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Evaluation of Nanoclay Additives for Improving Resistance to Moisture Damage in Hot Mix Asphalt (HMA)

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MTI MINETA TRANSPORTATION INSTITUTE

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CSUTC California State University Transportation Consortium

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16. Abstract

Transportation has an enormous impact on the U.S. economy and on the lives of all Americans. Many modes of transportation rely on pavement, but pavement conditions deteriorate over time because of the combined effects of traffic and climate. Exposure to moisture often causes premature failure of asphalt pavements as it reduces the stiffness of the asphalt and enables stripping of the asphalt from the aggregate. This research evaluates the effectiveness of clay nanomaterials (i.e., nanoclays) in improving the resistance of hot mix asphalt (HMA) to moisture damage and compares the enhancement results to anti-stripping additives commonly used in pavement construction. Two types of surface-modified nanoclay, lime-treated aggregate, and two amine-based liquid antistripping agents (HP Plus and LOF 6500) were evaluated for improving HMA's moisture resistance. All additives tested for reducing moisture damage resulted in dry and wet tensile strength of the modified mixes higher than the minimum specified by Caltrans 2018 Standard Specifications (100 psi for dry tensile strength and 70 psi for wet tensile strength). The Tensile Strength Ratio (TSR) of all HMA modified mixes was higher than 0.80, which is the minimum specified by the Superpave mix design method (Asphalt Mix Design Methods MS-2, Asphalt Institute) and exceeded the TSR of the control mix. The TSR for HMA mixes modified using nanoclays were comparable to those for HMA mixes modified using liquid antistripping and lime slurry treated aggregate. Liquid antistripping agents tested herein were the least costly additive at an approximately $2.0/ton added cost. This research can be used to better understand pavement deterioration to enable the most efficient and cost-effective construction and preservation of our nation's critical transportation infrastructure.

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Executive Summary

Departments of Transportation spend substantial financial resources on various maintenance treatments to minimize pavement distresses and improve pavement life. Moisture-induced damage in hot mix asphalt (HMA) pavements is one of the most common problems encountered by departments of transportation. The goal of this project was to evaluate the use of surface-modified nanoclay as an alternative additive for enhancing HMA's moisture resistance. The specific objectives of the research were to: (a) evaluate the performance of innovative types of surface-modified nanoclays as modifiers for reducing the moisture sensitivity of hot mix asphalt; (b) compare the performance of the nanoclays adopted in this research to hydrated lime and liquid anti-stripping agents, which are the standard modifiers used by Caltrans for reducing moisture sensitivity of hot mix asphalt; and (c) conduct a multi-criteria decision analysis to evaluate the feasibility of using nanoclays in large-scale applications for reducing moisture sensitivity of hot mix asphalt.

The crushed stone aggregate and asphalt binder used for laboratory testing were obtained locally from CalPortland's Santa Maria asphalt plant. The 64-10 performance grade (PG) asphalt and the aggregate used herein produce Hot Mix Asphalt (HMA) commonly used on the central coast of California. Fresh batches of asphalt were heated and separated into small containers on a weekly basis to allow for quicker heating during asphalt mixing. The additives tested for enhancing moisture resistance were: (a) surface-modified nanoclays (nanoclay01: surface modified with trimethyl stearyl ammonium and nanoclay02: surface modified with octadecylamine and aminopropyltriethoxysilane), (b) lime-treated aggregate, and (c) amine-based liquid anti-stripping agent chemicals, namely HP Plus and LOF 6500. The surface-modified nanoclays were obtained from Sigma-Aldrich, the aggregate treated with lime slurry was supplied by CalPortland ready for testing, and the amine-based chemicals, HP Plus and LOF 6500, were obtained from ArrMaz Custom Chemicals in Florida.

Important properties and performance tests were conducted on the aggregate used in the asphalt mix design. The tests performed included bulk and apparent specific gravities as well as performance tests for durability, angularity, and clay content. The modified and unmodified binder was tested in its virgin and aged states using the dynamic shear rheometer (DSR) test.

Aggregate gradation curves were established for the mix design following Caltrans standards, and an optimum binder content was determined to be 5.75% using the Superpave mix design procedure Asphalt Mix Design Methods MS-2, Asphalt Institute, hereinafter referred to as "Superpave mix design." Using this mix design, varying amounts of each additive (i.e., nanoclays, lime-treated aggregate, HP Plus, and LOF 6500) were introduced to specimens following two different application methods. Specimens were prepared and tested for indirect tensile strength before and after being conditioned.

It was observed that the nanoclays have a stiffening effect on the asphalt binder, according to DSR test results. The two types of nanoclays tested, nanoclay01 and nanoclay02, exhibited the same effect on binder stiffness. On the other hand, liquid anti-stripping additives had a softening effect on the binder. All additives tested in this study (except HP Plus) resulted in dry tensile strengths that were higher than that for the control mix. The wet tensile strength for all mixes modified with the additives (including HP Plus) was higher than the control mix. All mixes tested resulted in dry and wet tensile strengths that were higher than the minimum specified by Caltrans 2018 Standard Specifications (100 psi for dry tensile strength and 70 psi for wet tensile strength). Except for the 6% nanoclay02 mix, all HMA modified mixes exhibited a Tensile Strength Ratio (TSR) higher than 0.80 (the minimum specified by Superpave mix design). Furthermore, all HMA-modified mixes resulted in TSRs that were higher than the control mix. TSR for HMA mixes modified using nanoclays was comparable to that for HMA mixes modified using liquid antistripping and lime slurry treated aggregate. Overall, the liquid antistripping agents tested were the least costly additive.

In addition to the experimental testing conducted in this study, a systematic multi-criteria decision analysis (MCDA) was performed to rank alternatives additives (including nanoclays) studied in the literature for enhancing HMA's moisture resistance. The ranking was based on performance for enhancing the moisture resistance, cost, and methods of addition to HMA. The literature review analysis and MCDA results indicated that nanoclay outperforms other antistripping agents, but it had the lowest ranking because of materials cost and the cost of mixing the nanomaterials with HMA to achieve a homogenous mixture.

1. Introduction

Moisture damage in asphalt pavements, also known as stripping or moisture susceptibility, can be defined as the breaking of the aggregate-binder bond by the intrusion of water (Behbahani et al., 2020a). The water seeps through tiny cracks in the asphalt surface. According to Kringos and Scarpas (2008), asphalt pavements that are exposed to water infiltration often begin losing aggregates. Due to the chemical attractiveness that aggregates have towards water, the bond between the asphalt binder and aggregates weakens, washing away the binder. With the continued action of moisture-induced weakening and cyclic traffic loading, progressive dislodgement of aggregates becomes the dominant mode of failure in asphalt pavements. Esarwi et al. (2008) state that this failure can appear in the form of distresses such as rutting, shoving, raveling, or cracking.

A 1991 National Cooperative Highway Research Project (NCHRP) concluded that 70% of state and provincial Departments of Transportation in North America that responded to the survey experienced moisture damage-related problems in their pavements (Hicks, 1991). Moisture damage-related premature distresses reported in the NCHRP study included rutting in the wheel paths, bleeding, and alligator cracking.

Adhesion is the attraction force that occurs between the interface of the bituminous film and aggregate surface. Loss of adhesion is the primary mechanism of moisture damage (Terrel and Al-Swailmi, 1994, Behbahani et al., 2020a). Other mechanisms of moisture damage include loss of cohesion, when water weakens the intermolecular attraction between molecules; hydraulic scouring, when water rubs against pavement through cyclic pressure; and rupture of the bituminous film surrounding the aggregates, when pore water pressure increases internal stresses; failure of the bond between the aggregate and the binder; and degradation of individual aggregate particles (Terrel and Al-Swailmi, Chakravarty et al., 2020a). For aggregates that have affinity for water absorption (hydrophilic aggregate), the binder is stripped off the aggregate surface. This eventually leads to potholes and a failure of the under-layers (Terrel and Al-Swailmi, 1994).

Santucci (2010) discussed the importance of asphalt surface chemistry, describing aggregates ranging from basic (limestone) to acidic (quartzite) in pH and describing asphalt binder as having neutral to acidic tendencies. As a result, the binder would most likely form a stronger bond with limestone. Also, clay present on the surface of aggregates can expand in the presence of water and form a barrier to adhesion, thus weakening the mix.

The result of pavement exposure to moisture is premature failure through stripping of the pavement. Stripping typically begins at the bottom layer of the HMA and progresses upward over time, though it can be difficult to detect since stripping can also cause cracking, rutting, and corrugations. Stripping that begins at the surface and progresses downward over time is known as raveling (Kennedy et al. 1983, Roberts et al., 1996, Chakravarty and Sinha, 2020a).

Moisture-related damage normally leads to a significant reduction in asphalt pavement performance and an increase in maintenance costs. One of the main causes of moisture damage is poor drainage that allows water infiltration. While bearing in mind the need for subgrade drainage, the typical repair method is to remove and replace the pavement (Chakravarty et al., 2020a). However, such repairs and maintenance can be costly, which is why researchers have sought adding materials to improve pavement resistance to moisture damage and prevent premature failure.

Various liquid antistripping and solid additives have been historically used to improve adhesion between the binder and aggregate. These chemicals are added directly to the binder either at the refinery or binder terminal, or at the contractor's facility during production of the mix (Tunnicliff and Root, 1984). Anerson and Dukatz (1982) reviewed experimental studies on the effects of commercially available anti-stripping additives on the binder's physical properties. Anti-stripping additives have been reported to tend to soften the binder, enhance resistance to temperature susceptibility, and improve the aging characteristics of binder (Anerson and Dukatz, 1982). Liquid antistripping agents enhance HMA's moisture resistance by reducing the surface tension between the aggregate surface and the asphalt binder, therefore enhancing the binder's adhesion to the aggregate surface.

Other solid additives, including hydrated lime, Portland cement, fly ash, flue dust, and polymers have been used to provide resistance to moisture in hot-mix asphalt mixtures. These additives are typically added to the aggregate before mixing with the binder in the HMA production process. However, hydrated lime or Portland cement has been added in the drum mixing operation at the point of entry of the binder to the heated aggregate (Epps et al., 2003). Hydrated lime neutralizes the acidity in the asphalt binder and improves the bond between the binder and the aggregate. By treating aggregate using hydrated lime, both anionic and cationic surfactants naturally present in the bitumen strongly bond with calcium ions.

A research study in which 1.0% concentration of class F fly ash was added to the asphalt mix showed that a resilient modulus similar to that for the control mixture was obtained, but slightly lower than that for HMA treated with hydrated lime. TSR tests showed a 15% higher ratio in tensile strength over the control mixture, although hydrated lime increased the TSR by 25% over that for the control mix (Huang et al., 2010).

The asphalt binder requirements can be significantly reduced by mixing CKD with asphalt binder before it is introduced to the aggregate. It also has the potential to replace hydrated lime and reduce moisture damage in pavements due to its high lime content (Siddique, 2007). Huang et al. (2010) verified this behavior in their study testing various mineral fillers. Adding 1.0% CKD to the asphalt mix produced a TSR within a few percent of the hydrated lime variations and nearly 25% higher than the untreated control mixture.

1.1 Additives for Enhancing HMA Resistance to Moisture Damage

The California Department of Transportation (Caltrans) has been using hydrated lime and anti-stripping liquids to mitigate stripping in HMA (TRB, 2003). However, other additives, including nanomaterials, are being investigated in the literature to provide more improvements in moisture resistance than the commonly used ones. Research investigations showed that modification of asphalt binders with nanoclays improved the performance of the mix by, e.g., increasing the dynamic shear complex modulus, reducing the strain failure rate, improving rutting resistance, reducing the penetration value, increasing the softening point temperature and viscosity, and improving the fatigue life of the asphalt mix (Ezzat et al., 2016, Mansourian et al., 2019, You et al., 2011). Nanoclays have been reported to increase cohesion of the asphalt binder, which can increase the healing potential of micro-cracks (Hossain et al., 2015). In addition, amine-modified nanoclays contain alkyl amines, which are among the most commonly used chemicals in antistripping liquids for reducing HMA's moisture sensitivity. Table 1 outlines some of the studies on using nanoclay for HMA's moisture resistance. The table includes nanoclay types used, dosage, test methods, and results on stripping resistance and moisture susceptibility of the asphalt mixtures modified with nanoclays.

