.2

Note. Values express the percentage of the total sum of squares corresponding to each source of variation, computed with Type II sums of squares on the full factorial model. AC = asphalt cement.

Reading the table reveals a consistent pattern across the six indicators. Asphalt cement content governs the behavior of the mixture, with proportions of explained variance ranging between 70.3% and 98.2%, while PET dosage contributes a considerably smaller margin, between 0.5% and 11.6%. Stiffness is the indicator where PET reaches its greatest prominence, followed by flow, whereas in stability and in the volumetric parameters its contribution is marginal compared with that of the binder. This contrast substantively qualifies the reading of the results: the PET effect is real and statistically supported, but it operates as a fine adjustment on a behavior that binder content essentially determines.

Equally relevant is the behavior of the interaction between the two factors, which did not reach statistical significance for any of the six indicators, with probability values between 0.181 and 1.000 and proportions of explained variance not exceeding 6%. This absence of interaction indicates that the effect of PET dosage remains constant across the entire range of asphalt cement content evaluated, that is, between 4.5% and 6.5%. From a practical standpoint, the finding has a direct implication: the incorporation of PET requires neither redesigning the mix nor re-optimizing the binder content, since the benefit obtained is equivalent at any of the binder proportions tested. The direct evidence points in the

same direction: the optimum asphalt cement contents that the laboratory determined for each PET level were 5.49, 5.47, 5.45, and 5.37% for 0, 3, 5, and 7%, with a total variation of 0.12 percentage points, four times smaller than the 0.5% step between binder levels. The partial effect size of each source of variation, which complements the share of total variance presented in Table 5, is reported in Table S14 of Supplementary S1.

2.6. Hypothesis Testing

From the inferential results obtained in both dimensions, it remains to determine to what extent the hypotheses formulated in the research are verified. This test integrates the statistical evidence of each indicator and allows a substantiated decision regarding the specific hypotheses and the general hypothesis. Table 6 summarizes the evidence and the decision adopted for each of them.

Table 6. Testing of the research hypotheses.

Hypothesis	Statistical Evidence	Decision
SH1. PET dosage influences the Marshall stiffness of flexible pavement.	Stiffness: $F(3, 40) = 12.30$, $p < 0.001$. Stability: $F(3, 40) = 6.06$, $p = 0.002$. Flow: $F(3, 40) = 6.67$, $p < 0.001$.	Supported
SH2. PET dosage does not significantly influence volumetric behavior, as part of the mechanical performance of the pavement.	Air voids: $F(3, 40) = 1.62$, $p = 0.199$. VMA: $F(3, 40) = 1.48$, $p = 0.235$. VFA: $F(3, 40) = 3.38$, $p = 0.027$ (weak effect, no significant post hoc pairs).	Supported
GH. PET dosage influences the mechanical performance of flexible pavement.	Significant influence on load-bearing capacity (stiffness and stability), without significant alteration of the volumetric structure.	Partially supported

Note. SH = specific hypothesis; GH = general hypothesis. Decisions are adopted at a significance level of $\alpha = 0.05$.

Regarding the first specific hypothesis, concerning Marshall stiffness, the evidence supports it without reservation. The three indicators of this dimension evidenced a significant influence of PET dosage, and moreover coincided in placing the improvement at the 7% dosage: stability increased, flow decreased, and the resulting stiffness, which integrates both parameters, recorded the effect of greatest magnitude. Consequently, it is concluded that PET favorably influences Marshall stiffness, improving the capacity of the mixture to resist loads and deformations.

As for the second specific hypothesis, concerning volumetric behavior, the results support it in the terms in which it was formulated. Air voids and VMA showed no significant variations with PET dosage, and although VFA recorded a significant effect, it was weak and without clear differences between pairs of dosages. Therefore, it is confirmed that PET dosage does not significantly influence the volumetric behavior of the mixture. Far from being a limitation, this finding reinforces the value of PET as an additive, since it shows that its incorporation improves the strength properties without compromising the internal void structure, an essential condition for pavement durability.

Finally, as regards the general hypothesis, the evidence leads to partial support. PET dosage significantly influences the mechanical performance of flexible pavement when this is understood in its strength dimension, that is, in the stiffness and stability of the mixture. However, that influence does not extend to volumetric behavior, which remains stable. This distinction is consistent with the expected behavior of a reinforcing additive, whose purpose is to increase the structural capacity of the material without altering its volumetric composition. In summary, the research confirms that the incorporation of recycled PET

improves the mechanical performance of flexible pavement selectively, raising its stiffness and stability while preserving the integrity of its internal structure.

