

Article

Environmental Susceptibility of Base–Prime–Seal–Surface Interlayers in Asphalt Pavements

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Abstract

Reliable bonding between a cement-stabilized base and an asphalt surface course is essential to the integrity of semi-rigid base asphalt pavements. Accordingly, this study evaluated the environmental susceptibility of complete base–prime–seal–surface interlayer systems by introducing adverse conditions at selected construction contact planes and then measuring the peak shear response of the completed system. Four representative seal systems were investigated: a non-tracking emulsified asphalt seal, a fine-chip seal, a hot asphalt chip seal, and a slurry seal. Five specimens were initially prepared for each condition. Field-constructed 150 mm cement-stabilized base cores were combined with a 40 mm AC-13 layer and tested in direct shear at 25 °C. The investigated variables included clean, moist, and soil-contaminated interface conditions, grade 0 automotive diesel contamination, prime-coat omission, pre-placement substrate temperatures from −5 to 35 °C, and 0–10 freeze–thaw cycles. The results showed that diesel contamination at the seal–surface contact reduced strength retention to 73.6–83.6%. Meanwhile, prime-coat omission produced pronounced losses in the fine-chip and slurry systems, whereas the hot asphalt chip seal remained comparatively stable. The temperature response was material-specific: the fine-chip seal showed no significant overall temperature effect ($p = 0.1019$), while the hot asphalt chip seal reached the higher statistical category only at 25–35 °C. In contrast, the effects of short-term freeze–thaw cycling were relatively limited; after 10 freeze–thaw cycles, strength retention remained at 93.8–98.2%. Overall, the results support material-specific control of surface cleanliness, prime-coat application, and construction temperature.

Keywords: asphalt pavement; interlayer bonding; prime coat; seal coat; interface condition; shear strength; environmental susceptibility; freeze–thaw cycle



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1. Introduction

1.1. Background

Adequate interlayer bonding is essential to the structural integrity and long-term serviceability of asphalt pavements. Although multilayer pavements are generally designed to behave as mechanically continuous systems, interfaces between adjacent layers can become weak planes under repeated wheel loading, braking, acceleration, temperature variation, and moisture intrusion. In semi-rigid base asphalt pavements, inadequate interlayer adhesion has been identified as a major contributor to cracking, deformation, slippage,

delamination, and premature deterioration [1]. Mechanistic analyses further indicate that interface debonding, particularly under combined vertical and horizontal wheel loads, can substantially increase tensile strain in the asphalt layer and shorten fatigue life [2]. Accordingly, field investigations and reviews of prime- and tack-coat systems commonly use interface shear strength as an indicator of bonding quality and have shown that binder type, application rate, pavement type, surface texture, and service time influence interlayer performance [3–5]. Existing shear and tensile devices nevertheless differ in normal pressure, loading rate, shear-gap width, specimen preparation, and boundary conditions, which hinders direct comparison among studies [6]. EN 12697-48 provides a standardized framework for asphalt interlayer-bond testing, but its prescribed configurations and loading conditions differ from those adopted for the present multilayer base–prime–seal system [7]. This limitation is particularly relevant to base-related interfaces, for which confinement, surface porosity, and nonuniform binder penetration can differ substantially from conventional asphalt–asphalt interfaces.

In asphalt pavements constructed on cement-stabilized bases, the transition from the semi-rigid base to the asphalt surface layer typically incorporates a prime coat and a seal coat. The prime coat is intended to penetrate the upper portion of the base, bind loose particles, improve waterproofing, and provide a transitional bonding medium. The seal coat further contributes to waterproofing, aggregate embedment, mechanical interlock, and constructability. Accelerated pavement testing has shown that prime-treated sections can exhibit lower tensile strain and improved fatigue and rutting resistance compared with unprimed sections [8]. Laboratory studies have also developed enhanced prime materials with greater pull-off and shear strength, deeper penetration, and improved resistance to water erosion [9–11]. Moreover, combined prime and seal treatments can provide substantially greater shear strength than a prime coat alone [12]. Nevertheless, the contribution of the prime coat remains debated. Some studies have found that a prime coat does not necessarily increase shear strength under ideal laboratory conditions but can limit strength loss after moisture or high-temperature exposure [13]. Full-scale testing further indicates that the effectiveness of prime- and tack-coat materials depends strongly on surface texture, cleanliness, and application rate [14]. Collectively, these findings suggest that the prime coat functions not only as an initial bonding layer but also as an environmental buffer whose effectiveness depends on the construction condition of the base surface.

Most previous studies have focused on asphalt–asphalt interfaces or simplified base–surface contacts, whereas the base–prime–seal–surface transition constitutes a multilayer interlayer system. Its shear resistance may be governed by the weakest contact plane among the base–prime, prime–seal, and seal–surface interfaces or, when the prime coat is omitted, the base–seal interface. Surface roughness, macrotexture, binder dosage, pavement type, and specimen source have all been shown to influence measured shear strength [15–19]. Seal-coat systems also differ in binder type, aggregate retention, constructability, early-age cohesion, and cracking resistance, as documented for chip seals, non-tracking emulsions, and slurry-type seals [20–22]. Consequently, different seal systems may develop distinct bonding mechanisms and environmental sensitivities. However, direct comparisons among complete base–prime–seal–surface systems remain limited, and the contact plane responsible for strength loss is rarely isolated. Material selection and construction control are therefore often based on the overall strength of composite specimens rather than on contact-plane-specific evidence.

Environmental exposure further complicates interlayer bonding. Moisture can affect emulsion breaking, binder penetration, aggregate–binder adhesion, and interfacial friction. Dust and loose particles may form a separation layer that prevents intimate contact,

while the combined presence of moisture and contamination can create an even weaker interfacial film. In cold regions, freeze–thaw cycling has been reported to reduce interface shear strength, particularly on cementitious surfaces, although suitable emulsified binders may retain acceptable bonding performance [23]. Modified binders have likewise been evaluated under freeze–thaw exposure, with some systems retaining more than 80% of their initial strength after repeated cycles [24]. Temperature is another important factor, but its effect depends on the stage considered. During mechanical testing or service, increasing temperature generally reduces measured bond strength and can produce losses exceeding 80% in some configurations [25–27]. By contrast, an excessively cold interface during construction may inhibit binder wetting and activation. Mechanical-interlocking treatments can partly mitigate temperature-related degradation, although their applicability to conventional prime–seal systems remains uncertain [28].

Most interlayer studies assess a completed transition as a single bonded zone, so it remains difficult to determine whether an adverse construction condition introduced at the base–prime, prime–seal, or seal–surface contact has a similar consequence for the completed system. In addition, dusty, moist, and oil-contaminated construction-stage surfaces remain underrepresented in comparative interlayer studies. Diesel contamination has been investigated as a pavement-surface abnormality because of its implications for traffic safety and material deterioration [29], but its influence when introduced immediately before asphalt placement has rarely been compared across seal systems.

1.2. Scope and Objectives

This study aims to clarify the environmental susceptibility of the completed base–prime–seal–surface interlayer system and to identify construction conditions and material combinations associated with more stable measured shear responses. The specific objectives are as follows:

- (1) Quantify how moisture, particulate contamination, and diesel pollution introduced at selected contact planes affect the measured shear strength of the completed interlayer system;
- (2) Evaluate the consequences of prime-coat omission under different base–seal surface conditions;
- (3) Characterize material-specific sensitivity to substrate temperature immediately before AC-13 placement, without assuming a universal temperature threshold;
- (4) Assess short-term freeze–thaw response over the investigated 0–10-cycle laboratory conditioning range.

2. Materials and Methods

The overall experimental framework, from specimen preparation and conditioning-plane-specific testing to the normalized susceptibility summary, is shown in Figure 1.

2.1. Materials and Interlayer Systems

The composite specimens comprised a cement-stabilized crushed-stone base, a prime coat where specified, one of four seal-coat systems, and an overlying dense-graded AC-13 asphalt mixture. The four systems were selected because they are among the most widely used interlayer treatments for asphalt pavements on semi-rigid bases in Chinese highway engineering practice. Their selection was guided primarily by the Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) [30] together with the field construction practices associated with this study. The systems also represent four distinct forming mechanisms: a continuous non-tracking emulsion film, an emulsion-plus-fine-chip layer, a hot-applied SBS-modified binder-plus-chip layer, and an ES-2 slurry-type matrix. Structural mixtures were kept constant across the environmental test conditions.