Analysis of Table 1 shows that nanoclays, in general, showed improvement in moisture susceptibility compared to non-modified asphalt binders. However, no evaluation exists comparing the improvements to standard stripping resistance additives used in California (e.g., hydrated lime and liquid antistripping) and no analysis has been conducted on the economic and practical feasibility of using nanoclays as asphalt binder modifier. Therefore, a need exists for a systematic investigation into the practicality and feasibility of using nanoclays as asphalt binder modifiers to resist moisture-related damages in the pavement. Furthermore, other types of surface-modified nanoclays could show better performance than those studied in the literature. Specifically, this research proposal investigated amine-modified nanoclay because alkyl amines are among the most commonly used chemicals additives for enhancing moisture resistance of asphalt binders.

Table 1. Literature Examples on Using Nanoclays for Reducing Moisture Susceptibility of Hot Mix Asphalt

Nanoclay Type and Dose	Nanoclay Organic Modifier	Moisture Sensitivity Test Method	Moisture Sensitivity Results	Compared to California Standard*	Ref.
Type montmorillonite nanoclay, Cloisite 15A and Cloisite 30B *Dose* 2–6% by weight of bitumen	2M2HT MT2EtOH	Tensile strength ratio (TSR) was used as indicator for moisture susceptibility	- both nanoclays improved resistance to moisture damage - TSR for the modified samples was consistently above the control mixture which had TSR = 80%. - 6% Cloisite 30B showed the best results (TSC >95%)	No	Ameri et al. (2016)
Type montmorillonite nanoclay *Dose* 1.5–2% by weight of bitumen	Polysiloxane	Tensile strength ratio (TSR) was used as indicator for moisture susceptibility	- the modified samples exhibited TSR values ≥ the unmodified control mixture - more than half of the nanoclay modified samples exhibited TSR values >1	No	Goh et al. (2011)
Type montmorillonite nanoclay *Dose* 0.5–1.8% by weight of bitumen	Polysiloxane	Modified boiling water test based on ASTM standard method D3625-96	nanoclay increased stripping resistance for the mix exposed to deicer solutions at different concentration levels regardless of the type of deicer solution	No	Yang et al. (2018)

1.2 Study Objectives

The goal of this project was to evaluate the use of surface-modified nanoclay additives for enhancing the resistance of HMA to moisture-related damage, which is considered one of the most common problems experienced by transportation agencies. The specific objectives of the proposed research were to: (a) evaluate the performance of innovative types of surface-modified nanoclays as modifiers for reducing moisture sensitivity of hot mix asphalt; (b) compare the performance of the nanoclays developed in this research to the standard modifiers used by Caltrans for reducing moisture sensitivity of hot mix asphalt; and (c) conduct a multi-criteria decision analysis to evaluate the feasibility of using nanoclays in large-scale applications for reducing moisture sensitivity of hot mix asphalt. Aggregates and asphalt binder commonly used in California's Central Coast were used herein to design the HMA in accordance with the Superpave mix design procedure. Both aggregate and binder tests required by Superpave mix design were conducted as well.

2. Impact of Nanoclay on Moisture Resistance of HMA

The moisture sensitivity was evaluated according to the modified Lottman indirect tensile test (AASHTO T 283). In addition, other performance tests were conducted on the aggregate, asphalt binder, and uncompacted specimens. All tests on aggregate, asphalt binder, loose mixtures, and compacted specimens were conducted according to respective AASHTO and ASTM testing standards.

2.1 Material Selection

Several materials were required to produce asphalt specimens. In addition to aggregate and asphalt binder, several additives were tested including nanoclay, aggregate treated with lime slurry, and two amine-based chemicals—HP Plus and LOF 6500.

The crushed stone aggregate and asphalt binder used for laboratory testing were obtained locally from CalPortland Construction's Santa Maria asphalt plant. This mixing plant produces the HMA used on the central coast of California. Over 250 kg (500 lb) of aggregate was required to produce the HMA specimens tested in this study. Aggregate was delivered in pre-sieved sacks, which helped significantly with the sieving process, even though all aggregate had to be sieved to meet gradations used in the lab and for quality control. Aggregate sizes passing ¾", ½", 3/8" and dust passing the #200 sieve were supplied. These aggregate gradations were used to develop the gradation curve presented in Section 2.2.7.

Approximately 30 liters (8 gallons) of PG 64-10 binder was required to produce the specimens. The 64-10 performance grade is a common type of asphalt used locally on the central coast of California. The asphalt was then heated and separated into small containers on a weekly basis to allow for quicker heating during asphalt mixing.

The additives tested for enhancing moisture resistance were surface-modified nanoclay, lime-treated aggregate, and two amine-based liquid anti-stripping agent chemicals. The surface-modified nanoclays were obtained from Sigma-Aldrich (Table 2), the aggregate treated with lime slurry was supplied by CalPortland ready for testing, and the amine-based chemicals (HP Plus and LOF 6500) were obtained from ArrMaz Custom Chemicals in Florida.

Table 2. Types and Properties of Nanoclays Used in the Study

Nanoclay	Properties
1. **Nanclay01:** Nanoclay, surface modified with trimethyl stearyl ammonium	• Montmorillonite clay • Contains 25–30% by wt. trimethyl stearyl ammonium
2. **Nanoclay02:** Nanoclay, surface modified with octadecylamine and aminopropyltriethoxysilane	• Montmorillonite clay • Contains 13–35% by wt. octadecylamine and 0.5 5% by wt. aminopropyltriethoxysilane

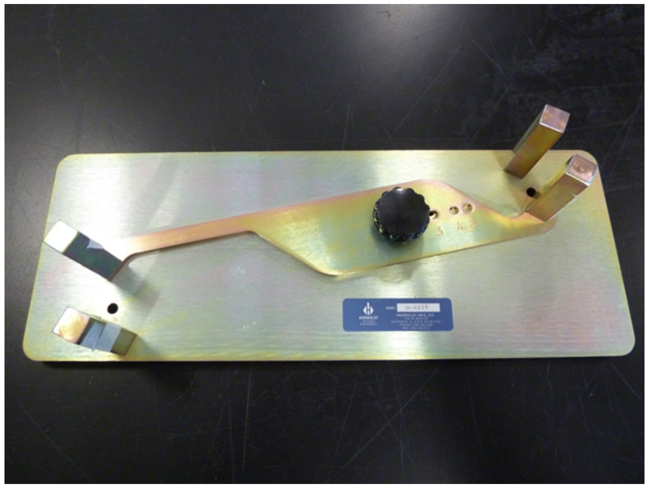
2.2 Aggregate Tests and Preparation

Important properties and performance tests were conducted for selecting the aggregate used in the asphalt mix design. The tests performed include bulk and apparent specific gravities as well as performance tests for durability, angularity, and clay content.

2.2.1 Flat and Elongated Particles in Coarse Aggregate (ASTM D 4791)

The flat, elongated, or flat and elongated particles tests were used to determine the percentage of flat and elongated particles in the coarse aggregate. This is a critical test since flat and elongated particles in HMA mixes have difficulty reorienting during compaction and thus, have a tendency to break along their thin, weak axis. This can cause issues achieving the correct air to void ratio in a pavement and lead to degradation. To conduct this test, a proportional caliper apparatus, shown in Figure 1, was used. This device has several pivot points, which may be adjusted to different ratios. The Superpave mix design specified a coarse aggregate testing ratio of 5:1 for both flatness (width to thickness) and elongation (length to width). None of the particles tested in the batch had a ratio this large, thus easily meeting the maximum batch limitation of 10%.

Figure 1. Flat and Elongated Particle Apparatus



2.2.2 Specific Gravity and Absorption of Fine Aggregate (AASHTO T 84)

This test was conducted to determine the bulk and apparent specific gravity, as well as the absorption of the fine aggregate (aggregate passing #4 sieve). In this test, one kg (2.2 lb) of dry fine aggregate was submerged into water, as shown in Figure 2, for a period of 15–19 hours. Then, excess water was removed, and the specimen was dried to a surface dry condition. A cone tamping test was used to ensure the correct moisture content. Then, half of the specimen was placed into a pycnometer partially filled with water and agitated to remove air bubbles. The total mass was then recorded and used for bulk specific gravity calculations as follows:

$$\text{Bulk Specific Gravity} = A/(B + S - C)$$

Where:

A = mass of oven-dry specimen in air (g);

B = mass of pycnometer filled with water (g);

C = mass of pycnometer with specimen and water (g); and

S = mass of saturated-surface-dry specimen (g).

The percentage of water absorbed into the aggregate's pores was computed using the following equation, and the specific gravity and water absorption results are presented in Table 3.

$$\text{Absorption (\%)} = [(S - A) / A] \times 100$$

Figure 2. Submerged Coarse and Fine Aggregate for Bulk Specific Gravity Test

Table 3. Specific Gravity and Absorption Test Results for Fine Aggregate

Bulk SG, gm/cm^3 (pcf)	Bulk SG_{SSD}, gm/cm^3 (pcf)	SG_{App}, gm/cm^3 (pcf)	Water Absorption, %
2.40 (149.83)	2.54 (158.57)	2.79 (174.18)	5.0

2.2.3 Specific Gravity and Absorption of Coarse Aggregate (AASHTO T 84)

The specific gravity and absorption of coarse aggregate (retained on the #4 sieve) was determined following a similar procedure to that of the AASHTO T 84. Two kg (4.4 lb) of coarse aggregate was sampled and immersed in water for 15–19 hours. Then the aggregate was removed from the water and placed on an absorbent cloth where it was dried to a saturated-surface-dry state and weighed. The specimen was placed in a basket and submerged in a water tank to acquire the saturated mass. The bulk specific gravity of the aggregate was calculated using the equation below:

$$\text{Bulk Specific Gravity} = A / (B - C)$$

Where:

A = mass of oven-dry specimen (g);

B = mass of saturated-surface-dry specimen (g); and

C = mass of saturated specimen (g).

The %absorption was also determined using the following equation and the results are presented in Table 4.

$$\text{Absorption (\%)} = [(B - A) / A] \times 100$$

Table 4. Specific Gravity and Absorption Test Results for Fine Aggregate

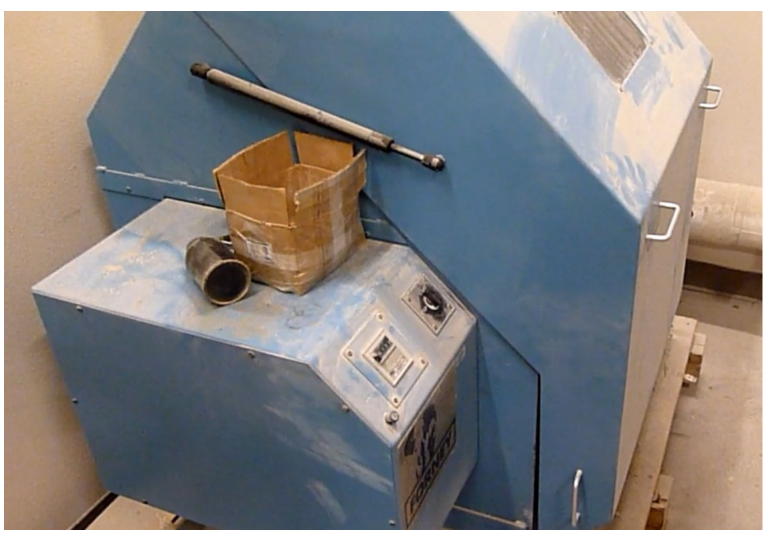
Bulk SG, gm/cm^3 (pcf)	Bulk SG_{SSD}, gm/cm^3 (pcf)	SG_{App}, gm/cm^3 (pcf)	Water Absorption, %
2.58 (161.10)	2.63 (141.20)	2.71 (169.20)	1.8

2.2.4 Los Angeles Abrasion Test (AASHTO T 96)

The Los Angeles abrasion test was conducted to evaluate the resistance of small-size coarse aggregates to degradation. This test involved placing the coarse aggregate in a mechanical rotating drum, as shown in Figure 3, along with steel spheres, which impacted and pulverized the aggregate. Approximately 5 kg (11 lb) of aggregate was needed for this test. For a ½" nominal size, grading B was used, which consisted of 2.5 kg (5.5 lb) of aggregate retained on a ½" sieve and 2.5 kg (5.5 lb) of aggregate retained on a 3/8" sieve. Also, for grading B, 11 spheres, 46.8 mm (1.84 in) in diameter, were required for the impact charge. Both the spheres and aggregate were placed in a standardized rotating drum for 500 revolutions at a rate of 30 revolutions per minute.