3. Discussion

3.1. Marshall Stiffness Against the Literature

The first finding is that Marshall stiffness responds to PET in its three indicators and in the same direction: stability rises, flow falls, and stiffness grows steadily up to 7%, where the supported differences concentrate. In terms of the attribution problem, the PET effect exists once binder content is accounted for, but its weight changes with the indicator, and reading that weight requires two external criteria. Richardson [34] warns that partial η^2 discounts the other factors and that the real weight of an effect is read in total η^2, and Cohen [36] sets the thresholds of 0.01, 0.06, and 0.14 to rate it. With those two criteria, the PET effect is medium for stiffness and small for stability, where the binder governs almost the entire response. Flow adds a methodological nuance: its effect only became visible with the binder inside the model, that is, once the variation of the binder stopped hiding it. That is the same masking that Yoo and Al-Qadi [17] sought to avoid by fixing the binder. The factorial design achieves the same separation statistically and, in addition, measures how much each factor contributes.

In its direction, the finding confirms the consensus and agrees with those who measured the same properties. Wu and Montalvo [9] summarize the consensus: PET raises stiffness and resistance to permanent deformation. The studies that support it, with the same indicators as this study, point in the same direction: Maharaj et al. [26] recorded a Marshall quotient 21 to 22% higher than the control; Ahmadinia et al. [13], a resilient modulus up to 16% higher with particles finer than 2.36 mm; and Suddeepong et al. [15], on the same dosage basis as this study, a stability 26% higher and a flow 17% lower with only 0.6% of the aggregate. Moghaddam et al. [14] explained that behavior with a twofold mechanism, in which the softened fraction of PET reinforces the bond between aggregate and binder while the solid fraction absorbs energy under load. The results of this study bear that signature, and what separates them from those precedents is not the direction but the magnitude, which in those studies is greater at lower dosages. The cause lies in the comparison and not in the material: those studies contrast PET with the control at the optimum binder content, whereas in this study each mean per dosage averages five binder contents, including those far from the optimum, so that the percentage gain is diluted even though the effect is equally significant.

The contradictions have causes that are just as identifiable. Moghaddam et al. [19] saw stiffness fall with PET, but they measured a dynamic modulus at variable temperature, which is not Marshall stiffness, so the difference lies in the property measured. Movilla-Quesada et al. [21] saw flow grow with coarse PET of 5 to 10 mm, and there the difference lies in size: a coarse particle acts as a deformable aggregate and yields under load, while the fine particle of this study acts as reinforcement. Angelone et al. [24] saw stability and flow rise at the same time with polyethylene, and the difference lies in the polymer, because polyethylene melts at the mixing temperature and integrates into the binder, which PET does not do. Hassani et al. [11] and Rahman and Omardin [12] saw neither stability nor stiffness improve with PET that replaced aggregate, and the difference lies in the route: a replacement removes stone skeleton and an addition preserves it. No contradiction is left, therefore, without a cause, and the four causes are design variables. That is why the present finding is confined to the addition of fine PET onto unaltered aggregate.

There remains the result that did not turn out as expected, and to say why it was expected one must return to the literature. Taherkhani and Arshadi [16] placed the optimum at 4% of the binder, beyond which stability reverses, and Moghaddam et al. [14] attributed

the decline to the excess of particles that weakens the structure. Medrano-Sánchez et al. [33] observed the same pattern of optimum and decline when stepping up the dosage of another waste type in a construction material. With those three precedents, the range of this study was extended up to 7% to capture that pattern and it did not capture it: the highest dosage was also the best. The improvement was still rising at the edge of the tested range, so the decline threshold was not reached. The practical implication therefore carries two limits: 7% by weight of aggregate is the dosage with a supported improvement in all three indicators and is, at the same time, the edge of the tested range.

3.2. Volumetric Behavior Against the Literature

The second finding is the reverse of the first: volumetrics did not respond to PET. Air voids and VMA did not change with dosage, and VFA showed only a gentle trend, significant but without distinguishable pairs. For the attribution problem, this means that the mechanical improvement was obtained without altering the internal structure of the mixture and that, when the binder enters the model, it is the binder that governs the air voids while PET barely moves them. It is not an isolated result. Moghaddam et al. [18], in the only precedent that crossed both factors, found exactly that: the binder took air voids from 6.49 to 2.96% and the interaction with PET was non-significant for air voids, VMA, and density. And even without crossing the factors, two studies saw the same from the PET side: Suddeepong et al. [15], on the same dosage basis as this study, obtained density, VMA, and VFA identical to the control, and Movilla-Quesada et al. [21] kept air voids within specification up to 18% PET. The present result agrees with all three and, unlike the last two, does so with the binder inside the model.