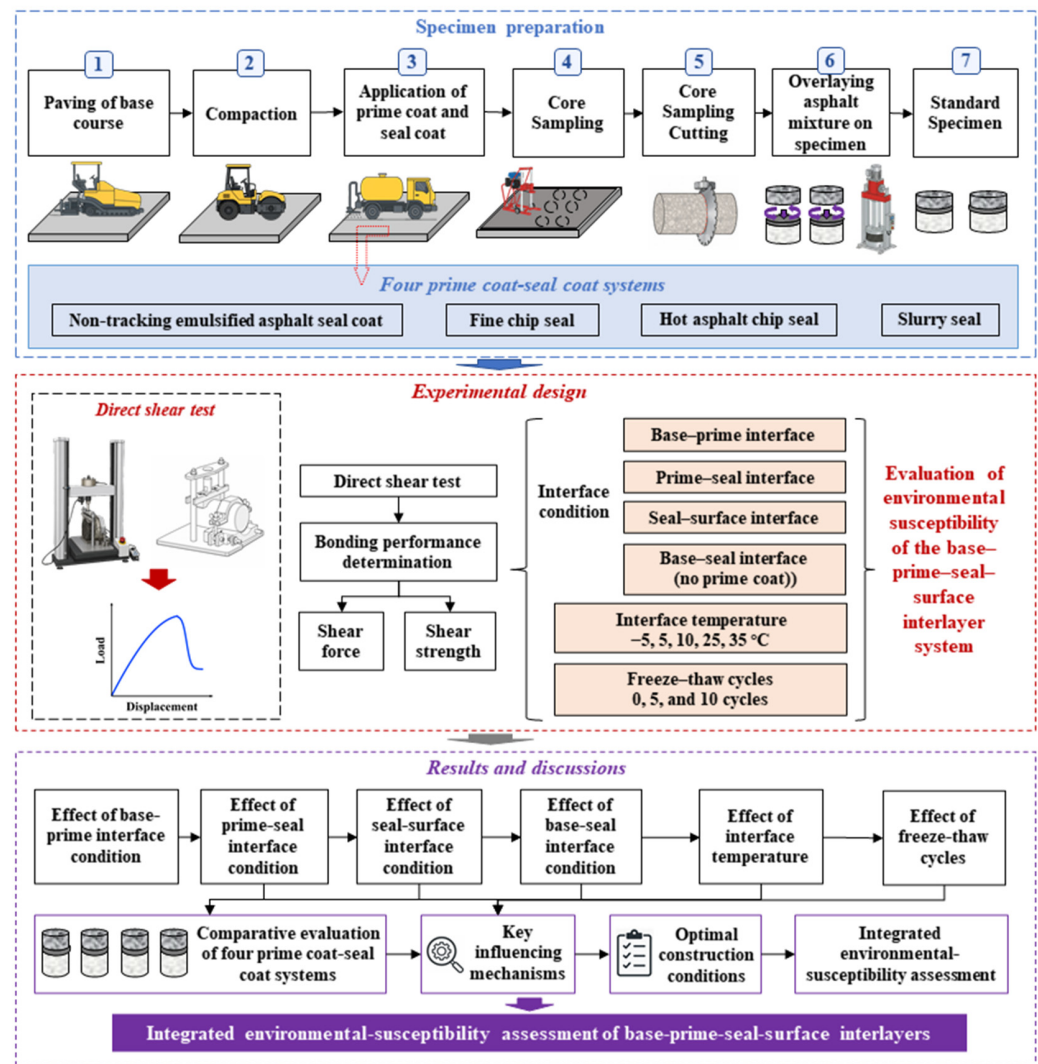


Figure 1. Experimental framework and analysis workflow.

A conventional cationic asphalt emulsion was used as the prime-coat material. The selected prime-coat application rate was 1.0 kg/m^2 . The principal material properties are listed in Table 1; the asphalt and emulsion characterization tests were conducted in accordance with JTG E20-2011 [31].

Table 1. Principal properties of the asphalt emulsions used as prime coats.

Property	Values
Ionic charge	Cationic
Engler viscosity (E25)	3.2
Residue on 1.18 mm sieve, %	0
Evaporation residue, %	52
Penetration of residue at 25 °C, 0.1 mm	93
Ductility of residue at 5 °C, cm	>100
Solubility of residue, %	99.36
Storage stability, 5 d, %	2

Four seal-coat systems were investigated. The non-tracking emulsified seal used 1.0 kg/m^2 of non-tracking modified asphalt emulsion without aggregate spreading. The fine-chip seal used 1.0 kg/m^2 of modified asphalt emulsion followed by approximately 80% surface coverage with 3–5 mm limestone chips. The hot asphalt chip seal used 1.0 kg/m^2

of hot SBS-modified asphalt followed by approximately 80% coverage with 5–10 mm limestone chips; the SBS-modified binder was the same SXG-II binder used in the AC-13 mixture. The slurry seal used an ES-2 gradation with mineral aggregate smaller than 4.75 mm; on a mineral-aggregate basis, the mixture used 100 parts aggregate and 6.0 parts added water, with an asphalt-to-aggregate ratio of 7.1%. For every slurry-seal specimen, an ordinary asphalt–emulsion tack coat was applied at 0.45 kg/m² after coring. The emulsion was allowed to break for approximately 4 h before AC-13 molding; tack-coat application was therefore a constant construction component rather than an experimental variable. The constituent materials and construction-related characteristics of the four systems are summarized in Table 2.

Table 2. Seal-coat materials and principal construction-related properties.

Seal System	Binder/Material	Setting or Forming Mechanism	Representative Properties
Non-tracking emulsified seal	Non-tracking modified asphalt emulsion	Rapid-setting emulsion	Engler viscosity (E25) 5.2; evaporation residue 51%; residue penetration 17 (0.1 mm); residue softening point 78 °C; 5 d storage stability 3%
Fine-chip seal	Slow-setting modified asphalt emulsion with fine limestone chips	Emulsion breaking and aggregate embedment	Standard viscosity 16 s; Engler viscosity (E25) 7; evaporation residue 55%; residue penetration 99 (0.1 mm); softening point 55 °C; rotational viscosity at 60 °C 670 Pa·s
Hot asphalt chip seal	SXG-II SBS-modified asphalt with limestone chips (same binder as AC-13)	Hot-applied binder cooling and chip embedment	Penetration 75 (0.1 mm); softening point 73 °C; ductility at 5 °C 48 cm; viscosity at 135 °C 2.46 Pa·s; elastic recovery 96.3%
Slurry-type seal	Conventional slow-setting asphalt emulsion and fine aggregate	Slurry mixing, breaking, curing, and constant tack-coat application before AC-13 placement	Engler viscosity (E25) 3; standard viscosity 14 s; evaporation residue 55%; 5 d storage stability 4%; ES-2 aggregate gradation (<4.75 mm)

2.2. Structural Mixtures

The asphalt surface course consisted of a dense-graded AC-13 mixture prepared with SXG-II polymer-modified asphalt. The binder penetration, softening point, and ductility at 5 °C were 75 (0.1 mm), 73 °C, and 48 cm, respectively. The same SXG-II binder was used in the hot asphalt chip seal. Basalt and limestone aggregates were blended with mineral filler and Portland cement in accordance with the AC-13 gradation envelope in JTG F40-2004 [30], as shown in Figure 2a. The stockpile mass proportions, together with mineral filler and Portland cement, were 18%, 32%, 16%, 30%, 2%, and 2% of total aggregate mass, respectively. The mixture was designed by the Marshall method. The optimum asphalt-to-aggregate mass ratio was 5.0%, the design air-void content was 4.0%, the voids in mineral aggregate (VMA) were 14.7% (requirement ≥14.5%), and the voids filled with asphalt (VFA) were 69.6% (requirement 65–75%).

The lower substrate was a cement-stabilized crushed-stone base (CTB) representative of a semi-rigid pavement structure, as shown in Figure 2b. P.S.A 32.5 Portland slag cement and limestone aggregates were used. Aggregate fractions of 20–25, 10–20, 5–10, 3–5, and 0–3 mm were blended at mass proportions of 20%, 35%, 22%, 5%, and 18%, respectively. The cement and fly-ash contents were 4.5% and 4.0%, respectively. Compaction testing yielded a maximum dry density of 2.398 g/cm³ and an optimum water content of 4.92%. The experimental base had an average 7 d unconfined compressive strength of 6.4 MPa and an average in-place degree of compaction of 98.6%. The CTB mixture design and construction requirements followed JTG/T F20-2015 [32], while the compaction test and 7 d unconfined compressive strength test were conducted in accordance with JTG E51-

2009 [33]. The reported in-place degree of compaction was obtained from field quality-control measurements.

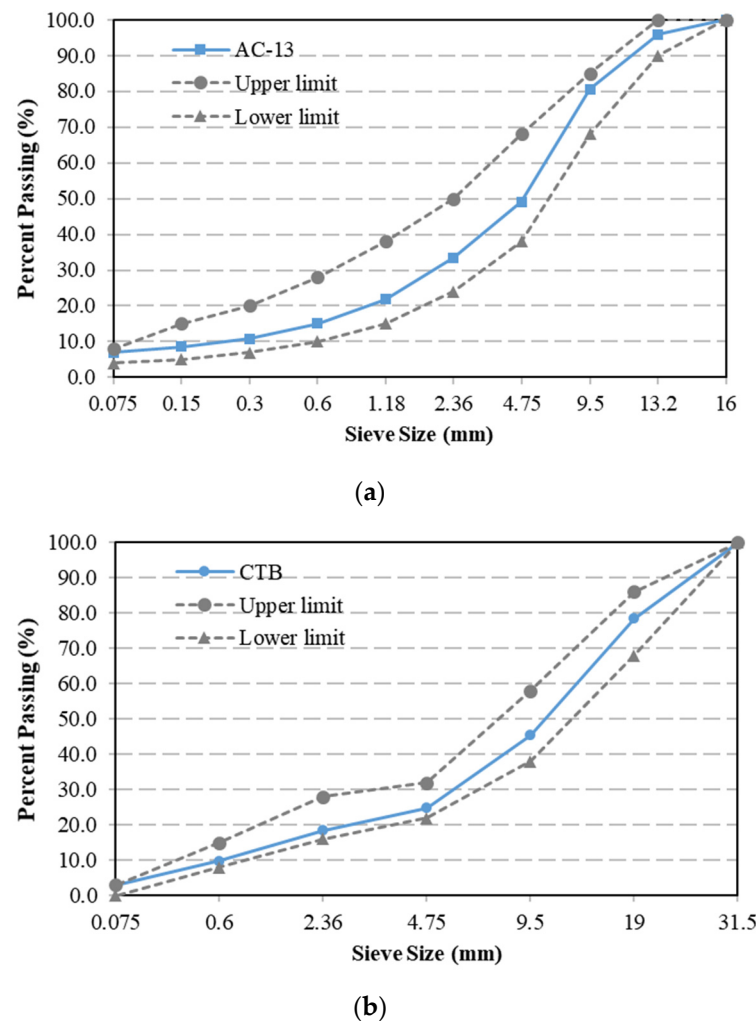


Figure 2. Aggregate gradations of (a) the AC-13 asphalt mixture and (b) the cement-stabilized crushed-stone base (CTB) mixture.