After completing the test, all material was removed from the drum and aggregate was sieved through a #12 sieve. The remaining coarse material was washed, oven dried at 110°C, and weighed. The percentage of aggregate lost was calculated by subtracting the difference between the tested specimen's original and final mass and dividing by the original mass. For the aggregate tested, this value was 24.0%, which was under the 40% maximum acceptable loss specified in Caltrans' Standard Specifications for HMA Type A (Caltrans 2018 Standard Specification).

Figure 3. Los Angeles Abrasion Machine



2.2.5 Uncompacted Void Content of Fine Aggregate (AASHTO T 304)

Determining the uncompacted void content of fine aggregate was essential to determine the aggregate's angularity and surface texture in comparison to other aggregates of the same gradation, as well as workability in a mix. With this test, there were three gradation options for fine aggregates to choose from. Method A (standard grading) was selected. A 190 g (0.42 lb.) specimen of aggregate passing the #8 sieve was tested. The aggregate was poured into a plugged funnel. Once the funnel was full and leveled on the top, the bottom hole was opened, and the aggregate was allowed to pour into the measuring cylinder (Figure 4). The mass of the cylinder was measured, and the uncompacted voids were determined using the following equation:

$$U = [V - (F / G)] / V \times 100$$

Where:

V = volume of cylindrical measure (mL);

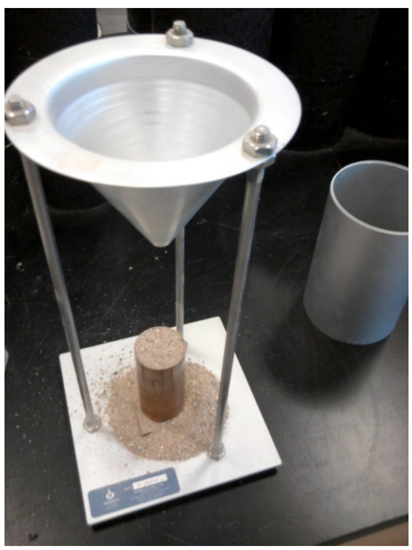
F = net mass of fine aggregate in measure (g);

G = bulk dry specific gravity of fine aggregate (g/cm3); and

U = uncompacted voids (%).

The fine aggregate's uncompacted void content was calculated to be 44%, which was close to the recommended value of 45%.

Figure 4. Uncompacted Void Apparatus



2.2.6 Sand Equivalency Test (AASHTO T 176)

The sand equivalency test was conducted to determine the amount of dust or clay-like particles in the fine aggregate gradation. To conduct this test, approximately one kg of aggregate passing the #4 sieve was obtained and moistened until it could hold its shape in a cast. The aggregate was then thoroughly mixed and compacted in a three-ounce moisture tin. A graduated cylinder was filled to the 102 mm (4 in) mark with a calcium chloride solution, and the aggregate was poured in using a funnel. After 10 minutes of standing, the cylinder was agitated to remove air bubbles, and the sides of the cylinder were washed down with solution. A calcium chloride solution was added until it reached the 381 mm (15 in) mark. After 20 minutes of settling, the clay reading was taken, followed by the sand reading. Dividing the sand reading by the clay reading resulted in a sand equivalent of 85%, which surpasses the Superpave mix design minimum requirement of 47%.

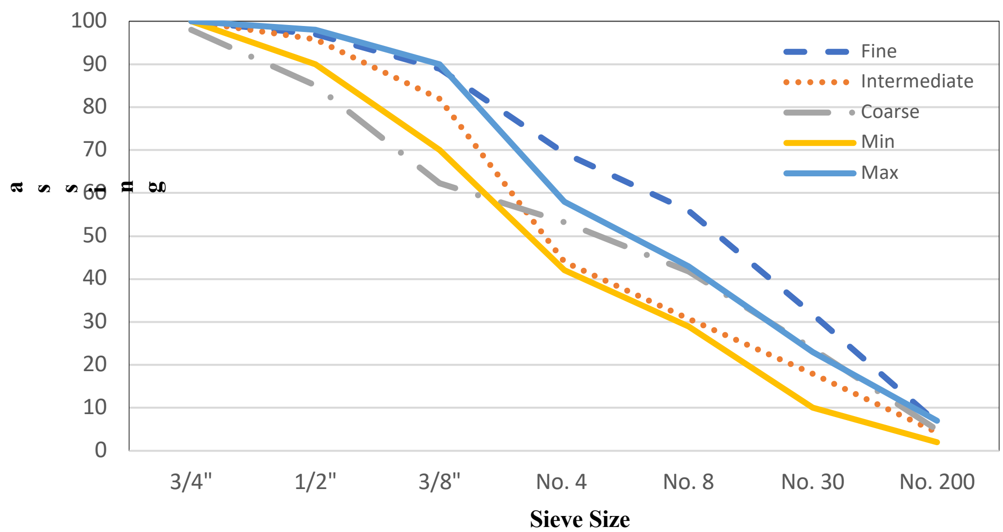
2.2.7 Gradation

After determining the acceptable quality of the aggregates, gradation curves were developed to meet the Caltrans standard specifications shown in Table 5 (Caltrans 2018 Standard Specifications), which dictated different sieve ranges for different nominal size mixes. Within the ½” nominal range, three mix blends were developed—coarse, intermediate, and fine—as shown in Figure 5. Properties such as specific gravity and air voids of these blends were determined as well.

Table 5. Caltrans Grading Requirements for ½ inch Aggregate Mixes (Caltrans 2018 Standard Specifications)

Sieve Size	Target Value (TV) Limit	Allowable Tolerance
¾”	100	----
½”	90-98	TV ± 5
3/8”	70-90	TV ± 5
No. 4	42-58	TV ± 5
No. 8	29-43	TV ± 5
No. 30	10-23	TV ± 4
No.200	2-7	TV ± 2

Figure 5. Aggregate Gradation Curves



2.3 Asphalt Binder Tests and Results

The PG 64-10 asphalt binder that is commonly used on the central coast of California and supplied by CalPortland was used herein for the mix design and in HMA-specimen preparation. The binder was tested in its virgin and aged states using the dynamic shear rheometer (DSR) test. The test results are presented in the following sections.

2.3.1 Dynamic Shear Rheometer (DSR) Test (AASHTO T 315)

The Dynamic Shear Rheometer (DSR) test, shown in Figure 6, was used for testing the properties of the asphalt binder, particularly the binder's dynamic shear modulus and phase angle. Asphalt binder is considered a viscoelastic material, which means it exhibits characteristics of both properties; it behaves like an elastic solid, rebounding after loading, and like a viscous liquid. The complex modulus represents the vector component of both the elastic and viscous portions, while the phase angle represents how viscous or elastic the asphalt binder is. To measure these properties, the asphalt binder was compressed between two parallel plates while the upper plate oscillates, exerting a shear force on the binder. Then, sensitive sensors in the DSR recorded the properties.

Figure 6. Dynamic Shear Rheometer

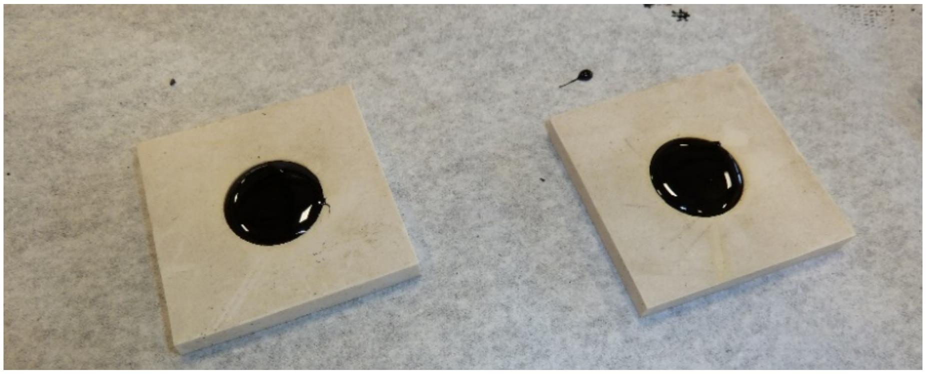
Since the nanoclay and the liquid anti-stripping agent were added to the asphalt binder directly as a percentage of the binder, the DSR test examined the effect of adding these to the PG 64-10 binder. At least two specimens with various additive concentrations were tested (Table 6). The binder was heated, and additives were thoroughly mixed into the asphalt binder manually before being poured into silicone specimen molds, as depicted in Figure 7, and tested at 64°C.

Table 6. Additive Concentrations[1]

Nanoclay, %	Liquid Antistripping, %
1.0	0.25
2.0	0.50
4.0	0.75
6.0	

[1] Percentage of binder weight

Figure 7. DSR Specimens in Silicone Molds



2.3.2 Un-aged Asphalt Binder Results

Table 7 presents the DSR test results of un-aged binder for all asphalt additive concentrations tested. The properties of unmodified (control) asphalt binder are also presented for comparison.

Table 7. DSR Test Results for Un-aged Asphalt Binder

Additive Concentration	Complex Modulus,	Elastic Modulus,	Viscous Modulus,	Phase Angle
	Pa (psi)	Pa (psi)	Pa (psi)	°
Control				
0%	1,434 (0.208)	75.80 (0.011)	1,433 (0.208)	87.1
Nanoclay01				
1%	1,815 (0.263)	110.80 (0.016)	1811 (0.263)	86.5
2%	1,860 (0.269)	123.27 (0.018)	1,856 (0.269)	86.2
4%	1,895 (0.274)	128.90 (0.019)	1,891 (0.274)	86.1
6%	2,265 (0.328)	158.00 (0.023)	2,259 (0.328)	86.0
Nanoclay02				
1%	1,823 (0.264)	103.60 (0.015)	1,820 (0.264)	86.7
2%	1,848 (0.268)	115.00 (0.017)	1,843 (0.267)	86.4
4%	1,911 (0.277)	118.00 (0.017)	1,906 (0.276)	86.3
6%	2,323 (0.336)	153.00 (0.022)	2,318 (0.336)	86.2
HP Plus (HP+)				
0.25%	449 (0.065)	34.45 (0.005)	448 (0.065)	85.6
0.50%	331 (0.048)	30.00 (0.004)	330 (0.048)	84.8
0.75%	207 (0.030)	27.00 (0.004)	205 (0.029)	82.5
LOF 6500				
0.25%	837 (0.121)	12.80 (0.002)	836 (0.121)	89.1
0.50%	467 (0.068)	10.10 (0.001)	467 (0.068)	88.8
0.75%	345 (0.050)	13.61 (0.002)	345 (0.050)	87.7

2.3.3 Rolling Thin-Film Oven Test (AASHTO T 240)

The rolling thin-film oven (RTFO) test was used to measure the effect of heat and air on a moving film of asphalt binder to simulate asphalt aging. This conditioning method was used in conjunction with the DSR test to measure the change in asphalt binder properties.