Against that agreement, the studies that did see volumetrics move do not contradict it, because they share one of two conditions that this study does not have. The first is the fixed binder. Taherkhani and Arshadi [16] saw air voids rise from 4.15 to 4.80% and VMA from 13.3 to 14.6% and attributed it to the binder that PET consumes as it is coated and to its elastic recovery after compaction; Yoo and Al-Qadi [17] saw air voids open from 4.82 to 6.30% with PET fiber. What both share is the design, and the design explains the difference: at a fixed binder content, every change in air voids is charged to the additive; with the binder as a factor, that change is apportioned and PET is left with the fraction that belongs to it. The second condition is replacement, and it is shared by four studies with four replaced materials. Movilla-Quesada et al. [22] saw air voids rise when the plastic replaced bitumen, because it does not fill the gap the bitumen leaves; Ferreira et al. [23] saw them rise when micro-PET replaced sand; Hassani et al. [11], when it replaced coarse aggregate by volume; and Sojobi et al. [20], when it was added onto aggregate and filler at an extreme dosage. The two conditions are reduced to one: every published volumetric change occurs when PET replaces something or when the binder cannot compensate for it. Added onto the unaltered aggregate and with the binder free, as in this study, it does not occur.

That same framework explains what was not expected. Enfrin and Giustozzi [5] place the compactability threshold near 4% by weight of mixture, and this study reaches 6.2% by weight of mixture (7% by weight of aggregate), which exceeds it. Yet the threshold did not show in the air voids, which suggests that in a dense-graded mixture, the particle finer than 2.36 mm lodges in the skeleton without interrupting it and that the threshold is specific to each gradation; it is not a constant of the material. The gentle trend of VFA points in the same direction, and the mechanism already cited explains it: Moghaddam et al. [14] describe a fraction of PET that softens and reinforces the bond with the binder, and that same fraction may occupy part of the space the binder would fill, which would explain the slight increase in VFA without it being enough to distinguish dosages from one another. The foregoing has a national reading. Paredes et al. [27] report, for Peru, air voids

varying between −46.0 and +59.0% depending on the work consulted, without the review being able to say what that dispersion depends on. The finding orders it with a verifiable condition: with fine addition and binder as a factor, volumetrics are preserved.

3.3. Independence of the PET Effect from the Binder

The third finding is the one that answers the question that opened this study: the interaction between PET dosage and binder content was non-significant for all six indicators, and the fraction of variance corresponding to it is minimal. Lakens [35] and Richardson [34] hold that an effect is judged by its size and not only by its significance. By that criterion, the interaction would have no consequence in the field even if it existed. The PET effect is therefore the same between 4.5 and 6.5% binder, and the binder governs the response in all indicators while PET acts as a fine adjustment on it. That constancy is precisely what the one-factor literature took for granted without testing it. Movilla-Quesada et al. [21], Taherkhani and Arshadi [16], and Yoo and Al-Qadi [17] fixed the binder under the assumption that its optimum does not change with PET and that fixing it suffices to isolate the additive. With this result, the assumption ceases to be one and becomes a proven fact, within the tested range and for the addition of fine PET in a dense-graded mixture. None of those three studies could have tested it, and the reason was given by Moghaddam et al. [19] when they warned that the one-factor-at-a-time approach does not allow interactions to be examined. Nor did the only Peruvian factorial study in the line test it: Huaricallo et al. [31] did examine an interaction, that of size by rubber dosage, but kept the binder constant, so the interaction that matters to this study was left outside their design.