2.3. Environmental Interface Design

The experimental program was organized into conditioning-plane-specific blocks. Within each block, an adverse condition was introduced at one selected contact plane, while the remaining contacts were maintained in a nominally clean, surface-dry state. This design was intended to compare the response of the completed interlayer system after a particular contact plane had been conditioned. The base-prime, prime-seal, seal-surface, and no-prime base-seal blocks were examined as separate experimental blocks rather than as one combined full-factorial experiment.

Five interface states were defined. The clean-dry state was the reference condition, with visible loose particles removed and the surface naturally dried. Before coring, circular target areas approximately 150 mm in diameter (0.0177 m^2) were marked at the intended sampling locations, and each adverse condition was applied individually within the corresponding target area. For the clean-moist condition, 3 mL of water was atomized uniformly within each target area (approximately 170 mL/m^2). For the contaminated-dry condition, 25 g of field-collected fine soil passing the 0.6 mm sieve was distributed uniformly within each target area (approximately 1.41 kg/m^2). For the contaminated-moist condition, the same amounts of soil and water (25 g soil + 3 mL water per target area) were premixed

and spread uniformly. Diesel contamination was evaluated only at the seal–surface contact using grade 0 automotive diesel conforming to GB 19147-2016 [34]; 3.5 mL was brushed uniformly within each target area (approximately 198 mL/m²). The imposed contaminants were allowed to remain on the treated surface for approximately 1 h before the subsequent construction procedure. The soil dosage was intentionally selected as a severe contamination condition to accentuate the effect of particulate contamination and should not be interpreted as a representative level of routine field contamination. The preparation procedures and engineering interpretations are summarized in Table 3.

Table 3. Preparation and engineering interpretation of the adverse interface states.

Interface State	Preparation Principle	Engineering Implication	Applied Contact Planes
Clean–dry	Surface cleaned and kept naturally surface dry	Reference condition required for standard construction	Base–prime, prime–seal, seal–surface, and no-prime base–seal
Clean–moist	3 mL water per 150 mm target area (~170 mL/m ²), atomized uniformly; ~1 h dwell; moist film without visible standing water.	Premature construction after incomplete drying or rain-induced wetting	Base–prime, prime–seal, seal–surface, and no-prime base–seal
Contaminated–dry	Field-collected fine soil, particle size <0.6 mm; 25 g per 150 mm target area (~1.41 kg/m ²), uniformly spread; ~1 h dwell	Severe particulate contamination imposed to accentuate the adverse-interface effect; not intended as a representative routine field level	Base–prime, prime–seal, seal–surface, and no-prime base–seal
Contaminated–moist	25 g field soil + 3 mL water per 150 mm target area, premixed at the same proportion and uniformly spread; ~1 h dwell	Combined pollution and moisture, representing the most unfavorable common interface state	Base–prime, prime–seal, seal–surface, and no-prime base–seal
Diesel-contaminated	Grade 0 automotive diesel (GB 19147-2016), 3.5 mL per 150 mm target area (~198 mL/m ²), uniformly brushed to form a thin film; ~1 h dwell	Fuel leakage or oil contamination from construction equipment	Seal–surface interface only

A common construction chronology was used for all test groups containing a prime coat. The cement-stabilized base was cured for 1 d before the 1.0 kg/m² prime coat was applied. The primed base was then conditioned for approximately 27 d before construction of the designated seal coat, so the base age at seal-coat construction was approximately 28 d. For the no-prime block, the base was cured directly for 28 d before seal-coat construction. The temperature and freeze–thaw blocks followed the same 1 d prime-coat plus 27 d conditioning sequence. Thus, the different experimental blocks did not intentionally use different base ages at seal construction. The base–prime interface series was conducted earlier as an independently prepared preliminary series, whereas the later blocks were prepared in a unified campaign; this distinction is considered when discussing cross-block controls and repeatability. Table 4 consolidates the target planes, variable interface states, and controlled conditions for the four design blocks.

Two additional blocks assessed pre-placement substrate-temperature sensitivity and short-term freeze–thaw response. In the temperature block, normally prepared primed/sealed base specimens with clean–dry contacts were conditioned to −5, 5, 10, 25, or 35 °C immediately before placement of the hot AC-13 mixture. The freeze–thaw conditioning protocol was adapted from Method T 0729-2000 of JTG E20-2011 [31] for the present composite specimens and subsequent direct shear test. Five specimens were initially prepared for each condition. Before the first cycle, specimens were vacuum-saturated at a vacuum degree of approximately 97.3–98.7 kPa for 15 min; after atmospheric pressure was restored, they remained in water for an additional 0.5 h. Each specimen was then sealed in a plastic bag containing approximately 10 mL of water. One freeze–thaw cycle consisted of freezing at -18 ± 2 °C for 16 ± 1 h followed by thawing in a 60 ± 0.5 °C

water bath for 24 h. Vacuum saturation was performed only once before the first cycle, and the freezing–thawing sequence was repeated continuously until 0, 5, or 10 cycles were reached. After the final cycle, the specimens were conditioned in a 25 °C water bath for 4 h before direct shear testing. The 5- and 10-cycle levels were selected to characterize relative short-term freeze–thaw susceptibility and early-stage performance evolution. The levels and purposes of these two conditioning blocks are provided in Table 5.

Table 4. Conditioning-plane-specific experimental blocks and controlled conditions.

Design Block	Target Contact Plane	Variable Interface States	Controlled Conditions
Base–prime interface	Cement-stabilized base/prime coat	Clean–dry, clean–moist, contaminated–dry, contaminated–moist	CTB cured 1 d before prime application; seal constructed ~27 d later (base age ~28 d); upper contacts kept clean–dry
Prime–seal interface	Prime coat/seal coat	Clean–dry, clean–moist, contaminated–dry, contaminated–moist	CTB cured 1 d before prime application; seal constructed ~27 d later; base–prime and seal–surface contacts kept clean–dry
Seal–surface interface	Seal coat/AC-13 asphalt mixture	Clean–dry, clean–moist, contaminated–dry, contaminated–moist, diesel-contaminated	Same 1 d prime + 27 d conditioning sequence; lower contacts kept clean–dry; diesel condition included only in this block
No-prime base–seal interface	Cement-stabilized base/seal coat	Clean–dry, clean–moist, contaminated–dry, contaminated–moist	CTB cured 28 d before direct seal-coat construction; prime omitted; AC-13 placed on the clean–dry seal surface

Table 5. Construction-temperature and freeze–thaw conditioning blocks.

Block	Seal Systems Considered	Levels	Purpose of Conditioning
Pre-placement substrate temperature	Non-tracking emulsified seal, fine-chip seal, hot asphalt chip seal, and slurry-type seal	−5, 5, 10, 25, and 35 °C	Evaluate material-specific sensitivity to the initial substrate temperature immediately before hot AC-13 placement
Freeze–thaw conditioning	Non-tracking emulsified seal, fine-chip seal, hot asphalt chip seal, and slurry-type seal	0, 5, and 10 cycles	Evaluate relative short-term freeze–thaw susceptibility under a conditioning protocol adapted from Method T 0729-2000 of JTG E20-2011

2.4. Preparation of Composite Specimens

To retain field-formed base characteristics while maintaining controlled specimen geometry, the composite specimens were prepared using a combination of field construction, core sampling, and laboratory compaction. The CTB was paved and roller compacted in an experimental pavement section. For primed groups, the base was cured for 1 d before prime application, and the seal coat was constructed approximately 27 d later; for the no-prime group, the base was cured for 28 d before seal construction. The assigned interface condition was established at the relevant construction step. Seal treatments were allowed to stabilize overnight before coring; the hot asphalt chip seal was allowed to cool overnight, whereas emulsion/slurry-based treatments were allowed to break or cure overnight.

On the day after seal-coat construction, cylindrical cores with a nominal diameter of 150 mm were extracted, and the lower CTB portion was trimmed to 100 mm while preserving the treated upper surface. For the non-tracking, fine-chip, and hot asphalt chip systems, the cored specimen was subsequently used to form the AC-13 overlay. For the slurry system, the prescribed seal–surface condition, where applicable, was imposed directly on the cured slurry surface before tack-coat application. After the approximately 1 h conditioning period, an ordinary asphalt–emulsion tack coat was sprayed uniformly

at 0.45 kg/m^2 . The tack coat was then allowed to break for approximately 4 h before the AC-13 layer was molded. Specimens were excluded if the overall layer configuration was clearly noncompliant, the core/overlay was visibly eccentric, or the specimen was damaged during coring, trimming, or handling.

Each 150 mm diameter treated base core was placed at the bottom of a 150 mm mold of an AFG2C gyratory compactor (Pine Test Equipment, Grove City, PA, USA) with the interlayer surface facing upward. AC-13 was mixed at approximately 175°C and compacted at approximately 140°C under a vertical pressure of 600 kPa, a gyration angle of 1.25° , and a rotational speed of 30 r/min. Compaction was terminated when the AC-13 layer reached the target thickness of 40 mm rather than at a prescribed number of gyrations. The mixture was designed at 4.0% air voids, and accepted composite specimens had measured air-void contents of approximately 3.5–4.5%. No obvious edge loosening, eccentric compaction, or other macroscopic compaction nonuniformity was observed. Five replicate specimens were initially prepared for each condition. The complete field-to-laboratory preparation sequence is illustrated in Figure 3.