Two asphalt specimens of 35 g (0.08 lb) were prepared in standardized glass jars for each additive variation and allowed to cool. Since there were eight spots in the oven's rotating carriage, up to eight specimens were tested at one time. Specimens were placed in a 163°C oven, shown in Figure 8, with the carriage and fan rotating, and the air jet on for 85 minutes. After the test, the remaining asphalt residue was quickly scraped out into containers so DSR specimens could be molded. A mass change calculation was also determined at this time. Specimens were then tested in the DSR, and the results for asphalt binder specimens conditioned by the RTFO test are shown in the following section.

Figure 8. A Rolling Thin-film Oven

2.3.4 RTFO Aged Asphalt Binder Results

The rheological properties of the unmodified binder and different combinations of the modified binder, after being aged in the RTFO, were tested and the results are shown in Table 8.

Table 8. DSR Test Results for RTFO Aged Asphalt Binder

Additive Concentration	Complex Modulus, Pa (psi)	Elastic Modulus, Pa (psi)	Viscous Modulus, Pa (psi)	Phase Angle, °
Control				
0%	3,082 (0.45)	276 (0.04)	3,068 (0.45)	84.5
Nanoclay01				
1%	3,698 (0.54)	393 (0.06)	3,677 (0.53)	83.9
2%	4,950 (0.72)	578 (0.08)	4,916 (0.71)	83.3
4%	7,455 (1.08)	779 (0.11)	7,714 (1.11)	84.0
6%	9,960 (1.44)	1,110 (0.16)	9,898 (1.44)	83.6
Nanoclay02				
1%	3,883 (0.56)	344 (0.05)	3,864 (0.56)	84.3
2%	5,198 (0.75)	543 (0.08)	5,170 (0.75)	84.0
4%	7,828 (1.14)	845 (0.12)	7,782 (1.13)	83.8
6%	10,458 (1.52)	1,166 (0.17)	10,393 (1.51)	83.6
HP+				
0.25%	2,896 (0.42)	228 (0.03)	2,889 (0.42)	85.4
0.50%	2,503 (0.36)	172 (0.03)	2,496 (0.36)	86.1
0.75%	1,751 (0.25)	90 (0.01)	1,751 (0.25)	87.1
LOF 6500				
0.25%	2,367 (0.34)	133 (0.02)	2,363 (0.34)	86.8
0.5%	2,235 (0.32)	126 (0.02)	2,231 (0.32)	87.0
0.75%	913 (0.13)	13 (0.002)	913 (0.13)	89.2

2.4 Uncompacted Asphalt Mix Test

2.4.1 Theoretical Maximum Specific Gravity and Density (AASHTO T 209)

The theoretical maximum specific gravity and density of an asphalt mixture was an important parameter to determine the overall mix design process. This property was essential in calculating the percentage of air voids in the compacted asphalt mixture and the amount of binder absorbed by the aggregate particles. For this test, asphalt-mix specimens for each mix variation were prepared and cured for two hours. Mixes were then cooled in a loose, uncompacted state and placed in a vacuum container filled with water. A high-vacuum pump, shown in Figure 9, was attached to the container and activated for at least 15 minutes, removing entrapped air. Shaking was required to remove air bubbles. After vacuum saturation, the container was removed from the pump and filled to the calibrated level with water. Then, the mass of the container, specimen, and water was determined. This value, along with the dry mass of the specimen and mass of the container filled with just water, was used to determine the theoretical maximum specific gravity by the following equation:

Theoretical Maximum Specific Gravity = A / (A + D - E)

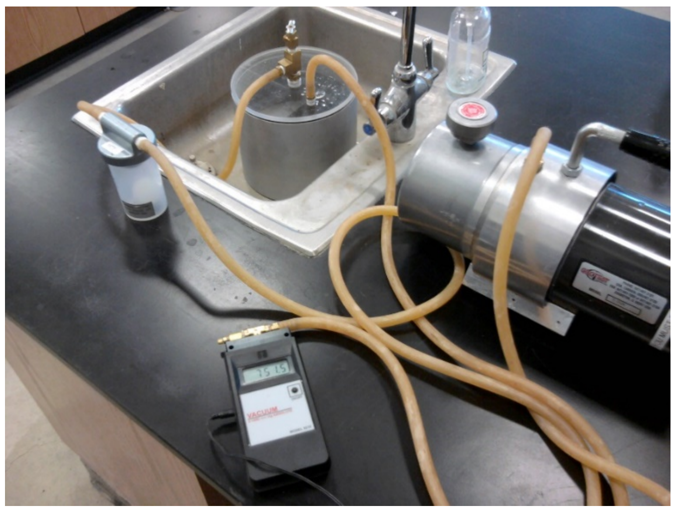
Where:

A = mass of oven dry specimen (g);

D = mass of container filler with 25° C water (g); and

E = mass of container filled with specimen and water (g).

Figure 9. Vacuum Saturating a Loose HMA Specimen



The theoretical maximum specific gravities were determined to be 2.46 g/cm^3 (153.75 lb/ft^3), 2.48 g/cm^3 (155 lb/ft^3), and 2.45 g/cm^3 (153.13 lb/ft^3) for coarse, intermediate, and fine blends, respectively.

2.5 Asphalt Mix Design

2.5.1 Superpave Mix Design

The Superpave mix design procedure was developed by the Strategic Highway Research Program (SHRP) in the early 1990s. The goal was to develop a standardized method of asphalt mix design that accounts for traffic loading and environmental conditions and can evaluate asphalt binder and analyze the final mix design. The Superpave mix design procedure includes several steps: aggregate selection, asphalt binder selection, specimen preparation, performance testing, density and voids analysis, optimum binder content selection, and moisture susceptibility evaluation. Many of these steps incorporate the tests mentioned herein.

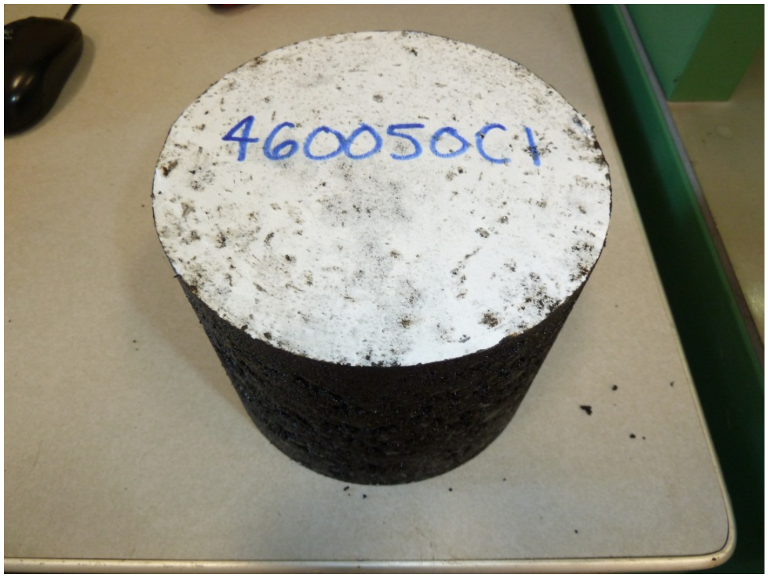
2.5.2 Specimen Preparation

Two specimens of each of the three gradation blends were oven dried. Then, 5% asphalt binder was added and thoroughly mixed until all aggregate surfaces were covered with binder. Specimens were placed in a 163°C oven for two hours of aging; mixing was conducted every half hour to ensure consistency. After aging, specimens were placed in a 150 mm (6 in) diameter compactor mold and compacted to appropriate parameters based on design equivalent single axle loads (ESALs). An ESAL of 3 to 30 million, which is common for most U.S. highways, was used here. The initial, design, and maximum compaction parameters are 8, 100, and 160 revolutions.

A Rainhart Superpave gyratory compactor, shown in Figure 10, was used to compact the asphalt specimens. This device was designed to simulate in the laboratory the kneading action of a smooth-wheeled roller used to compact asphalt in the field. It accomplished this by placing 600kPa (87 psi) vertical pressure on the specimen inside the mold. Rollers were then lifted which helped gyrate the mold at a 1.25° angle for the predetermined number of revolutions. Once the compaction was completed, the angle was removed, and the hydraulic ram was retracted. The specimens were then extracted and left to cool as shown in Figure 11.

Figure 10. Superpave Gyratory Compactor Ready to Compact a Specimen

Figure 11. Compacted Trial Specimen



Next, the bulk specific gravity and maximum specific gravity of the mix were determined by AASHTO tests T166 and T209, respectively. The compaction data for the three trial blends are shown in Table 9. The intermediate aggregate blend was selected from the three blends due to its compactibility (final height), air voids, and bulk specific gravity. These properties' values indicated that this blend would satisfy Superpave mix design 5% air void requirements after determining the optimum binder content.

Table 9. Mix Design Trial Specimen Results

Trial Specimen		Coarse 1	Coarse 2	Int 1.	Int. 2	Fine 1	Fine 2
% Binder	%	5	5	5	5	5	5
Dry Mass	(g)	4587.2	4582.9	4594.2	4588.4	4594.2	4588.4
Wet Mass	(g)	2578	2574.8	2592.5	2595.7	2592.5	2595.7
SSD Mass	(g)	4626.5	4619.4	4625.8	4620.1	4625.8	4620.1
Gmm	g/cm3	2.401	2.401	2.392	2.392	2.392	2.392
Height@N_{des}	Mm	118.19	118.44	117.3	116.64	117.3	116.64
Gmb@N_{des} est.	g/cm3	2.196	2.190	2.216	2.226	2.216	2.226
Corr. Gmb @ N_{des} est.	g/cm3	2.217	2.219	2.232	2.239	2.232	2.239
Corr. Air Voids @ N_{des}	%	7.67	7.58	6.70	6.41	6.70	6.41

* Superpave mix design recommends 5.0% air voids which was obtained after determining the optimum binder content

2.5.3 Optimum Binder Content

With an aggregate blend selected, the optimum binder content could be selected. This was achieved by preparing specimens of varying binder content. Superpave mix design recommends preparing two specimens with a binder content of ± 0.5% and + 1.0% of the estimated binder content. After evaluating specimens, a 5.75% optimum binder content was selected since it met the 5% air void requirement. This binder content was used for all subsequent specimen preparations for moisture susceptibility evaluation.

2.5.4 Additive Application Methods

Once the mix design was completed, the ranges of additives to be tested were determined based on previous research. Asphalt additives were introduced to the asphalt mix by two different methods. The first consisted of adding the nanoclay or liquid anti-stripping agent directly to the asphalt binder after being heated and thoroughly mixed for approximately 15 minutes. Then the modified binder was added to the aggregates and mixed as previously outlined. The second method was the lime slurry additive. The lime slurry modified aggregate was provided by CalPortland ready to mix. The additive concentrations tested are summarized in Table 10.

Table 10. Additive Concentrations Tested

Nanoclay, %	Lime Slurry, %	HP Plus, %	LOF 6500, %
1		0.25	0.25
2	1.3	0.50	0.50
4		0.75	0.75
6			

2.6 Moisture Sensitivity Tests and Results

2.6.1 Modified Lottman Indirect Tensile Test (AASHTO T 283)

The modified Lottman indirect tensile test is an incorporated step in the Superpave mix design. Test specimens were produced and compacted in a 100 mm (4 in) diameter mold to air voids of approximately 7% and a height of approximately 63.5 mm (2.5 in), in accordance with AASHTO T 283. Specimens were weighed and separated into unconditioned and conditioned sets according to average air voids. The unconditioned specimens were set aside while the conditioned specimens were vacuum saturated and placed in a freezer for a minimum of 16 hours. After 16 hours, conditioned specimens were placed in a 160°C hot water bath for 24 hours and then in a 25°C bath with the unconditioned specimens for 2 hours as shown in Figure 12.