The literature had, on that assumption, one confirmation and two objections. The confirmation is from Ferreira et al. [23], in whom micro-PET at 8% by volume did not alter the optimum binder content; the present finding agrees with it and extends it from one level to four and from volumetrics to all six indicators. To that extension is added the direct verification that the laboratory design left available: the optimum binder contents determined for 0, 3, 5, and 7% PET varied between 5.49 and 5.37%, less than the 0.5% step between binder levels, so that the null interaction and the constant optimum are two readings of the same fact. The two objections are those the introduction left facing each other, and each is resolved by a different cause. The first is from Ben Zair et al. [32], who saw the optimum rise slightly with PET that replaced 10 to 30% of the aggregate by volume. A replacement of that magnitude changes the surface the binder must coat and with it its demand; fine addition does not change it. The invariance of the optimum must therefore be understood as belonging to addition and not to replacement. The second objection is the fundamental disagreement, with Moghaddam et al. [18], who in the only previous crossing of both factors found the interaction non-significant for air voids, VMA, and density, as in this study, but significant for stability. Four design differences explain the discrepancy, and none of the four are minor. That study sought an optimum, not to decompose variance: its thirteen-run central composite design concentrated the replicates at the center point and left a single observation in each of the other eight combinations, whereas in this study, the twenty combinations carry three replicates each, which is the condition for estimating the interaction with the same error throughout the experimental space. Its PET range, from 0 to 1%, is ten times narrower than that of this study, and an interaction detected in so narrow a range may not hold outside it. Its mixture was SMA, with a coarse skeleton and high binder content, where PET competes with the mastic for space, and not a dense-graded mixture. And it reported no effect size, so its significant interaction for stability cannot be compared in magnitude with that of this study, which explains at most 6% of the variance. The reading that reconciles both results is that the interaction, if it exists, is small and sensitive to mixture type, and that in a dense-graded mixture with fine addition it is not enough to change the practical rule: PET can be dosed onto the existing mix design without re-optimizing the binder. The value of that rule

is measured by what replaces it today. Wu and Montalvo [9] note that the optimum must be identified case by case, and Calderón-Ramírez et al. [10], that there are no protocols for dosage or compatibility; each project therefore tends to redesign the mix. Under the conditions tested, with fine PET added to a dense-graded mixture and binder between 4.5 and 6.5%, the rule reduces that work to a single variable, the PET dosage.

Taken together, the contribution of the study lies in crossing PET dosage with binder content in a replicated Marshall design, which measured the PET effect with the binder as a factor. That design shows, for fine addition and within the tested range, that PET raises Marshall stiffness, preserves volumetrics, and produces the same benefit at any binder content between 4.5 and 6.5%. That result answers a demand the literature had already formulated: Calderón-Ramírez et al. [10] and Enfrin and Giustozzi [5] note that the adoption of the material is still awaiting standards and protocols, and Suddeepong et al. [15] call for design guidelines for road agencies. This is part of the evidence those standards need, and it comes with two limits that the literature itself sets. The first is one of route: Ben Zair et al. [32] and Movilla-Quesada et al. [22] show that the rule does not hold for PET that replaces aggregate or binder, but only for added PET. The second is one of range: this study sustains it up to 7%, where the decline remains unlocated. Within those limits, the rule also has an adoption value that the Peruvian context makes visible. Medrano-Sánchez and Mamani-Salinas [37] showed that at the subnational level progress toward the development goals depends more on the stability of resources than on their volume. In that setting, being able to add PET without redesigning an approved mix lowers one of the barriers to its use in the field.

3.4. Limitations and Future Research

The tested dosage range stopped where the improvement was still growing. It was stepped up to 7% by weight of aggregate because its equivalent of 6.2% by weight of mixture exceeds the compactability threshold that Enfrin and Giustozzi [5] place near 4% by weight of mixture, and the decline that threshold announced did not appear. The 7% is therefore the edge of the range and not the optimum of the material, and the dosage at which fine PET stops helping remains unlocated. Locating it requires extending the same factorial design, with the same gradation and the binder as a factor, to 9, 11, and 13% PET, so that the maximum and the decline fall inside the test.

That extension would still remain, however, within a single gradation, a single particle size, and a single incorporation mode, and it is those three conditions that bound the rule of independence: binder between 4.5 and 6.5%, dense-graded mixture, PET finer than 2.36 mm added onto the aggregate. The bounding is not rhetorical caution, because the two precedents that saw the opposite differ precisely in those conditions: Moghaddam et al. [18] found interaction in an SMA mixture and Ben Zair et al. [32] saw the optimum rise with PET that replaced aggregate. With this evidence, independence does not extend to coarse skeletons, coarse particles, or replacement. Resolving it calls for replicating the factorial design in SMA and incorporating particle size as a third factor.