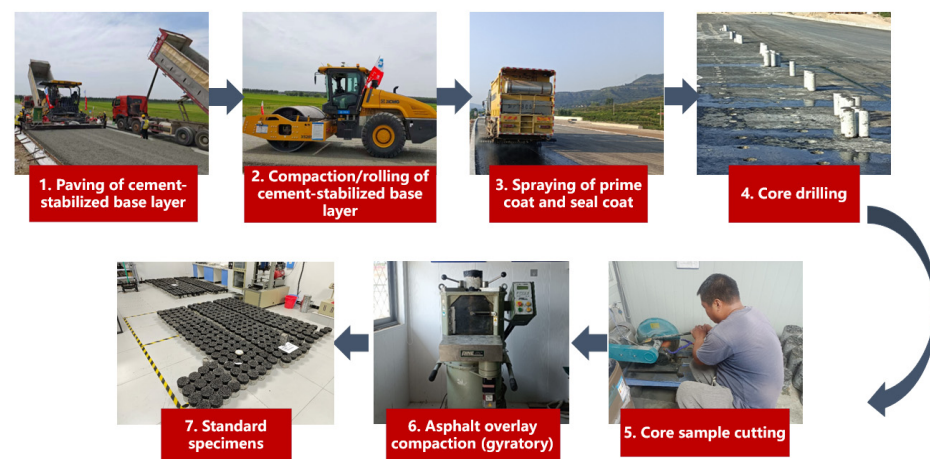


Figure 3. Field-laboratory procedure for preparing the composite specimens.

2.5. Direct Shear Test

Bonding performance was evaluated using an in-house direct shear fixture mounted in a UTM-30 servo-hydraulic universal testing machine equipped with an environmental chamber (IPC Global, Controls Group, Liscate, MI, Italy). Before testing, specimen diameter was measured at four equally spaced locations, and the mean value, D , was used in the strength calculation. Unless otherwise specified, completed specimens were conditioned and tested at 25°C . Before formal shear loading, an approximately 100 N seating load was applied to ensure stable contact between the specimen and loading apparatus. No externally applied normal stress was imposed during shear. The CTB half of the composite specimen was fixed in the shear fixture, while the loading head displaced the AC-13 half. The construction-temperature block varied only the substrate temperature before AC-13 placement; all subsequent shear tests were performed at 25°C .

Preliminary sensitivity tests were conducted to determine the shear gap and displacement rate. At 25°C and 3 mm/min, gaps of 2, 6, 10, and 14 mm were compared. The mean peak shear force decreased markedly from 2 to 6 mm and then approached a stable level at 10–14 mm, while the 10 mm group exhibited the lowest variability; 10 mm was therefore adopted to balance response stability and repeatability while limiting excessive constraint or shear-band/eccentric-loading effects. Using the 10 mm gap at 25°C , displacement rates of 1, 3, 5, and 7 mm/min were compared. The mean peak shear force increased from approximately 6.9 kN at 1 mm/min to 12.2 kN at 5 mm/min, but increased by only 1.9% from 5 to 7 mm/min.

The corresponding coefficients of variation were 19.1%, 6.5%, 6.9%, and 9.5%, respectively. Accordingly, 5 mm/min was selected as the standard displacement rate. The peak shear force was converted to maximum interfacial shear strength using Equation (1):

$$\tau_{max} = \frac{4F_{max}}{\pi D^2} \quad (1)$$

where τ_{max} is the maximum interfacial shear strength, MPa; F_{max} is the peak shear force, N; and D is the mean diameter of the shear plane, mm. When F_{max} is expressed in N and D in mm, τ_{max} is obtained in N/mm², which is numerically equivalent to MPa.

2.6. Data Processing and Statistical Analysis

Five replicate specimens were initially prepared for each treatment condition. All data processing and statistical analyses were performed using MATLAB R2023a (The MathWorks, Inc., Natick, MA, USA). Before statistical analysis, each test was screened for technical validity. Tests showing abnormal loading histories caused by hydraulic-pressure instability of the loading system were classified as technically invalid and excluded from the statistical dataset. Grubbs' test was then applied only to technically valid measurements at $\alpha = 0.05$. The test was applied iteratively where the remaining sample size permitted; when an observation satisfied the Grubbs criterion, it was removed, and the remaining dataset was re-evaluated. No further Grubbs test was performed when the sample size was insufficient. Thus, the groups reported with $n = 2$ were not produced by repeatedly removing three observations from an original set of five using Grubbs' test; in several freeze–thaw groups, only two technically valid measurements remained after abnormal loading records were excluded. Means, standard deviations, within-block retention ratios, and one-way eta-squared (η^2) effect sizes were calculated. Statistical significance was assessed at $\alpha = 0.05$; different lowercase letters denote Tukey groups that differ significantly at the 95% confidence level. The clean–dry seal–surface dataset was intentionally reused as the 25 °C and 0-cycle reference because those three conditions represented the same physical baseline and the same specimens. Those three analyses therefore share a control and are not statistically independent. In contrast, the earlier base–prime series was independently prepared as a preliminary experimental series, and the no-prime base–seal series used separate specimens because its interlayer configuration was physically different.

3. Results and Discussion

3.1. Effect of Base–Prime Interface Condition on Bonding Performance

The base–prime construction contact governs prime penetration and anchorage into the CTB. To assess the consequence of adverse conditions introduced at this construction step, the four completed interlayer systems were compared under clean–dry, clean–moist, contaminated–dry, and contaminated–moist treatments. Figure 4 shows the measured peak shear strengths, and Table 6 gives the final sample sizes, Tukey HSD groupings, one-way ANOVA results, and η^2 effect sizes.

As can be seen from Figure 4 and Table 6, the hot asphalt chip seal exhibited the most stable response to the four base–prime contact conditions, with mean shear strength varying only from 0.485 to 0.502 MPa and no statistically significant overall difference detected ($p = 0.8682$; $\eta^2 = 0.046$). This indicates a comparatively stable completed-system response to the tested base–prime construction states.

In contrast, the fine-chip seal showed a clear reduction after particulate contamination was introduced, with the mean strength decreasing from 0.432 and 0.417 MPa under the clean–dry and clean–moist conditions to 0.375 and 0.378 MPa under the contaminated–dry and contaminated–moist conditions, respectively ($p < 0.001$; $\eta^2 = 0.768$). Tukey HSD placed

the two clean states in one group and the two contaminated states in a lower group. This pattern is consistent with a detrimental effect when field soil is present at the base–prime construction contact.

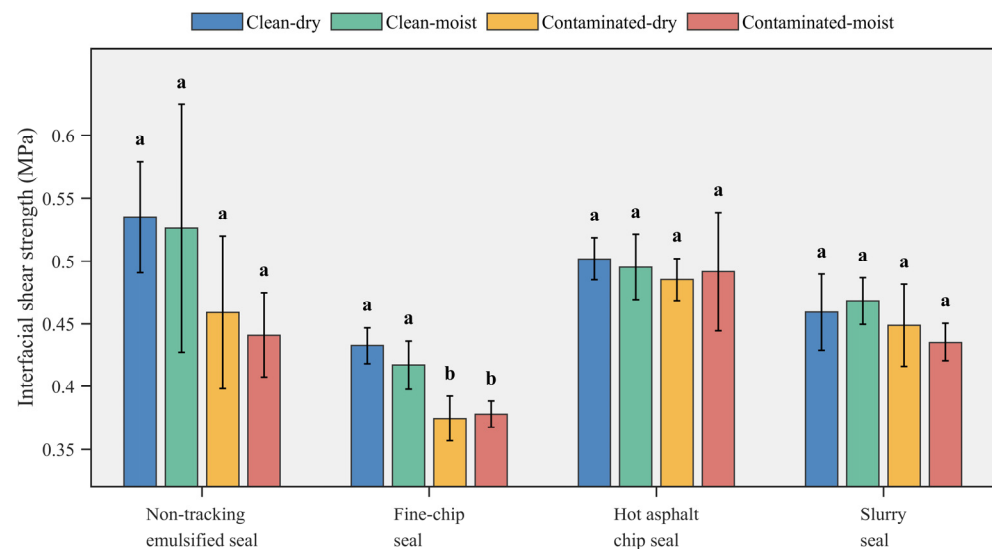


Figure 4. Effect of base–prime contact conditioning on measured shear strength of the completed interlayer systems. Different lowercase letters above the bars indicate statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 6. Peak shear strength of the completed interlayer systems after base–prime contact conditioning.