Figure 12. Asphalt specimens Conditioning in Water Bath

Once specimens reached the testing temperature, they were removed from the water bath and placed in the steel loading apparatus in the hydraulic test machine as shown in Figure 13. The indirect tensile strength (ITS) for each specimen was calculated using the following equation:

$$St = 2P / (\pi tD)$$

Where:

St = tensile strength (psi);

P = maximum force placed on specimen during loading (lbs.);

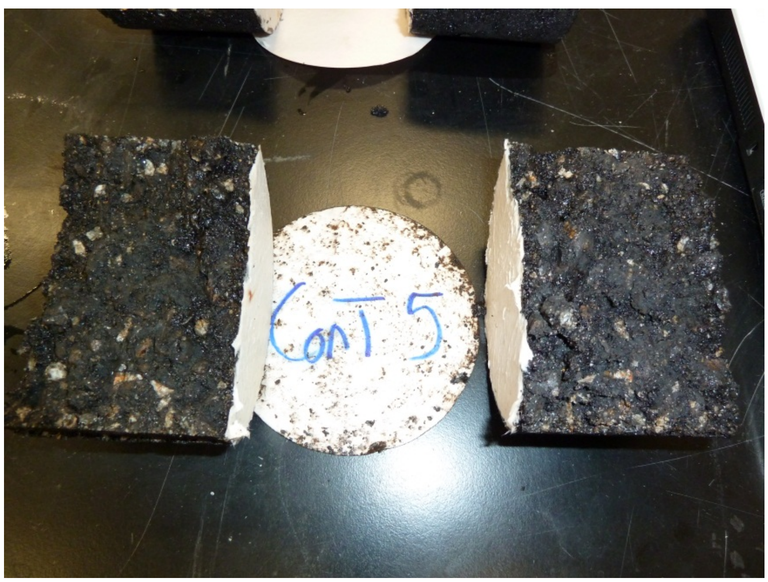
t = specimen thickness (in); and

D = specimen diameter (in).

Figure 14 illustrates a typical cross-section of a specimen after an indirect tensile test. Final results are included in the following section.

Figure 13. Specimen Ready to be Tested for Tensile Strength

Figure 14. Specimen after Indirect Tensile Test



2.6.2 Modified Lottman Indirect Tensile Test Results

Table 11 presents the results of the compacted asphalt specimens tested for tensile strength. The average strengths for both the unconditioned and moisture-conditioned sets are presented in the table along with the tensile strength ratios (TSRs). The 2018 Standard Specification for the California Department of Transportation does not specify a minimum indirect tensile strength ratio. However, it specifies a minimum indirect tensile strength of 100 psi for the unconditioned/dry specimens and a minimum of 70 psi for the conditioned/wet specimens. The

TSR represents the proportion of tensile strength retained between the moisture damaged and unconditioned sets of a specific additive concentration. The TSR was calculated using the following equation:

$$\text{Tensile Strength Ratio (TSR)} = ITS_2 / ITS_1$$

Where:

ITS_2 = average tensile strength of the conditioned (moisture damaged) set (psi); and

ITS_1 = average tensile strength of the unconditioned set (psi).

The tensile strength for moisture-damaged specimens with each additive concentration was also compared with the unconditioned control tensile strength using the following equation:

$$\text{Tensile Strength Ratio (TSR)} = ITS_2 / ITS_{1Unconditioned}$$

Where:

ITS_2 = average tensile strength of the conditioned (moisture damaged) set; and

$ITS_{1Unconditioned}$ = average tensile strength of the unconditioned control set.

Nanoclay additives and liquid antistripping (HP+ and LOF 6500) were added directly to the binder and mixed thoroughly, while the lime slurry was added to the aggregate in the mixing plant that provided the materials (CalPortland).

Table 11. AASHTO T283 Indirect Tensile Strength (ITS) Rest Results

Additive %	Dry Tensile Strength psi	Wet Tensile Strength Psi	TSR	TSR compared to control
Control				
0%	261.0	203.2	0.78	0.78
Lime Treated Agg.				
1.3%	249.6	229.0	0.92	0.88
Nanoclay1				
1%	278.9	251.0	0.90	0.96
2%	280.0	227.6	0.81	0.87
4%	279.5	263.5	0.94	1.01
6%	276.6	221.7	0.80	0.85
Nanoclay 2				
1%	277.9	221.6	0.80	0.85
2%	292.3	250.0	0.86	0.96
4%	261.6	213.6	0.82	0.81
6%	239.3	186.6	0.78	0.90
HP Plus				
0.25%	233.9	222.2	0.95	0.85
0.50%	221.27	211.4	0.96	0.81
0.75%	234.6	218.19	0.93	0.84
LOF 6500				
0.25%	286.3	241.5	0.84	0.93
0.50%	273.7	245.0	0.88	0.94
0.75%	266.0	215.6	0.81	0.83

Even though the control mix passed the Caltrans requirements, it did not pass the 80% TSR specified by the Superpave mix design. In addition, the study's goal was to provide a comparison between unmodified (control) and modified mixes, rather than improving a failing control mix.

2.7 Summary

Section II discussed the materials and testing methods involved in this study. After obtaining the needed materials from their respective sources, the physical and mechanical properties of aggregates and asphalt binder were evaluated in accordance with AASHTO, ASTM, Caltrans, and Superpave mix design specifications. The asphalt binder was then combined with varying concentrations of each of the additive and tested using a Dynamic Shear Rheometer (DSR) before and after being aged in a Rolling Thin Film Oven (RTFO). Aggregate gradation curves were established for the mix design following Caltrans standards and an optimum binder content was determined to be 5.75% using the Superpave mix design procedure. Using this mix design, varying amounts of each additive were introduced to specimens following two different application methods. Specimens were fabricated and tested for indirect tensile strength before and after being conditioned. Results were then organized and tabulated for moisture sensitivity analysis, which is presented in the following section (Section III).

3. Analysis and Discussion

3.1 Introduction

This section discusses the test results of all binder and moisture sensitivity tests conducted in this study. The binder complex modulus (G*), phase angle (δ), and rutting factor (G*/sinδ) graphs are presented for all additive concentrations tested, followed by a discussion of the results. Plots were created to graphically represent differences among the different additives, concentrations, and application methods. First, results from DSR tests for both unaged and aged binder are analyzed to determine asphalt binder-additive interactions. Then, moisture sensitivity test results presented in Section II are analyzed. Note that all specimens are compared to their unconditioned counterparts (not subjected to moisture damage) and to the unconditioned control specimens. An analysis of the results is incorporated into each group of graphs.

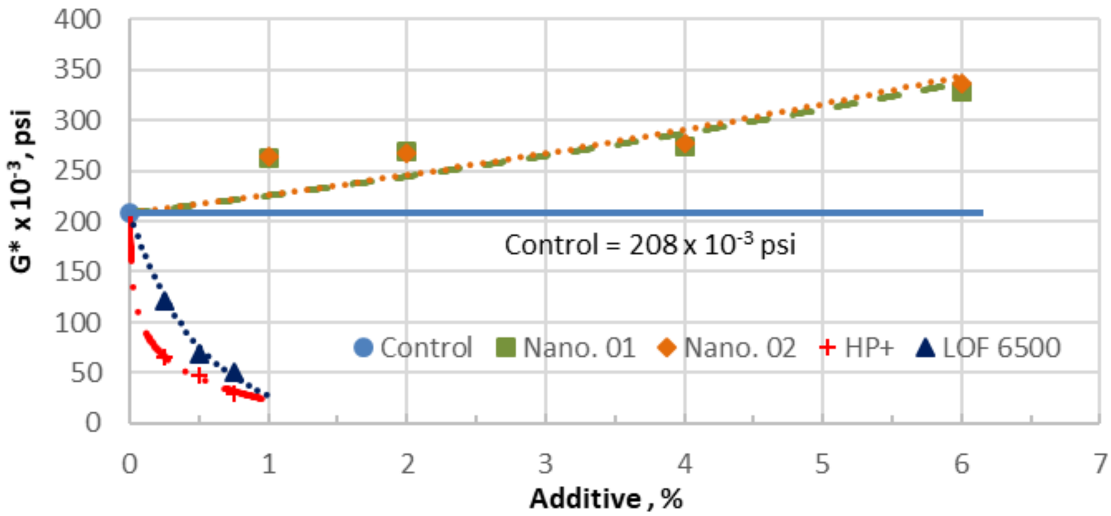
3.2 Asphalt Binder

Results from DSR tests for the asphalt binder before and after RTFO aging are discussed and analyzed in this section. The most important properties are the complex modulus (comprised of the elastic modulus and viscous modulus), phase angle, and rutting factor. These binder properties, before and after additive modification, are discussed.

3.2.1 Complex Modulus (G)*

The complex modulus (G*) represents the total amount of resistance an asphalt binder specimen has against deformation. The complex modulus is simply the vector summation of both the elastic and viscous portions of the binder. Generally, the higher the complex modulus, the stiffer the binder will be against deformation. Figure 15 shows the relationship between additive concentration and complex modulus for different types of additives.

Figure 15. Complex Modulus (G*) of Asphalt Binder Specimens Before RTFO Conditioning



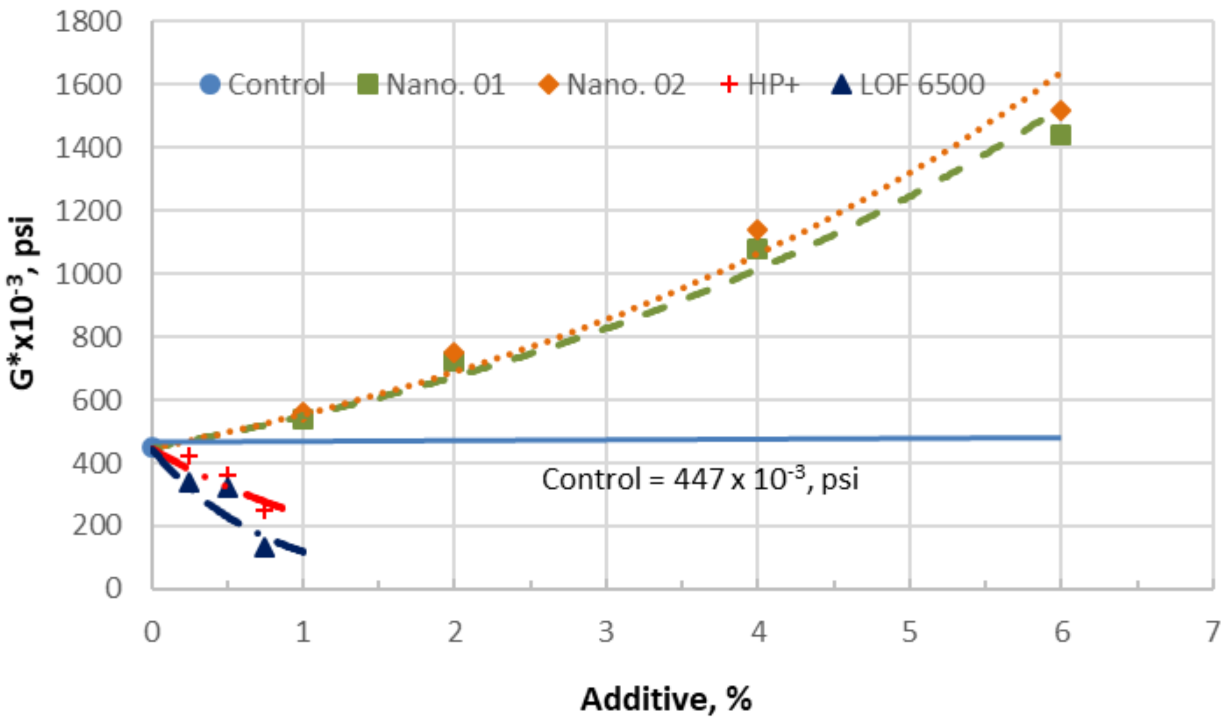
From the DSR tests, the complex modulus (G*) for the control specimens (no additives) was 0.208 psi, which, when divided by the sine of the phase angle (δ), meets the Superpave mix design requirement of 0.145–0.290 psi. The above graph shows the results for control (unmodified) binder as a horizontal straight line in order to compare with the varying additive concentrations. Since the DSR test was conducted at 64°C, the increase in G* for nanoclay-modified binder is an indication that the nano-modified binder has higher resistance to rutting (stability) than base original binder due to the higher complex shear modulus at high temperatures. Note that the two nanoclay additives exhibited nearly the same performance, as shown in Figure 15.