Both that replication and the original factorial design would measure performance with the same Marshall indicators, and there lies the next limit. Wu and Montalvo [9] place the cost of PET in moisture resistance, and Ferreira et al. [23] and Angelone et al. [24] measured changes in indirect tensile strength and rutting that the Marshall test does not capture. That PET can be dosed without re-optimizing the binder is not equivalent, for that reason, to the mixture being ready for the field. Closing that gap means applying, on the same twenty combinations, the tensile strength ratio after immersion and the dynamic modulus, with the same factorial analysis, to verify whether independence from the binder holds where PET has its weak point.

Even with those tests, the evidence would still be from the laboratory, and the laboratory does not answer for the field or for the long term. Wu and Montalvo [9] warn that laboratory properties do not necessarily reflect in-service performance, and Enfrin and Giustozzi [5] point to the lack of knowledge about long-term behavior as the obstacle holding back these pavements. The dosing rule is proven for mix design, not for service life. Taking it to the field requires a trial section with 7% PET on an approved design, with an adjacent control section, in which the IRI and the cracking that Ccorahua et al. [8] used in the Andean corridor are measured over time, which is the path that Suddeepong et al. [15] followed to move from the laboratory to road agency guidelines.

Any of those studies, in the laboratory or in the field, finally inherits a question of precision that this design leaves open. With three replicates per combination, the factorial design detects interactions of relevant size but does not rule out minimal interactions, and the permutation tests that supported flow and stiffness confirm the conclusion without increasing that power. The absence of interaction is proven, consequently, for effects that would matter in the field and not for any effect, and it was so formulated above, in the discussion of the interaction, with the criterion of Lakens [35] and Richardson [34]. Narrowing that margin is the most immediate of everything proposed: it suffices to increase the replicates per cell or to add intermediate binder levels in order to affirm, and not merely fail to reject, that the interaction is null in practice.

4. Materials and Methods

4.1. Research Design and Variables

A laboratory experimental design was adopted in which PET dosage was manipulated at four levels, 0%, 3%, 5%, and 7% by weight of aggregate, comparing a control mixture without PET against three modified mixtures, with asphalt cement content incorporated as a second factor of the model. Data were collected in a single evaluation period under controlled conditions.

The unit of analysis consisted of 60 Marshall specimens fabricated in the laboratory, prepared by combining the four PET dosages with five asphalt cement contents (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%) and three replicates per combination. In this way, each PET level was represented by fifteen specimens, configuring a balanced design that proved especially suitable for the subsequent statistical treatment.

The design has two experimental factors, both set by the researchers. PET dosage is the factor of interest, and thus the independent variable, because the study sets out to measure its effect. Asphalt cement content is the second factor, varied at five levels because it is a recognized determinant of mixture behavior whose influence had to be separated from that of PET. The response, or dependent variable, is the mechanical performance of the mixture, measured on each specimen in two complementary dimensions. The first, Marshall stiffness, was evaluated through stability, flow, and stiffness, the latter understood as the ratio between the former two. The second, volumetric behavior, was analyzed through air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). Table 7 summarizes the factors and the response variables.

Table 7. Experimental factors and response variables.

Role in the Design	Variable	Levels or Indicators
Factor of interest (independent variable)	PET dosage	0%, 3%, 5%, and 7% by weight of aggregate
Second factor	Asphalt cement content	4.5%, 5.0%, 5.5%, 6.0%, and 6.5% by weight of mixture
Response (dependent variable), Marshall stiffness	Mechanical performance	Stability (kg), flow (mm), and stiffness (kg/mm)
Response (dependent variable), volumetric behavior	Mechanical performance	Air voids (%), VMA (%), and VFA (%)

Note. Both factors were set by the researchers and crossed in a full factorial design with three replicates per combination.

4.2. Materials and Mix Design

The materials used were previously characterized at the TECNILAB S.A.C. laboratory (Lima, Peru), in accordance with current technical standards. The binder was a penetration grade (PEN) 60/70 asphalt cement, widely used in hot mix asphalt, while the coarse aggregates came from the Bella 1 quarry and the sands, consisting of crushed sand and screened sand, from the Pedragal quarry, both in Lima, Peru. Both aggregates were characterized with the standardized tests summarized in Table 8, and all results fall within the admissible ranges for this type of mixture. PET, in turn, was obtained from recycled plastic bottles that were washed, dried, and ground into flakes [10,38], and then sieved through the No. 8 sieve; the fraction passing 2.36 mm and retained on the No. 200 sieve (0.075 mm) was used and incorporated by the dry process, that is, by mixing it with the heated aggregates before the binder was added following the Marshall procedure of the laboratory, in the proportions defined by the experimental design. Recycled bottle-grade PET has a density of 1.33 to 1.37 g/cm^3 [39], a glass transition near 80 °C, and a melting range of about 241 to 250 °C [40], so at the mixing temperature of about 150 °C the flakes soften without melting.