Seal-Coat System	Clean–Dry (MPa)	Clean–Moist (MPa)	Contaminated–Dry (MPa)	Contaminated–Moist (MPa)	ANOVA Result
Non-tracking emulsified seal	0.535 ± 0.044 a (n = 5)	0.526 ± 0.099 a (n = 5)	0.459 ± 0.061 a (n = 5)	0.441 ± 0.034 a (n = 5)	$p = 0.0814$; $\eta^2 = 0.335$
Fine-chip seal	0.432 ± 0.014 a (n = 5)	0.417 ± 0.019 a (n = 4)	0.375 ± 0.018 b (n = 5)	0.378 ± 0.010 b (n = 5)	$p < 0.001$; $\eta^2 = 0.768$
Hot asphalt chip seal	0.502 ± 0.017 a (n = 5)	0.495 ± 0.026 a (n = 5)	0.485 ± 0.017 a (n = 4)	0.492 ± 0.047 a (n = 5)	$p = 0.8682$; $\eta^2 = 0.046$
Slurry seal	0.459 ± 0.030 a (n = 5)	0.468 ± 0.019 a (n = 4)	0.449 ± 0.033 a (n = 4)	0.435 ± 0.015 a (n = 4)	$p = 0.3453$; $\eta^2 = 0.218$

Note: Values are mean $\pm$ SD; final n is shown in parentheses; different lowercase letters denote Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

The non-tracking emulsified and slurry systems showed weaker statistical evidence of treatment-state differences. For the non-tracking system, mean strength declined from 0.535 MPa under clean–dry conditions to 0.441 MPa under contaminated–moist conditions, but the overall one-way effect was not significant ($p = 0.0814$). The slurry system ranged from 0.435 to 0.468 MPa with no significant overall difference ($p = 0.3453$). These results reinforce the need to distinguish descriptive mean changes from statistically resolved differences.

These findings identify the base–prime interface as a material-dependent construction-control point. Although a clean, dry base generally produced the most favorable bonding condition, the fine-chip seal was particularly susceptible to contamination because its thin seal structure depends strongly on effective prime penetration and localized mechanical interlock.

3.2. Effect of Prime–Seal Interface Condition on Bonding Performance

The prime–seal construction contact reflects the compatibility between the penetrated prime layer and the subsequently applied seal. Figure 5 compares the completed-system shear responses under the four treatment states, and Table 7 reports the associated statistics.

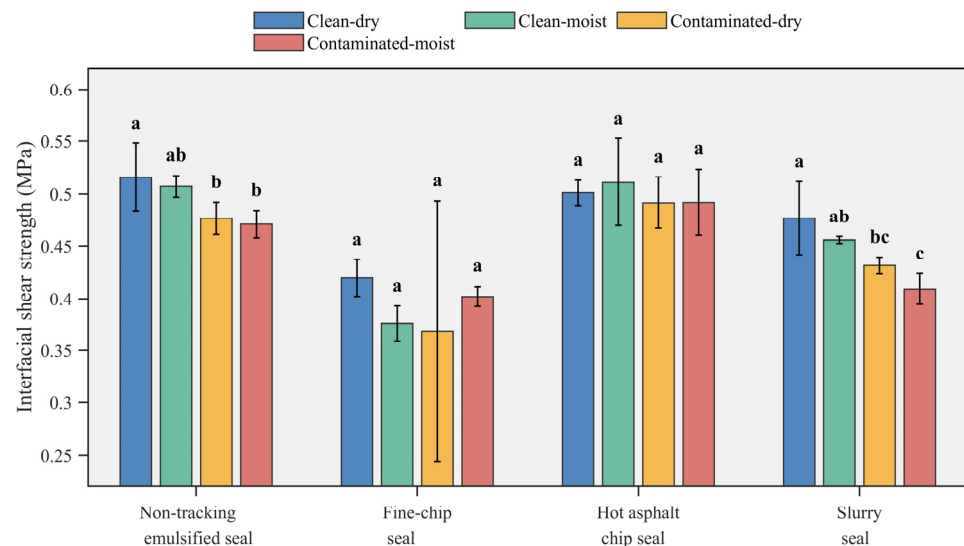


Figure 5. Effect of prime–seal contact conditioning on measured shear strength. Different lowercase letters above the bars indicate statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 7. Peak shear strength and statistical comparison after prime–seal contact conditioning.

Seal-Coat System	Clean–Dry (MPa)	Clean–Moist (MPa)	Contaminated–Dry (MPa)	Contaminated–Moist (MPa)	ANOVA Result
Non-tracking emulsified seal	0.516 ± 0.032 a (n = 5)	0.507 ± 0.010 ab (n = 3)	0.477 ± 0.016 b (n = 4)	0.471 ± 0.013 b (n = 4)	$p = 0.0136$; $\eta^2 = 0.576$
Fine-chip seal	0.420 ± 0.042 a (n = 5)	0.376 ± 0.017 a (n = 4)	0.369 ± 0.125 a (n = 5)	0.402 ± 0.009 a (n = 4)	$p = 0.7030$; $\eta^2 = 0.099$
Hot asphalt chip seal	0.501 ± 0.019 a (n = 5)	0.511 ± 0.041 a (n = 5)	0.492 ± 0.025 a (n = 5)	0.492 ± 0.032 a (n = 5)	$p = 0.7173$; $\eta^2 = 0.084$
Slurry seal	0.477 ± 0.035 a (n = 4)	0.456 ± 0.003 ab (n = 3)	0.431 ± 0.008 bc (n = 3)	0.409 ± 0.015 c (n = 4)	$p < 0.001$; $\eta^2 = 0.882$

Note: Values are mean $\pm$ SD; final n is shown in parentheses; different lowercase letters denote Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

As shown in Figure 5 and Table 7, the non-tracking emulsified seal exhibited a clear reduction in mean shear strength after particulate contamination was introduced at the prime–seal contact. The mean strength decreased from 0.516 and 0.507 MPa under the clean–dry and clean–moist conditions to 0.477 and 0.471 MPa under the contaminated–dry and contaminated–moist conditions, respectively ($p = 0.0136$; $\eta^2 = 0.576$). Tukey HSD separated the clean–dry state from the two contaminated states, while the clean–moist state was intermediate.

The slurry seal showed the strongest overall prime–seal treatment effect ($p < 0.001$; $\eta^2 = 0.882$). Mean strength decreased from 0.477 MPa in the clean–dry group to 0.409 MPa in the contaminated–moist group. Tukey HSD indicated a stepwise pattern: clean–dry was highest, clean–moist and contaminated–dry were intermediate, and contaminated–moist was lowest. This is consistent with greater sensitivity of the slurry-based system to adverse contact preparation.

No significant difference in mean strength was detected among the four conditions for the fine-chip seal ($p = 0.7030$). Nevertheless, the contaminated–dry group exhibited a large standard deviation of 0.125 MPa, indicating strong sensitivity to local contact heterogeneity, such as nonuniform aggregate distribution or partial interference between the chips and the prime film.

The hot asphalt chip seal again showed a stable completed-system response, with means of 0.492–0.511 MPa and no significant difference among the four treatment states ($p = 0.7173$). Taken together, the prime–seal results show stronger statistical sensitivity for

the non-tracking and slurry systems than for the hot asphalt chip system under the tested laboratory conditions.

At the lower contact planes, bonding is primarily governed by binder penetration, surface suction, and continuity of the prime film. Moisture may delay emulsion breaking without completely preventing contact when the surface remains clean. Fine particles or mud, by contrast, can form a physical separation layer that obstructs prime penetration into the base pores and interrupts bonding with the overlying seal.

3.3. Effect of Seal–Surface Interface Condition on Bonding Performance

The seal–surface construction contact is established immediately before hot-mixture placement and is directly exposed to the final cleanliness and contamination state. Figure 6 compares the response to moisture, field-soil contamination, combined wet contamination, and grade 0 automotive diesel contamination, with the statistical results summarized in Table 8.

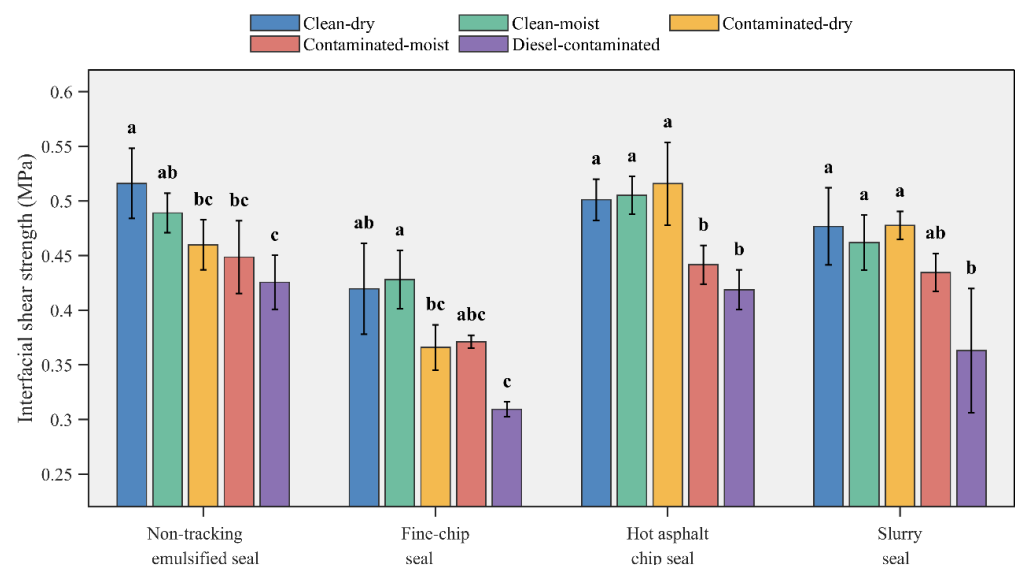


Figure 6. Effect of seal–surface contact conditioning on measured shear strength. Different lowercase letters above the bars indicate statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 8. Peak shear strength and statistical comparison after seal–surface contact conditioning.