On the other hand, the two liquid antistripping (HP Plus and LOF 6500) additives had a significant softening effect on the asphalt binder. This explains the difficulty encountered while loading specimens into the DSR, which quickly began melting. It is normal for liquid antistripping additives to soften binder; however, HP Plus seemed to have a slightly higher pronounced effect than that of LOF 6500. It should be noted here that G*/sinδ for binder modified using liquid antistripping additive falls below the minimum of 0.145 specified by Superpave mix design for the three additive concentrations tested in this study.

After conditioning binder specimens in a RTFO, DSR tests were again conducted, producing the results displayed in Figure 16. Some changes were observed in the complex modulus compared to unconditioned specimens. First, G* for the control specimens increased to 0.447 psi, which continues to meet the minimum of 0.319 psi specified by Superpave mix design.

The complex modulus for binder specimens with nanoclay additives exhibited significant increase in G* after aging in RTFO with G*/sinδ that meets the minimum of 0.319 psi for all additive dosages. Note that the two nanoclay additives exhibited nearly the same performance as shown in Figure 16. This was also the case for binder modified by 0.25% and 0.5% liquid antistripping. As the liquid antistripping dosage exceeded 0.50% G*/sinδ decreased below the minimum of 0.319 psi specified by Superpave mix design.

Figure 16. Complex Modulus (G*) of Asphalt Binder Specimens After RTFO Conditioning



3.2.2 Phase Angle (δ)

The phase angle represents how elastic or how viscous an asphalt binder is. A phase angle of 0° represents a purely elastic binder, while a 90° phase angle represents a purely viscous binder. Table 12 shows the phase angle for binder with different additives concentration before and after RTFO conditioning. It is shown that the phase angle slightly decreased for binder modified using nanoclay and liquid antistripping (lower phase angle means more elastic binder). Also, the phase angle decreases between 1.4° and 5° for additives after RTFO aging, except for HP Plus for which the phase angle slightly increased after aging in RTFO.

Table 12. Phase Angle of Specimens Before and After RTFO Conditioning

Additive Concentration	Phase Angle, °	
	Before RTFO	After RTFO
Control		
0%	87.1	84.5
Nanoclay 01		
1%	86.5	83.9
2%	86.2	83.3
4%	86.1	83.0
6%	86.0	82.7
Nanoclay 02		
1%	86.7	84.3
2%	86.4	84.0
4%	86.3	83.5
6%	86.2	83.4
LOF 6500		
0.25%	89.1	83.9
0.50%	88.8	83.1
0.75%	87.7	84.4
HP +		
0.25%	85.6	86.5
0.50%	84.8	85.4
0.75%	82.5	85.2

3.2.3 Rutting Factor (G/sinδ)*

It is only one-sided to assess the properties of bitumen from the perspective of G* or δ. If G* is the same, their phase angle values may not be the same, and vice versa. Therefore, different indicators can be used to evaluate the performance of bitumen for various performances at different test temperatures. Rutting factor (G*/sinδ) of asphalt binder represents how well the binder can rebound to its original shape after removing a load and how resistant it is to deformation at high temperature. Binders with high rutting factors will have better resistance to permanent deformation (rutting).

Figures 17 and 18 present the relationship between additive concentration and rutting factor for all binder combinations before and after RTFO conditioning, respectively. From Figure 17, the two nanoclay additives increased the rutting factor (G*/sinδ) above the maximum of 0.249 psi specified by Superpave mix design. However, G*/sinδ for nanoclays with concentrations of 1% to 4% remain very close to the maximum limit of 0.249 psi. The two liquid antistripping agents reduced the rutting factor below the lowest limit specified by Superpave mix design for the binder tested in this study.

Figure 17. Rutting Factor of Asphalt Binder Unaged in RTFO

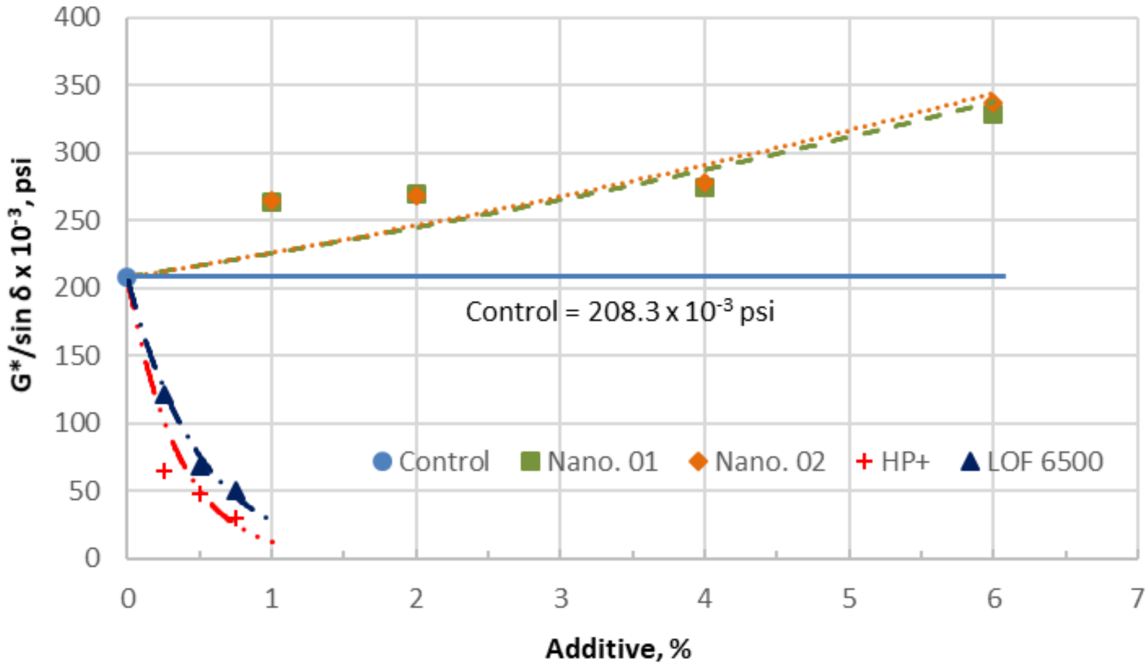
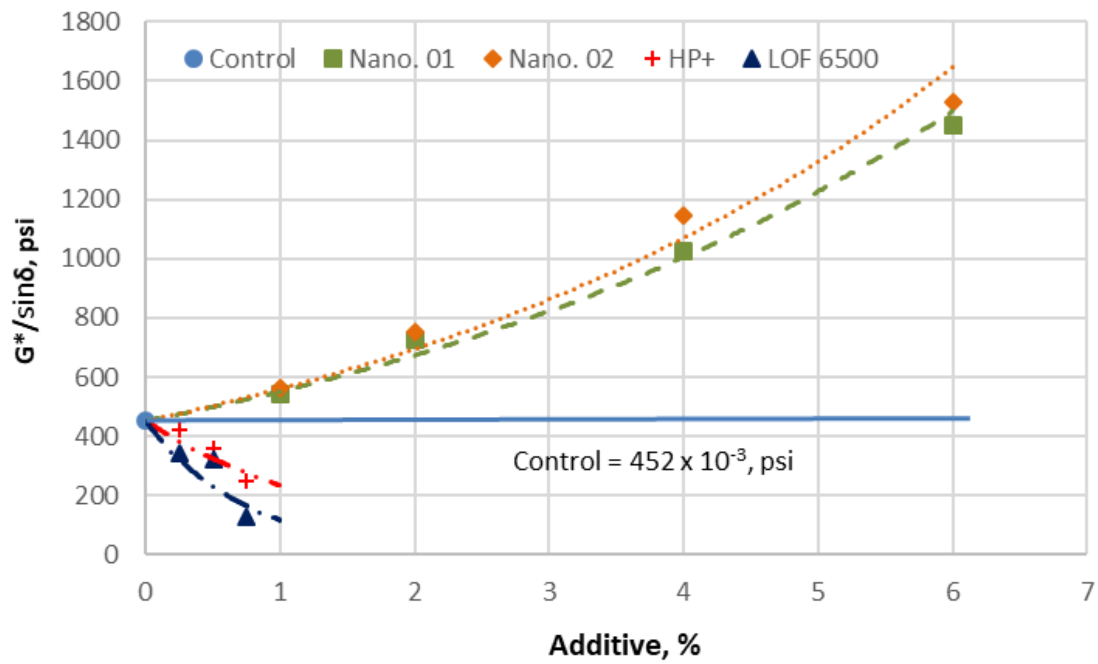


Figure 18 presents the effect of short-term aging in RTFO on G*/sinδ for binder modified with different additive types and concentrations. The results show a G*/sinδ that exceeds the 0.319 psi minimum requirements for a virgin binder and a binder modified with the two nanoclays at 1% to 6% concentrations. However, liquid antistripping with only 0.25% and 0.5% resulted in G*/sinδ that stayed at or slightly above the minimum of 0.319 psi.

Figure 18. Rutting Factor of Asphalt Binder after Aging in RTFO



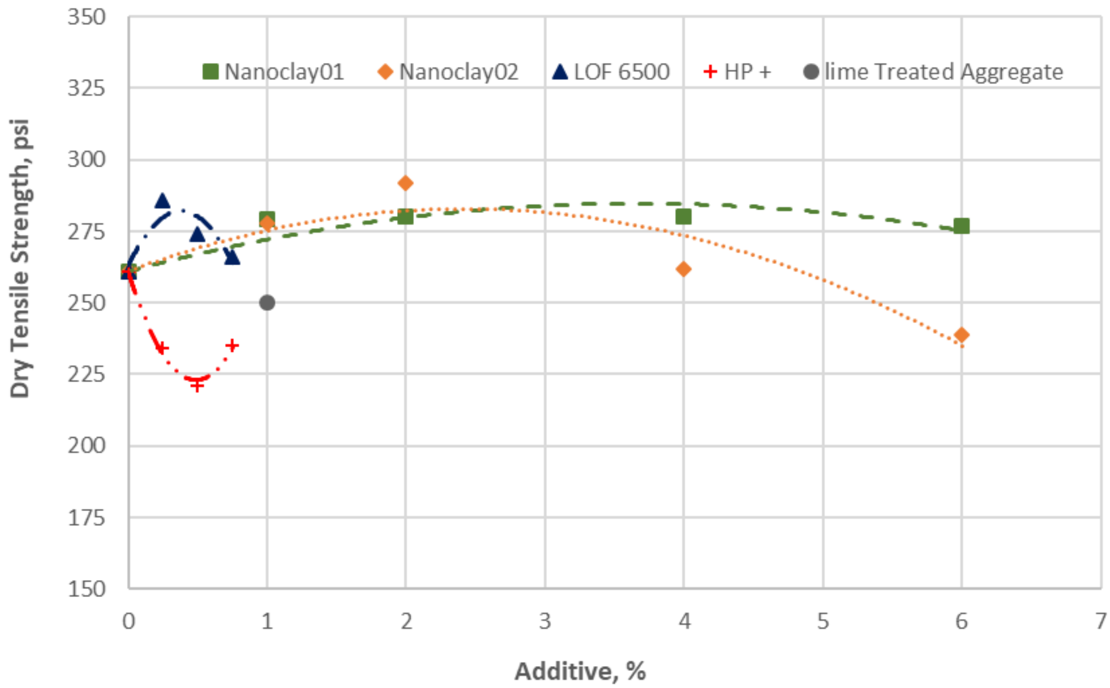
3.3 Performance Testing Resulting of Asphalt Concrete Mixes

For each mix, two subsets (three specimens for each subset with a total of 90 specimens) compacted with 7.0% ± 0.5% air voids and optimum binder content of 5.75% were tested. The first subset was tested in an unconditioned state and the second subset was subjected to partial vacuum saturation (a degree of saturation of 70% to 80%) followed by one freeze-thaw cycle in accordance with AASHTO T-283. Results for indirect tensile strength for unconditioned and conditioned sets were presented in Section II and are discussed in this section. The Tensile Strength Ratio (TSR) is calculated by two different methods. In the first, TSR is calculated by dividing the wet tensile strength by the dry tensile strength for each additive combination, which is the normal method in practice. However, the wet tensile strength, after adding the modifiers/additives, needs to be normalized by comparing it to the dry tensile strength for the mix before adding the modifiers (control mix) to standardize the comparison. Therefore, this second method is explored in this study, and TSR will be referred to as $TSR_{normalized}$.