Table 8. Aggregate properties.

Property	Coarse Aggregate (Bella 1 Quarry)	Fine Aggregate (Pedragal Quarry)	Test Standard	International Equivalent
Bulk specific gravity, dry basis (–)	2.653	2.586	NTP 400.021 [41]/MTC E 206 [42] (coarse); NTP 400.022 [43]/MTC E 205 (fine)	ASTM C127, AASHTO T 85 (coarse); ASTM C128, AASHTO T 84 (fine)
Water absorption (%)	0.71	1.08	NTP 400.021/MTC E 206 (coarse); NTP 400.022/MTC E 205 (fine)	Same as above
Los Angeles abrasion (%)	22.9	—	NTP 400.019 [44]/MTC E 207	ASTM C131, AASHTO T 96 [a]
Soundness, magnesium sulfate (%)	8.4	—	NTP 400.016 [45]/MTC E 209	ASTM C88, AASHTO T 104 [a]
Durability index (–)	64.0	65.1	MTC E 214	ASTM D3744, AASHTO T 210
Fractured faces, two or more (%)	99.7	—	MTC E 210	ASTM D5821
Flat and elongated particles (%)	8.6	—	NTP 400.040 [46]/MTC E 223	ASTM D4791
Sand equivalent (%)	—	68	NTP 339.146 [47]/MTC E 114	ASTM D2419, AASHTO T 176 [a]
Uncompacted void content (%)	—	48.7	MTC E 222	ASTM C1252, AASHTO T 304 [a]
Soluble salts (%)	0.07	0.04	NTP 339.152 [48]/MTC E 219	— (LNV 8, Chile)
Aggregate-bitumen affinity (% coating)	≥95	—	MTC E 519	ASTM D2489
Adhesiveness, Riedel-Weber (rating)	—	6	MTC E 220	— (NLT-355, Spain)

Note. NTP = Peruvian Technical Standard; MTC = Ministry of Transport and Communications; ASTM = American Society for Testing and Materials; AASHTO = American Association of State Highway and Transportation Officials; (–) = dimensionless, since specific gravity is a ratio of masses and the durability index is a value on a 0 to 100 scale. International equivalents are those referenced in the MTC test manual [42] and in the laboratory reports; [a] same test method, with the equivalence not stated in the MTC manual. Tests performed at TECNILAB S.A.C. (Lima, Peru) in May 2026. The complete reports are included in Supplementary S7 and S8.

The aggregate blend combined 42% crushed gravel, 31% crushed sand, and 27% screened sand, with a maximum size of 3/4 in. Its gradation lies within the MAC-2 band (MAC, hot mix asphalt, in Spanish) at every sieve (Table 9). The mix design was developed by the Marshall method, from which an optimum asphalt cement content of approximately 5.49% was determined for the reference design, with slight variations according to PET dosage. The design was repeated for each PET dosage, with specimens at the five binder

contents, and the optimum was read on the curves of unit weight, air voids, VMA, VFA, stability, and flow against binder content (Supplementary S3–S6). The volumetric and mechanical parameters obtained at this stage, summarized in Table 10, served as the basis for preparing the specimens and for the subsequent comparative evaluation between the control mixture and the modified mixtures. The optimum binder content was 5.47, 5.45, and 5.37% for the designs with 3, 5, and 7% PET (Supplementary S4–S6). With the PET mass added to the aggregate and binder mixture, the dosages of 3, 5, and 7% by weight of aggregate correspond at those contents to 2.8, 4.5, and 6.2% by weight of mixture and to 52, 87, and 123% by weight of binder (Table S17 of Supplementary S1). Whether the optimum changes with PET dosage was judged in two ways, directly from the spread of the four optima against the 0.5% step between binder levels, and indirectly from the PET × binder interaction in the analysis of variance.

Table 9. Gradation of the aggregate blend.

Sieve	Opening (mm)	Passing (%)	MAC-2 Band (%)
3/4 in	19.0	100.0	100–100
1/2 in	12.5	99.4	80–100
3/8 in	9.5	87.8	70–88
No. 4	4.75	64.2	51–68
No. 10	2.00	48.1	38–52
No. 40	0.425	22.9	17–28
No. 80	0.180	14.0	8–17
No. 200	0.074	7.7	4–8

Note. Blend of 42% crushed gravel, 31% crushed sand, and 27% screened sand, with a maximum size of 3/4 in. Values from the gradation report of the laboratory (Supplementary S3), identical in the reports of the modified designs (Supplementary S4–S6). The MAC-2 limits are those reported by the laboratory.