Seal-Coat System	Clean–Dry (MPa)	Clean–Moist (MPa)	Contaminated–Dry (MPa)	Contaminated–Moist (MPa)	Diesel–Contaminated (MPa)	ANOVA Result
Non-tracking emulsified seal	0.516 ± 0.032 a (n = 5)	0.489 ± 0.018 ab (n = 5)	0.460 ± 0.023 bc (n = 5)	0.449 ± 0.033 bc (n = 5)	0.425 ± 0.025 c (n = 5)	$p < 0.001$; $\eta^2 = 0.635$
Fine-chip seal	0.420 ± 0.042 ab (n = 5)	0.428 ± 0.027 a (n = 4)	0.366 ± 0.021 bc (n = 4)	0.371 ± 0.006 abc (n = 3)	0.309 ± 0.007 c (n = 4)	$p < 0.001$; $\eta^2 = 0.783$
Hot asphalt chip seal	0.501 ± 0.019 a (n = 5)	0.505 ± 0.017 a (n = 4)	0.516 ± 0.038 a (n = 5)	0.442 ± 0.018 b (n = 5)	0.419 ± 0.018 b (n = 5)	$p < 0.001$; $\eta^2 = 0.776$
Slurry seal	0.477 ± 0.035 a (n = 4)	0.462 ± 0.025 a (n = 4)	0.478 ± 0.013 a (n = 4)	0.435 ± 0.017 ab (n = 4)	0.363 ± 0.057 b (n = 4)	$p = 0.0010$; $\eta^2 = 0.686$

Note: Values are mean $\pm$ SD; final n is shown in parentheses; different lowercase letters denote Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

Figure 6 and Table 8 collectively indicate that the non-tracking emulsified seal was adversely affected by seal–surface contamination, with the most pronounced reduction occurring under diesel contamination. The mean shear strength decreased from 0.516 MPa under the clean–dry condition to 0.425 MPa after grade 0 automotive diesel contamination, corresponding to a strength retention of 82.4% and a reduction of 17.6%. The overall treat-

ment effect was statistically significant ($p < 0.001$; $\eta^2 = 0.635$), and the diesel-contaminated group was classified in the lowest Tukey HSD category.

The fine-chip seal showed the largest diesel-related loss. Its clean-dry mean was 0.420 MPa, whereas the diesel-contaminated mean was 0.309 MPa, corresponding to 73.6% retention (26.4% reduction). The overall treatment effect was significant ($p < 0.001$; $\eta^2 = 0.783$).

The hot asphalt chip seal maintained mean strengths of 0.501–0.516 MPa under the clean-dry, clean-moist, and contaminated-dry conditions, but decreased to 0.442 MPa under contaminated-moist conditions and 0.419 MPa under diesel contamination (83.6% retention relative to clean-dry). The overall treatment effect was significant ($p < 0.001$; $\eta^2 = 0.776$).

The slurry seal showed comparable means of 0.462–0.478 MPa for the clean-dry, clean-moist, and contaminated-dry states, followed by reductions to 0.435 MPa under contaminated-moist conditions and 0.363 MPa after diesel contamination (76.1% retention). The overall treatment effect was significant ($p = 0.0010$; $\eta^2 = 0.686$).

Across the four systems, diesel contamination introduced at the seal–surface construction stage produced one of the most consistent adverse responses. Because fracture planes were not systematically recorded, this result should be interpreted as the response of the complete interlayer system after seal–surface contamination rather than to the intrinsic strength of the seal–surface contact itself. It should also be noted that the slurry-seal specimens were the only system with an additional 0.45 kg/m² tack coat directly beneath the AC-13 layer. Therefore, cross-system differences involving the slurry seal reflect the combined effects of the seal system and the additional tack coat and should not be attributed exclusively to the slurry-seal material; within-slurry comparisons remain directly comparable because the tack-coat type and application rate were held constant.

The results also emphasize that statistical significance should be interpreted together with data dispersion. In systems containing coarse or discrete aggregate contacts, failure may propagate along different local paths, producing substantial variation in measured strength. Both the mean response and its variability should therefore be considered when evaluating bonding robustness.

3.4. Effect of Base–Seal Interface Condition Without a Prime Coat

The no-prime base–seal block directly evaluated completed systems in which the seal was constructed on the CTB without a penetrating prime layer. Figure 7 presents the measured peak shear strengths, and Table 9 summarizes the statistical comparisons.

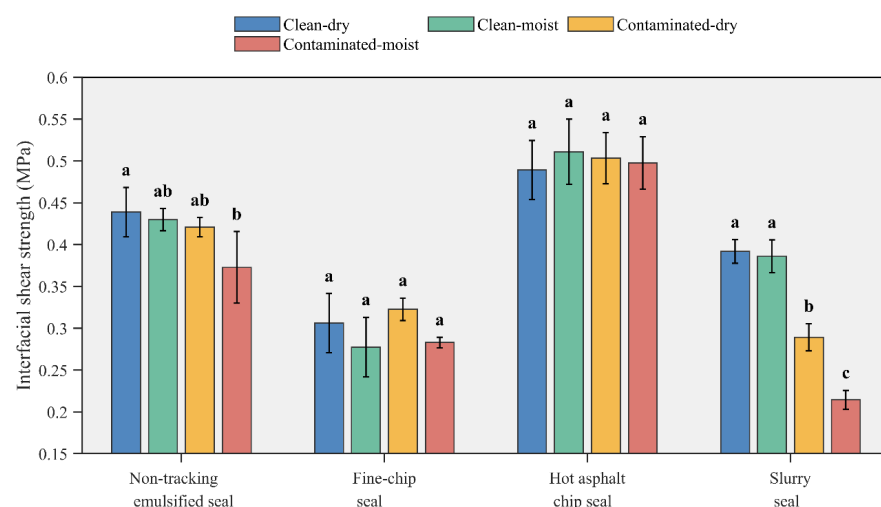


Figure 7. Effect of base–seal contact conditioning on measured shear strength without a prime coat. Different lowercase letters above the bars indicate statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 9. Peak shear strength and statistical comparison for base–seal conditions without a prime coat.

Seal-Coat System	Clean–Dry (MPa)	Clean–Moist (MPa)	Contaminated–Dry (MPa)	Contaminated–Moist (MPa)	ANOVA Result
Non-tracking emulsified seal	0.439 ± 0.029 a (n = 4)	0.430 ± 0.013 ab (n = 4)	0.421 ± 0.011 ab (n = 4)	0.373 ± 0.043 b (n = 4)	$p = 0.0228$; $\eta^2 = 0.535$
Fine-chip seal	0.306 ± 0.035 a (n = 5)	0.277 ± 0.036 a (n = 5)	0.323 ± 0.013 a (n = 4)	0.283 ± 0.006 a (n = 4)	$p = 0.1025$; $\eta^2 = 0.348$
Hot asphalt chip seal	0.489 ± 0.035 a (n = 5)	0.511 ± 0.039 a (n = 5)	0.503 ± 0.031 a (n = 4)	0.498 ± 0.031 a (n = 4)	$p = 0.7872$; $\eta^2 = 0.070$
Slurry seal	0.392 ± 0.014 a (n = 4)	0.386 ± 0.020 a (n = 4)	0.289 ± 0.016 b (n = 4)	0.214 ± 0.011 c (n = 5)	$p < 0.001$; $\eta^2 = 0.969$

Note: Values are mean ± SD; final n is shown in parentheses; different lowercase letters denote Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

As evidenced by Figure 7 and Table 9, the non-tracking emulsified seal retained a moderate level of shear resistance even when the prime coat was omitted, although its response deteriorated as the base–seal contact condition became more adverse. The mean strength decreased from 0.439 MPa under the clean–dry condition to 0.373 MPa under the contaminated–moist condition, with a significant overall treatment effect ($p = 0.0228$; $\eta^2 = 0.535$). Tukey HSD distinguished the clean–dry and contaminated–moist groups, whereas the clean–moist and contaminated–dry conditions exhibited intermediate responses.

The fine-chip seal showed consistently low mean strength under the no-prime configuration (0.277–0.323 MPa). Differences among the four surface states were not statistically significant ($p = 0.1025$; $\eta^2 = 0.348$). Relative to the independently prepared primed clean–dry reference used in the qualitative cross-block summary, the no-prime clean–dry value corresponded to approximately 70.8% retention; this ratio is interpreted descriptively because the two blocks used separate specimen batches.

The hot asphalt chip seal exhibited the highest and most stable direct response to the CTB without a prime coat. Mean strength remained within 0.489–0.511 MPa, and the four-state effect was not significant ($p = 0.7872$; $\eta^2 = 0.070$). Its clean–dry no-prime value corresponded to approximately 97.4% of the independently prepared primed reference used in the qualitative matrix.

The slurry seal was the most sensitive to adverse base conditions in the no-prime configuration. Mean strength was approximately 0.386–0.392 MPa under the two clean states but decreased to 0.289 MPa under contaminated–dry conditions and to 0.214 MPa under contaminated–moist conditions ($p < 0.001$; $\eta^2 = 0.969$). The contaminated–moist value was 45.3% lower than the no-prime clean–dry value. The no-prime clean–dry value corresponded to approximately 85.4% of the independently prepared primed reference used in the qualitative matrix.

These results show that prime-coat omission should not be generalized across seal types. The hot asphalt chip system was comparatively insensitive to omission in the tested configuration, whereas the fine-chip and slurry systems showed lower clean–dry responses relative to their independently prepared primed references.

3.5. Effect of Pre-Placement Substrate Temperature on Bonding Performance

The temperature of the treated substrate immediately before AC-13 placement influences heat transfer and contact development during compaction. The temperature-dependent completed-system responses are plotted in Figure 8, and Table 10 reports the statistical comparisons.