3.3.1 Tensile Strength for Dry Mixes

The comparison for indirect tensile strength for unconditioned/dry specimens is presented in Figure 19. The figure shows that HMAs that contain a nanoclay01 modifier had higher tensile strength which increased at a very small rate as the percentage of nanoclay01 increased with an optimum nanoclay01 percentage of approximately 3%. Nanoclay02 exhibited a similar trend as nanoclay01 with an optimum percentage of approximately 3.0%.

Figure 19. Indirect Tensile Strength for Unconditioned/dry Specimens



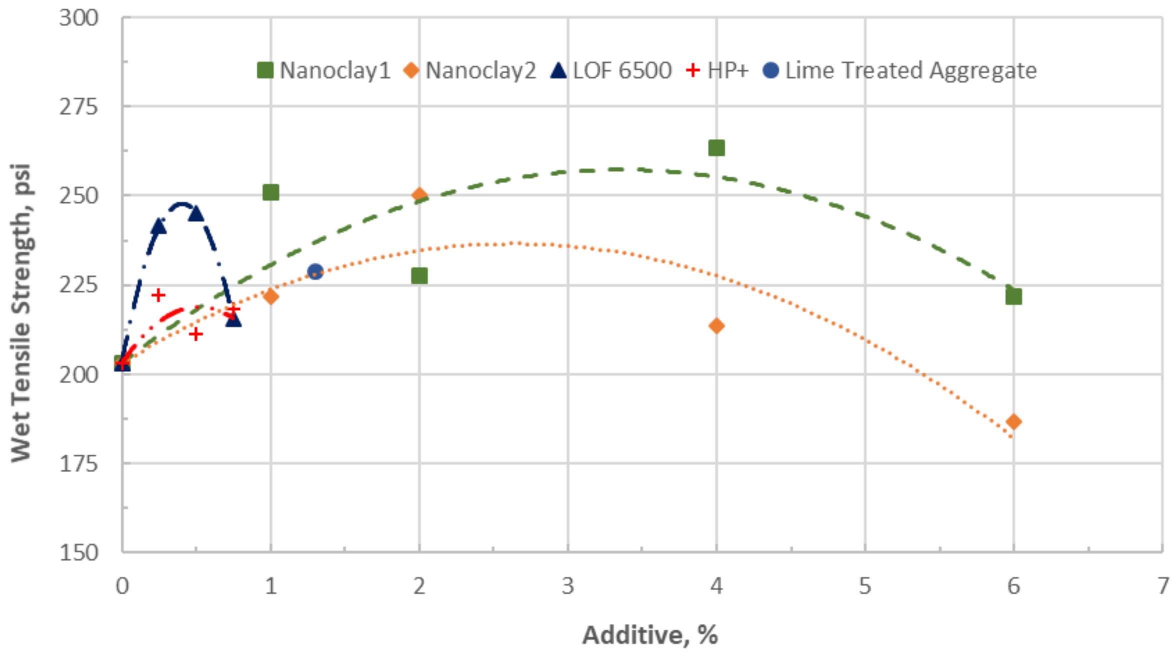
Note: The limit for dry tensile strength is 100 psi.

HMA with lime-treated aggregate had tensile strength that was slightly lower than that of the control mix. Note that HMAs with lime-treated aggregate were tested only at a lime content of 1.3%. The performance of HMA treated with liquid antistripping exhibited mixed performance. It was observed that LOF 6500 liquid antistripping increased the tensile strength of HMA with an observed optimum at approximately 0.5%. On the other hand, HMA treated with HP+ liquid antistripping exhibited tensile strength that was lower than that for the control mix. All mixes tested resulted in dry tensile strengths that were higher than the minimum of 100 psi specified by Caltrans (Caltrans Standard Specification, 2018).

3.3.2 Tensile Strength for Conditioned Mixes

The comparison of indirect tensile strength for conditioned/wet specimens is presented in Figure 20. The results show that all mixes tested exhibited the same performance trends. The data show that mixes treated with nanoclay01 and nanoclay02 exhibited higher strengths than that for the control mix, except for nanoclay02 mix with 6% nanoclay. Also, it is noted that mixes treated with nanoclay01 and nanoclay02 additives had optimum additive percentages of approximately 2.5% and 3.5%, respectively. HMA mix with lime-treated aggregate had wet tensile strength higher than that for the control mix, which was not the case when this mix was tested for dry tensile strength. The two liquid antistripping agents exhibited similar trends with an optimum antistripping percentage of approximately 0.5%. Note that all mixes resulted in wet tensile strengths greater than the minimum of 70 psi specified by Caltrans.

Figure 20. Indirect Tensile Strength for Conditioned/wet Specimens

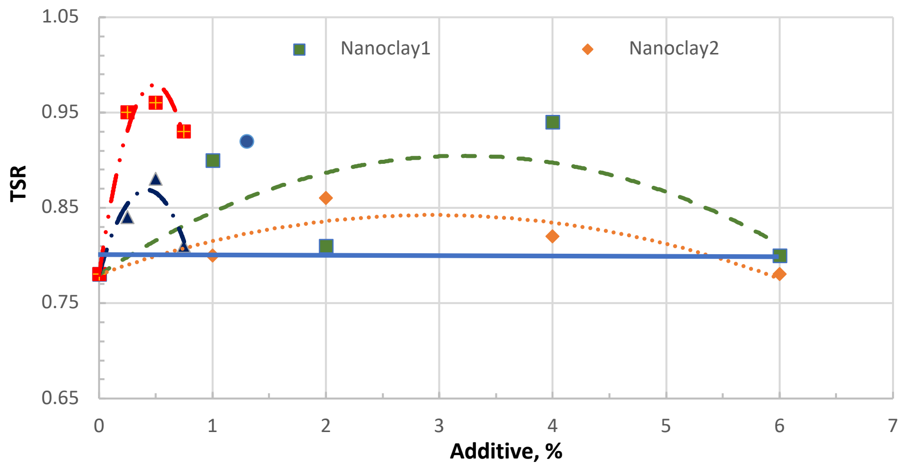


Note: The limit for conditioned tensile strength is 70 psi.

3.3.3 Tensile Strength Ratio (TSR)

The dry tensile strength divided by the dry tensile strength (TSR) for each specimen in the different subsets was calculated for comparison, and results are shown in Figure 21. This data show that TSR for all modified mixes outperformed the control mix and that all mixes exceeded the 0.70 minimum requirement specified by Caltrans. However, only the TSR for the control mix was slightly below the 0.80 specified by Superpave mix design. Among all the modifiers investigated in this study, mixes modified using HP+ liquid antistripping outperformed other modified mixes (nanoclays, lime-treated, and LOF 6500 liquid antistripping). It is noted that the peak TSR for mixes with nanoclay01, lime-treated aggregate, and LOF 6500 was equal. Among all modified mixes used in this study, HMA containing Nanoclay02 showed the least improvement in TSR. An optimum additive content was also observed for each of the mixes: 3.0% for Nanocaly01 and Nanoclay02 and 0.5% for both HP+ and LOF 6500. Note that an HMA with only one lime dosage (1.3%) was tested.

Figure 21. TSR for HMA with Different Additives



Note: The blue line is the Superpave mix design method's TSR requirement (0.8).

3.3.4 Wet Tensile Strength as Ratio of Dry Control ($TSR_{normalized}$)

To standardize the TSR, the tensile strength for conditioned/wet specimens was compared with the dry tensile strength for the control mix. This ratio is referred to as $TSR_{normalized}$ throughout the report, and the results are presented in Figure 22. The TSR for all modified mixes outperformed the control mix, and all mixes exceeded the 0.80 minimum specified by Superpve (Figure 22). However, $TSR_{normalized}$ and the optimum modifier content changed slightly for each of the mixes. The comparison between the two approaches used in calculating the TSR is shown in Table 4.2.

Figure 22. $TSR_{normalized}$ for HMA with Different Additives

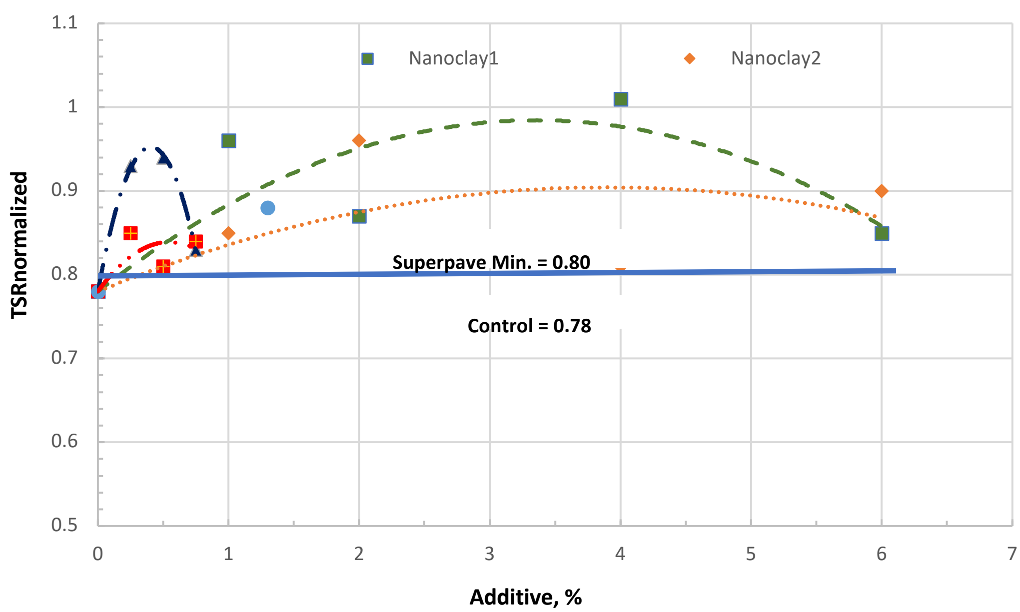


Table 13. Comparison Between the Two Approaches Used in Calculating the Tensile Strength Ratio

MODIFIER	TSR/MODIFIER OPTIMUM CONTENT, %	$TSR_{NORMALIZED}$/MODIFIER OPTIMUM CONTENT, %
NANOCLAY01	0.90 / 2.5	0.97 / 3.5
NANOCLAY02	0.84 / 3.0	0.87 / 3.5
LIME SLURRY	0.92 / NA1	0.88 / NA
LOF 6500	0.87 / 0.5	0.95 / 0.4
HP+	0.96 / 0.5	0.83 / 0.5

[1] Not applicable since only one lime slurry percentage was used.

The use of the two different approaches in calculating TSR had mixed results. $TSR_{normalized}$ was higher than TSR for three of the mixes (nanoclay01, nanoclay02, and LOF 6500) and lower for the other two mixes (lime-treated and HP+). These results warrant discussion among the pavement engineering community to generate a consensus as to which approach is appropriate in analyzing the results of AASHTO T283.