Table 10. Mix design parameters obtained by the Marshall method.

Parameter	Reference Value
Binder type	PEN 60/70 asphalt cement
Optimum AC content	5.49%
Unit weight	2.326 g/cm^3
Air voids	3.4%
Voids in mineral aggregate (VMA)	17.1%
Voids filled with asphalt (VFA)	77.0%
Stability	826 kg
Flow	3.3 mm
Stiffness index	2572 kg/cm

Note. Values corresponding to the reference design. Across the designs with 0, 3, 5, and 7% PET, air voids ranged from 3.4 to 2.8%, VMA from 17.1 to 16.3%, and VFA from 77.0 to 71.0% (Supplementary S3–S6). The stiffness index is read from the design curve at the optimum asphalt cement content, so it does not coincide with the ratio between the stability and the flow of this table.

The evaluation of the materials and the mixture was carried out through standardized tests. The design and mechanical response of the mixture were determined through the Marshall test (ASTM standard D1559 [49] and standard T 245 of the American Association of State Highway and Transportation Officials [AASHTO] [50]), from which stability and flow were obtained, as well as stiffness calculated as the ratio between the two. The specimens were compacted with 75 blows per face, the level the method prescribes for heavy-traffic design, from a mixture prepared at approximately 150 °C and compacted at approximately 140 °C, and were immersed in a water bath at 60 °C for 30 min before stability and flow were

read. The maximum specific gravity of the mixture was established through the Rice test (ASTM D2041 [51]/AASHTO T 209 [52]), while the specific gravity and absorption of the aggregates were evaluated according to NTP 400.021, equivalent to method MTC E 206, and the adhesion between the binder and the fine aggregates was verified with the Riedel-Weber procedure (MTC E 220). For each combination of PET dosage and asphalt cement content, the values of stability, flow, stiffness, air voids, VMA, and VFA were systematically recorded, forming a structured and reliable database for the statistical analysis.

4.3. Data Analysis

Statistical processing was performed in jamovi (version 2.7, based on R 4.5), adopting a significance level of 0.05. In a first stage, a descriptive analysis of the six indicators (stability, flow, and stiffness for Marshall stiffness, and air voids, VMA, and VFA for volumetric behavior) was carried out, calculating the mean and standard deviation per PET dosage level and examining box plots to identify the distribution of the data and the possible presence of outliers. The assumptions of the analysis of variance were then verified: the normality of the model residuals was assessed with the Shapiro and Wilk [53] W test, effective even in samples of fewer than twenty observations, and the homogeneity of variance with Bartlett's [54] test, appropriate when normality is confirmed. The latter was computed over the four PET dosage levels, with fifteen observations each, and also over the twenty cells of the factorial model (Table S15 of Supplementary S1), where Levene's test, centered on the mean and on the median, complements Bartlett's because it is less sensitive to departures from normality. With three specimens per cell these cell-wise tests carry limited power, so the residuals of each model were inspected as well, against the fitted values and in normal quantile plots (Figure S1 of Supplementary S1).

On the basis of this verification, a two-factor analysis of variance was applied that considered both PET dosage and asphalt cement content. Including both factors was decisive, since it made it possible to isolate the effect of PET from that exerted by the binder, preventing the variability associated with the binder from masking the influence of the recycled material. For stability, which met the assumptions in every check, the analysis was applied directly; for the volumetric indicators, whose normality was borderline but with confirmed homogeneity and balanced groups, it was applied relying on the robustness of the procedure to slight departures from normality. Flow and stiffness received a particular treatment, detailed below.

Flow, whose normality was slightly below the threshold because of the quasi-discrete nature of the flow meter reading, and stiffness, which is obtained from that reading and showed unequal variance across cells in Levene's test centered on the mean, retained the two-factor model. Their conclusions were subjected to a permutation test with 5000 resamples, blocked by asphalt cement content, which does not require the normality assumption because the permutation distribution of the statistic does not depend on the population distribution [55]; the blocking permutes observations only within each binder content and preserves the size of each dosage group, following Good [56]. This strategy was chosen instead of a one-factor nonparametric test because the latter does not allow the variability associated with the binder to be accounted for, so that a real effect of PET dosage can be masked by the dispersion that binder content introduces among the observations.