The results presented in Figure 8 and Table 10 indicate that the non-tracking emulsified seal exhibited a significant dependence on the substrate temperature immediately before AC-13 placement. Its mean shear strength increased progressively from 0.417 MPa at -5°C to 0.538 MPa at 35°C ($p < 0.001$; $\eta^2 = 0.785$). Tukey HSD placed the 25 and 35°C groups in

the highest statistical category, while the -5 and 5 °C groups were located at the lower end and the 10 °C group showed an intermediate response.

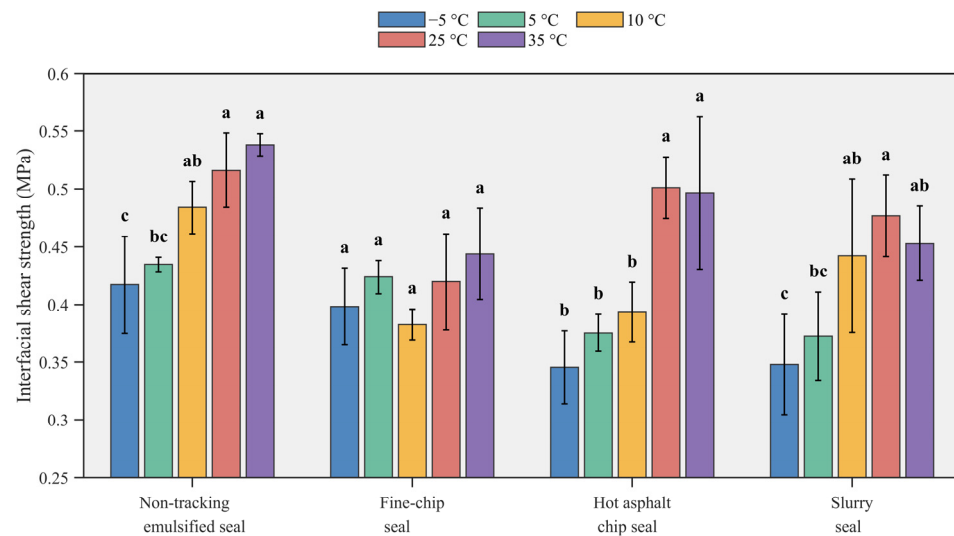


Figure 8. Effect of substrate temperature immediately before AC-13 placement on measured shear strength. Different lowercase letters above the bars indicate statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 10. Peak shear strength and statistical comparison at different substrate temperatures immediately before AC-13 placement.

Seal-Coat System	−5 °C (MPa)	5 °C (MPa)	10 °C (MPa)	25 °C (MPa)	35 °C (MPa)	ANOVA Result
Non-tracking emulsified seal	0.417 ± 0.042 c (n = 5)	0.435 ± 0.006 bc (n = 4)	0.484 ± 0.023 ab (n = 4)	0.516 ± 0.032 a (n = 5)	0.538 ± 0.009 a (n = 4)	$p < 0.001$; $\eta^2 = 0.785$
Fine-chip seal	0.398 ± 0.033 a (n = 5)	0.424 ± 0.014 a (n = 4)	0.383 ± 0.013 a (n = 4)	0.420 ± 0.042 a (n = 5)	0.444 ± 0.039 a (n = 4)	$p = 0.1019$; $\eta^2 = 0.350$
Hot asphalt chip seal	0.346 ± 0.032 b (n = 5)	0.375 ± 0.016 b (n = 5)	0.393 ± 0.026 b (n = 4)	0.501 ± 0.019 a (n = 5)	0.497 ± 0.066 a (n = 5)	$p < 0.001$; $\eta^2 = 0.789$
Slurry seal	0.348 ± 0.044 c (n = 5)	0.373 ± 0.038 bc (n = 4)	0.442 ± 0.066 ab (n = 5)	0.477 ± 0.035 a (n = 4)	0.453 ± 0.032 ab (n = 5)	$p = 0.0018$; $\eta^2 = 0.597$

Note: Values are mean $\pm$ SD; final n is shown in parentheses; different lowercase letters denote Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

The hot asphalt chip seal was strongly temperature-sensitive ($p < 0.001$; $\eta^2 = 0.789$). Mean strength remained in the lower Tukey category at -5 , 5 , and 10 °C (0.346 – 0.393 MPa) and increased to approximately 0.50 MPa at 25 and 35 °C. Thus, within the investigated range, the statistically resolved change occurred between 10 and 25 °C.

The slurry seal also showed a significant overall temperature effect ($p = 0.0018$; $\eta^2 = 0.597$). Its mean strength increased from 0.348 MPa at -5 °C to 0.477 MPa at 25 °C, followed by a slight decrease to 0.453 MPa at 35 °C. The 5 and 10 °C groups showed overlapping Tukey HSD groupings (bc and ab, respectively), suggesting a gradual transition in shear performance from cold toward moderate-to-warm substrate conditions.

The temperature response was material-specific. The fine-chip seal showed no statistically significant overall temperature effect from -5 to 35 °C ($p = 0.1019$). The non-tracking system improved progressively, the hot asphalt chip system reached the higher statistical category only at 25 – 35 °C, and the slurry system showed an intermediate response at 10 °C, with the highest mean at 25 °C. Construction temperature targets should be selected for the specific interlayer system and interpreted specifically as pre-placement substrate temperatures.

The temperature response also highlights the transitional function of the prime coat. In addition to acting as a bonding agent, the prime layer fills surface voids, stabilizes loose

base particles, and improves compatibility between the cementitious base and the asphaltic seal, thereby supporting contact development during asphalt-layer compaction.

3.6. Effect of Freeze–Thaw Cycling on Bonding Performance

Within the investigated 0–10-cycle short-term protocol, freeze–thaw conditioning produced smaller changes in mean shear strength than several adverse construction-state comparisons. Figure 9 shows the response, and Table 11 provides the one-way ANOVA results together with the final sample size in each group.

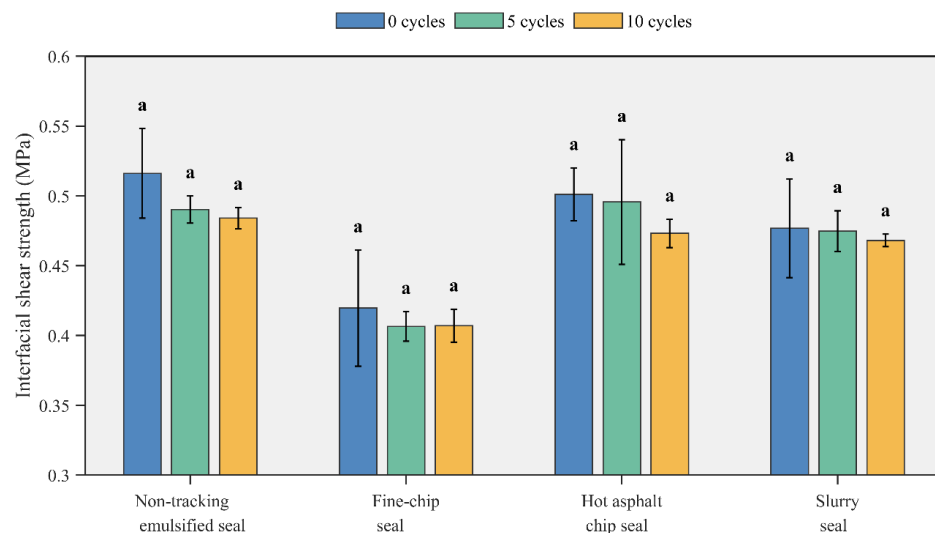


Figure 9. Effect of short-term freeze–thaw cycling on measured shear strength. Lowercase letter above the bars indicates statistically significant differences among treatment groups within the same seal-coat system according to Tukey’s HSD test at $\alpha = 0.05$.

Table 11. Peak shear strength and statistical comparison after 0, 5, and 10 short-term freeze–thaw cycles.

Seal-Coat System	0 Cycles (MPa)	5 Cycles (MPa)	10 Cycles (MPa)	ANOVA Result
Non-tracking emulsified seal	0.516 ± 0.032 a (n = 5)	0.490 ± 0.010 a (n = 2)	0.484 ± 0.008 a (n = 2)	$p = 0.3320$; $\eta^2 = 0.308$
Fine-chip seal	0.420 ± 0.042 a (n = 5)	0.406 ± 0.011 a (n = 3)	0.407 ± 0.012 a (n = 3)	$p = 0.7893$; $\eta^2 = 0.057$
Hot asphalt chip seal	0.501 ± 0.019 a (n = 5)	0.496 ± 0.045 a (n = 3)	0.473 ± 0.010 a (n = 3)	$p = 0.3812$; $\eta^2 = 0.214$
Slurry seal	0.477 ± 0.035 a (n = 4)	0.475 ± 0.015 a (n = 2)	0.468 ± 0.005 a (n = 2)	$p = 0.9393$; $\eta^2 = 0.025$

Note: Values are mean ± SD; final n is shown in parentheses; lowercase letter denotes Tukey HSD groups at $\alpha = 0.05$; η^2 is the one-way ANOVA effect size.

A comparison of Figure 9 and Table 11 shows that short-term freeze–thaw cycling caused relatively limited changes in the mean shear strength of the four interlayer systems within the investigated 0–10-cycle range. After 10 cycles, the strength-retention ratios were 93.8%, 97.0%, 94.4%, and 98.2% for the non-tracking emulsified, fine-chip, hot asphalt chip, and slurry seals, respectively, and no statistically significant differences were detected within any of the four datasets. Nevertheless, the small final sample sizes in several cycled groups, particularly those with $n = 2$, substantially limit the statistical power of these comparisons.