When the analysis of variance was significant, Tukey [57] multiple comparisons were applied to identify between which specific dosages the differences occurred. Finally, effect size was calculated through eta squared, reported both in its partial form, which expresses the proportion of variance explained by PET dosage once binder content is accounted for, and in its total form, which expresses it over the variability of the whole dataset [34].

Reporting both forms simultaneously makes it possible to distinguish the existence of the effect from its relative importance within the overall behavior of the mixture and supports the decomposition of the variance among its sources reported in Section 2.5 and Table 5. Magnitude was rated with Cohen's [36] thresholds for η^2, 0.01, 0.06, and 0.14 for small, medium, and large effects, applied to total η^2 because it is the proportion over the variance of all the data [35]. To preserve the conciseness of the main text, only the essential statistics of each test are reported in the manuscript; the complete tables, with sums of squares, degrees of freedom, mean squares, and all multiple comparisons, are presented in Supplementary S1.

5. Conclusions

The study crossed four PET dosages with five binder contents, and with three replicates per combination, to determine the effect of PET on the mechanical performance of a hot mix asphalt. PET dosage influenced Marshall stiffness in its three indicators, with stability rising from 691 to 714 kg, flow falling from 2.98 to 2.78 mm, and stiffness rising from 232 to 258 kg/mm, with supported differences at 7%, so the first specific hypothesis is supported. Air voids and VMA did not change and VFA showed only a weak effect without distinguishable pairs, so the second specific hypothesis is also supported and the general hypothesis is partially supported. The interaction between PET dosage and binder content was non-significant for all six indicators.

It is that null interaction, more than the improvement in stiffness, that constitutes the contribution of the study, because it turns into a proven result what the one-factor literature took for granted. With the binder inside the model, the PET effect turned out to be the same between 4.5 and 6.5% binder: small for stability, medium for stiffness, and null for volumetrics. The binder, by contrast, governs the response of the mixture, explaining between 70.3 and 98.2% of the variance depending on the indicator, against 0.5 to 11.6% for PET. Hence the field, which already knew that fine PET stiffens the mixture, now knows something different: that it does so independently of binder content, for addition onto unaltered aggregate, in a dense-graded mixture, and within that binder range. And the form of that knowledge matters as much as its content, because an optimum does not travel from one quarry to another, whereas a rule of independence can be tested in other mixtures that share its conditions.

Within those conditions, the rule is useful for those who design or approve mixtures. A plant that already has an approved mix design can incorporate fine PET up to 7% by weight of aggregate without re-optimizing the binder content, in what the title calls post-design integration. Under the conditions tested, the dosing decision thus comes down to a single variable, the PET dosage, which spares the redesign of an approved mix and eases the adoption of the material where resources are unstable.

For the waste itself, the dosage gives the magnitude. A 7% by weight of aggregate is equivalent to 70 kg of PET per tonne of aggregate; carried to a 5 cm thick, 7 m wide wearing course, which consumes on the order of 800 tonnes of mixture per kilometer, it represents some 50 tonnes of PET per kilometer, close to two million 25 g bottles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling11120214/s1, Supplementary S1: Complete statistical analysis, with Table S1: Descriptive statistics by PET level (n = 15 per group); Table S2: Tests of residual normality and homogeneity of variance; Tables S3–S8: Two-factor ANOVA for stiffness, stability, flow, air voids, VMA, and VFA; Tables S9–S12: Tukey post hoc comparisons for stiffness, stability, flow, and VFA; Table S13: Permutation test of the PET effect on flow, blocked by binder content; Table S14: Partial effect size of each source of variation; Table S15: Homogeneity of variance over the twenty cells of the factorial model; Table S16: Permutation test of the PET effect on stiffness,

blocked by binder content; Table S17: Equivalent PET content by total mixture mass and by binder mass; Figure S1: Residual diagnostics of the two-factor model for the six indicators; Supplementary S2: Dataset of the 60 Marshall specimens, with its description; Supplementary S3: Marshall mix design laboratory report for 0% PET; Supplementary S4: Marshall mix design laboratory report for 3% PET; Supplementary S5: Marshall mix design laboratory report for 5% PET; Supplementary S6: Marshall mix design laboratory report for 7% PET; Supplementary S7: Coarse aggregate characterization tests; Supplementary S8: Fine aggregate characterization tests; Supplementary S9: English guide to the laboratory reports of Supplementary S3–S8.

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