Accordingly, the freeze–thaw results should be interpreted as short-term descriptive evidence rather than definitive proof of freeze–thaw resistance. The absence of a statistically significant difference in these small-sample datasets does not demonstrate long-term freeze–

thaw resistance; field performance may be influenced by repeated annual cycling, water accumulation, aging, microcracking, and traffic loading.

3.7. Integrated Environmental-Susceptibility Assessment of Base–Prime–Seal–Surface Interlayers

The results in Sections 3.1–3.6 show that the measured response depends on the seal type, the construction contact at which an adverse state was introduced, prime-coat presence, pre-placement substrate temperature, and short-term freeze–thaw conditioning. Figure 10 and Table 12 present the normalized matrix only as a qualitative visual summary. Interface-condition values use the lowest adverse-state mean relative to the clean–dry mean within the same block; the seal–surface column uses the diesel-contaminated mean. The low-temperature and freeze–thaw columns use $-5\text{ }^{\circ}\text{C}/25\text{ }^{\circ}\text{C}$ and 10-cycle/0-cycle ratios, respectively. The prime-omission column compares the no-prime clean–dry mean with the independently prepared primed clean–dry reference.

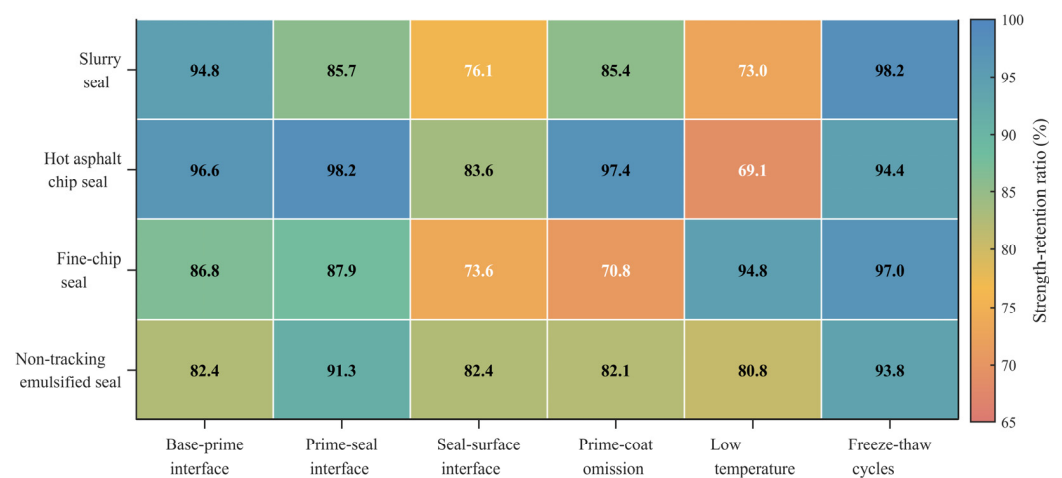


Figure 10. Integrated environmental-susceptibility matrix for the investigated interlayer systems.

Table 12. Within-block normalized strength-retention ratios used only as a qualitative susceptibility summary.

Seal-Coat System	Base–Prime Interface (%)	Prime–Seal Interface (%)	Seal–Surface Interface (%)	Prime–Coat Omission (%)	Low–Temperature Effect (%)	Freeze–Thaw Effect (%)
Non-tracking emulsified seal	82.4	91.3	82.4	82.1	80.8	93.8
Fine-chip seal	86.8	87.9	73.6	70.8	94.8	97.0
Hot asphalt chip seal	96.6	98.2	83.6	97.4	69.1	94.4
Slurry seal	94.8	85.7	76.1	85.4	73.0	98.2

Note: Ratios are descriptive normalizations from separate experimental blocks. The adverse exposures are not commensurate. The prime-omission ratio compares independently prepared primed and unprimed blocks. Small differences among ratios are not used for formal ranking.

As illustrated by Figure 10 and summarized in Table 12, the four seal systems exhibited distinctly different environmental-susceptibility patterns. The non-tracking emulsified seal showed moderate sensitivity to several construction-related factors rather than one dominant adverse condition; the fine-chip seal exhibited pronounced losses under diesel contamination and prime-coat omission; the hot asphalt chip seal was comparatively tolerant of contact-condition variations and prime omission but was strongly affected by low pre-placement substrate temperature; and the slurry seal maintained relatively high strength after short-term freeze–thaw conditioning but showed marked reductions under diesel contamination, low temperature, and contaminated base conditions in the no-prime configuration. Because only the slurry-seal specimens included an additional 0.45 kg/m^2 tack coat directly beneath AC-13, absolute cross-system comparisons involving slurry

should be interpreted as combined system effects rather than differences attributable solely to the seal material.

Across the four seal systems, the seal–surface conditioning block generally produced substantial losses when diesel contamination was introduced, emphasizing the need to prevent fuel or oil contamination immediately before asphalt placement. Because failure planes were not classified, this observation refers to the response of the complete interlayer system after seal–surface contamination, not to an intrinsic strength assigned uniquely to that plane.

The normalized matrix should therefore be used to identify broad construction sensitivities within each seal system, not to rank unlike exposures on a common severity scale. Field quality control should prioritize cleanliness, correct prime/seal construction, and material-appropriate temperature conditions, while recognizing that the relative importance of each item depends on the selected system.

From an engineering perspective, construction control should be material-specific. Cleanliness is particularly important immediately before AC-13 placement, prime-coat omission should not be generalized across seal types, and temperature limits should reflect the distinct responses in Section 3.5 rather than a single minimum value. The measured strengths in this study (approximately 0.21–0.54 MPa) fall within the broad range encountered in published direct-shear interlayer studies [6,14,19], but absolute values are strongly dependent on fixture geometry, normal confinement, loading rate, and specimen preparation. EN 12697-48 standardizes several interlayer-bond test methods [7] but does not provide a universal acceptance threshold for the specific CTB–prime–seal–AC-13 transition tested with the present in-house fixture. Consequently, terms such as comparatively high, low, or stable refer only to comparisons within this experimental program and are not formal field-acceptance judgments.

The limited freeze–thaw effect observed here should be regarded only as short-term laboratory evidence. In service, interface-related deterioration can interact with drainage deficiency, aging, repeated loading, and microcracking. Interface-related deterioration should also be distinguished from reflective cracking caused by drying and thermal shrinkage of the cement-stabilized base, which is a major distress mechanism in semi-rigid pavements but was not evaluated in the present monotonic shear program.

Several limitations should be considered when applying the results. Gyratory compaction over a rigid field core does not reproduce field roller compaction exactly and may alter near-interface heat loss and confinement. Only peak-load data were retained by the test system, so displacement at peak, shear stiffness, post-peak response, fracture energy, repeated traffic loading, and fatigue could not be evaluated. The 10 mm gap encompasses a multilayer transition region, and post-test fracture surfaces were not systematically photographed or classified; therefore, the conditioned construction contact cannot be assumed to be the actual failure plane. CTB macrotexture was not quantified. In addition, the clean–dry seal–surface dataset was reused as the 25 °C and 0-cycle reference, so those three analyses share a control and are not statistically independent. The earlier base–prime series was an independently prepared preliminary series. The constructed seal-layer thicknesses were not independently measured during the original experimental campaign; cross-system interpretation therefore relies on the prescribed material application rates and construction procedures rather than directly measured final seal thicknesses. Finally, hydraulic-pressure-related invalid tests reduced the number of technically valid measurements in several freeze–thaw groups, with final sample sizes as small as $n = 2$; these results are therefore used primarily as short-term descriptive evidence and have limited inferential power.

4. Conclusions

This study evaluated how adverse conditions introduced at selected construction contacts, prime-coat omission, pre-placement substrate temperature, and short-term freeze–thaw cycling affected the peak shear strength of complete CTB-prime-seal-AC-13 interlayer systems. Because the actual fracture plane was not systematically classified, the conclusions refer to the completed-system response after conditioning a selected contact region rather than to the intrinsic strength of that nominal contact plane.

(1) Adverse contact conditioning produced material-dependent changes in the completed-system response. Diesel contamination introduced at the seal–surface construction stage produced one of the most consistent losses, with seal–surface strength retention of 73.6–83.6% across the four systems. Preventing fuel/oil contamination during surface-course construction is therefore a high-priority quality-control measure.

(2) Prime-coat omission was material-dependent. Relative to independently prepared primed clean–dry references, the no-prime clean–dry retention ratios were approximately 70.8% for the fine-chip seal, 85.4% for the slurry seal, and 97.4% for the hot asphalt chip seal. Because these ratios compare separate experimental blocks, they are descriptive rather than paired inferential estimates; nevertheless, they show that prime omission should not be generalized across seal systems.

(3) Pre-placement substrate-temperature sensitivity was also material-specific. The fine-chip seal showed no significant overall temperature effect from -5 to 35 °C. The non-tracking and slurry systems performed less favorably at the cold end of the range, while the hot asphalt chip seal reached the higher statistical category only at 25 – 35 °C. The data therefore do not support a universal 10 °C minimum; construction targets should be system-specific.

(4) After 10 short-term freeze–thaw cycles, mean strength retention was 93.8–98.2%, and no statistically significant difference was detected within the analyzed datasets. However, several cycled groups had a final sample size of only $n = 2$ because hydraulic-pressure-related abnormal loading records were excluded during technical-validity screening. The freeze–thaw results should therefore be interpreted cautiously as short-term descriptive evidence and should not be extrapolated to long-term field durability or repeated traffic loading.

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