3.3.5 Cost Analysis

Cost is an important factor in determining which additive to use in HMA preparation. The most cost-effective additive will likely vary from region to region due to availability and transportation costs, as well as binder and aggregate composition. The costs used in this analysis were estimated for asphalt production on the central coast of California. According to CalPortland Construction, the unit cost of lime is estimated at $45 per ton of lime slurry, which equates to $0.023 per pound of lime. Assuming an optimum lime content of 1.5%, the material cost of lime would be $0.68 per ton of HMA mix. CalPortland also stated that the cost of stockpiling, hydrating, and adding lime to the HMA aggregates would add $4.00 per ton of HMA. This brings the final cost of adding lime to $4.68 per ton of HMA (Daniel Ortega, personal communication, August 2, 2022).

For HP Plus and LOF 6500, ArrMaz Chemicals quoted a price of $3.00 per pound of additive (P. Whittey, personal communication, October 28, 2011). Using an optimum concentration of 0.50% of the binder weight, the chemical cost comes to $1.73 per ton of asphalt mix. An in-line system is also required to add liquid anti-stripping agents to the HMA at the plant. These systems typically range between $10,000 and $25,000 in initial cost, which add about $0.10 to $0.20 per ton of HMA produced (Epps et al, 2003). Note that the cost for the in-line system is a one-time, non-recurring cost. However, for liquid antistripping the authors suggest an added cost of $2.0/ton of HMA. Lastly, for nanoclay01 and nanoclay02, assuming 3.0% of the binder content, about 3.5 lb of nanoclay is needed per ton of HMA. The average cost of nanoclay, including surface modification and mixing, is approximately $2.0/lb nanoclay. Thus, the nanoclay additive cost becomes $7.0 per ton of HMA.

3.4 Summary

Based on the DSR and RTFO tests, nanoclay01 and nanoclay02 had a stiffening effect on the binder, increasing complex and elastic moduli. Also, with increasing additive concentration, binder stiffness increased further. However, both liquid antistripping agents (HP+ and LOF 6500) had the opposite effect on the asphalt binder, decreasing both the elastic and complex modulus of the binder. After RTFO aging, similar trends for the additives were observed, except the binder became much stiffer in all cases, which is typical for this test. The phase angle also decreased for most additive concentrations, making the binder more elastic in nature. Only the 0.25% and 0.50% HP+ and LOF 6500 concentration met the minimum Superpave mix design requirement of 0.319 psi for RTFO aged binder.

Compacted specimens were molded and tested using the AASHTO T 283 indirect tensile test. Specimens were compared on the basis of unconditioned tensile strength, conditioned (after moisture damage) tensile strength, and tensile strength ratios. Dry tensile strength results for only nanoclay01, nanoclay02, and LOF 6500 modified mixes were higher than that for control mix. However, all modified mixes resulted in wet tensile strengths that were higher than that for control mix. TSRs for all modified mixes were higher than that for control mix and also exceeded the Superpave mix design minimum of 0.80 using the standard calculation method and as a ratio of the tensile strength of the unconditioned control mix.

4. Multi-Criteria Decision Analysis

One of the objectives of this study was to compare and rank HMA additives (from the literature) used to improve moisture resistance. A multi-criteria decision analysis (MCDA) was used to achieve this research objective. MCDA is a systematic approach that quantitatively ranks alternatives based on multi-criteria such as cost, performance, and the mixing method used for incorporating the additives into the HMA.

The first step towards the MCDA was conducting a comprehensive literature review to identify the alternatives used for modifying asphalt binders to resist moisture damage. The results of this literature review served as the inputs for the MCDA. The MCDA calculations were performed using the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The AHP was used to determine the weights of each evaluation criterion and TOPSIS utilized those weights for ranking the alternatives. The basis of the TOPSIS method is that the highest ranked alternative should have the shortest distance from the ideal solution and the farthest from the negative ideal solution.

4.1 Methodology

4.1.1 Literature Review

Articles were collected from two databases, ScienceDirect and Engineering Village, using sets of two keywords (Table 15). In total, there were 10 sets of keywords used for each database. For each set of keywords, the number of results per page, the number of pages viewed, the total number of pages available, and the number of relevant articles were recorded. This ensured consistency during the article collection process. Only relevant articles published between 2015 and 2021 were considered herein.

Table 14. Keyword Combinations Used for Article Collection

Set	Keywords
1	Moisture resistance, nanomaterial
2	HMA, nanomaterial
3	Moisture resistance, hydrated lime
4	Pavement, nanomaterial
5	HMA, hydrated lime
6	Pavement, hydrated lime
7	Moisture resistance, anti-stripping liquid
8	HMA, anti-stripping liquid
9	Pavement, anti-stripping liquid

The literature search resulted in the collection of 89 articles that were deemed relevant to the scope of the project. These 89 articles were analyzed by the following categories: additive material and amount used, mixing method, standard methods used to test improvements in moisture resistance, and improvement results. A summary of the outcomes of this literature search is presented in Appendix A.

4.1.2 AHP

The Analytic Hierarchy Process (AHP) is the process of assigning weights to multiple criteria through relative ranking. The hierarchical structure can be understood as the process of making a decision. In this study, the overarching decision or the first level in the structure was to choose the best additive to improve moisture resistance in pavement. The criteria considered in making this decision are additive material cost, mixing method to incorporate the additive in the HMA, equipment cost, and performance. Those criteria constituted the second level in the structure. The third level was the alternatives or possible additives that were being compared. The criteria being evaluated do not necessarily carry the same weight in the decision-making process. To determine the weight of each criterion, a scale of relative importance from 1 to 9 was incorporated, 1 meaning the criteria is of equal importance and 9 meaning the criteria is of extreme relative importance. The relative importance for criteria is inversely related as seen in Table 16. For example, since material cost is relatively important to the mixing method by a factor of 4, the mixing method is relatively important to material cost by a factor of ¼.

Table 15. AHP-Relative Importance Criteria

	Material Cost	Mix Method	Equipment Cost	Performance
Material Cost	1	4	3	1
Mixing Method	1/4	1	1	1/5
Equipment Cost	1/3	1	1	1/3
Performance	1	5	3	1

The columns in Table 16 were summed, and then each cell was divided by their respective column's sum. Next, the rows were averaged. This average is the theoretical criterion weight, which was rounded to whole number percentages. Then, each column from Table 16 was multiplied by their respective criteria weights, and each row was summed to give the weighted sum value (Table 17). For each criterion, the ratio of weighted sum value to criteria weights was then calculated (Table 17). The average of these ratios gave the λ_{max} value, which was used to find the consistency index as shown in the following equation:

$$C.I. = \frac{\lambda_{max} - n}{(n-1)}$$

Where, C.I. is the consistency index and n is the number of criteria

Following the equation presented below, the consistency index was divided by the coefficient for the case n = 4, resulting in a consistency ratio of approximately 0.05 (Table 18). Since this consistency ratio was less than 0.10, the criteria weights could be considered consistent according to the AHP method. This means that the relative importance assigned to each criterion is consistent with the weight percentages assigned.

$$C.R. = \frac{C.I}{c}$$

Where, C.R. is the consistency ratio, and c is the coefficient for n criteria

Table 16. AHP Criteria Weight Calculations

	Theoretical Criteria Weights	Selected Criteria Weights	Weighted Sum Value	Ratio of Weighted Sum Value/Criteria Weights
Material Cost	0.38	0.35	1.60	4.57
Equipment Cost	0.12	0.15	0.50	3.33
Mixing Method	0.09	0.10	0.42	4.18
Performance	0.40	0.40	1.70	4.25

Table 17. AHP Consistency Calculation

λ_{max}	Consistency Index (C.I.)	Coefficient for n = 4	Consistency Ratio
4.08	0.03	0.58	0.05

4.1.3 TOPSIS Analysis

The TOPSIS analysis is the process used for ranking the alternatives using the criteria weights determined by the AHP process. Values for each criterion consisted of the actual data retrieved from the studies for that criterion. There are two types of criteria: beneficial and non-beneficial. Beneficial criteria are evaluated by the maximum value since higher values are associated with the better option. Non-beneficial criteria are evaluated by the minimum value since lower values are associated with the better option. Cost would be an example of a non-beneficial criterion because the least expensive option is the better option.

For a column of a beneficial criteria, each row was divided by the maximum value in the column. For a column of a non-beneficial criteria, each row was divided by the minimum value in the column. Then, each column was multiplied by their respective weights. Finally, each row was summed to produce a score for the respective alternative. The score could then be used to rank the alternatives with the highest score being the best. A sample of MCDA calculations is presented in Table 18. For this study, the criteria used to compare alternatives were material cost, mixing method, equipment cost, and performance.

Table 18. Sample MCDA Calculations

	Step 1: Setup matrix		Step 2: Divide by min or max		Step 3: Multiple by weight		Step 4: Sum score	Step 5: Rank scores
Alternative	Beneficial Criteria	Non-Beneficial Criteria	Beneficial Criteria	Non-Beneficial Criteria	Beneficial Criteria — Weight 0.75	Non-Beneficial Criteria — Weight 0.25	Score	Ranking
A	1	1	1	0.25	0.75	0.06	0.81	4
B	2	2	2	0.50	1.50	0.13	1.63	3
C	3	3	3	0.75	2.25	0.19	2.44	2
D	4	4	4	1	3.0	0.25	3.25	1

The TOPSIS method followed a list of sequential steps. Step 1 consisted of determining the normalized pairwise matrix, which was calculated using:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} {x_{ij}}^2}}$$

Where, x_{ij} is the row element and n is the number of elements in the row. Step 2 involved calculation of the weighted normalized matrix by multiplying the weights of the criteria obtained from the AHP using the following equation:

$$v_{ij} = \bar{x}_{ij} \times w_j$$

Where, w_j is the weight of the criteria, and v_{ij} is the value of the normalized element. Step 3 was then used to determine the positive and negative ideal solutions as follows:

$$v_j^+ = (v_1^+, v_2^+, \ldots, v_n^+) = (max v_{ij})$$

$$v_j^- = (v_1^+, v_2^+, \ldots, v_n^+) = (min v_{ij})$$

Where, v_j^+ and v_j^- are the positive ideal and negative ideal solution, respectively. The positive ideal solution maximizes the beneficial criteria and minimizes the non-beneficial criterial, while the negative ideal solution does vice versa. Step 4 consisted of calculating the Euclidean distance from the positive and negative ideal solution using the following equations:

$$S_i^+ = \left[\sum_{j=1}^{m} (v_{ij} - v_j^+)^2\right]^{0.5}$$

$$S_i^- = \left[\sum_{j=1}^{m}(v_{ij} - v_j^-)^2\right]^{0.5}$$

Where, S_i^+ is the Euclidean distance from the ideal best solution, and S^{i-} is the Euclidean distance from the ideal worst solution. The performance index, or relative closeness to the ideal solution, was calculated using the following equation:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

The additives for improving moisture resistance of HMA were ranked by decreasing order (i.e., the best alternative has the shortest distance from the positive ideal solution and vice versa).

4.1.4 Sensitivity Analysis

Each criterion had an assigned weight determined by AHP. However, some assumptions were made by the authors, using engineering judgement, in order to determine these weights by the AHP method. Therefore, a sensitivity analysis was conducted to evaluate the effect of criteria weighting on the alternatives' rankings. This was achieved by testing a range of weights of each of the criteria used in order to determine if the results were heavily influenced by the criteria weights. For example, the weight of the material cost criterion was adjusted within 20% of the original AHP weight of 35%, and the TOPSIS was re-performed using these weights. From weightages (a) to (e), the material cost weightage was incrementally increased by 10% (Table 19). For each 10% increase for the material cost weight, a 10% decrease was distributed amongst the other criteria. The additive mixing method and equipment cost weights were decreased by 3% while the performance weight was decreased by 4% to keep the percentages as whole numbers. The performance weight took the greater decrease since their starting value was much larger. Tables 19–22 outline the weights used for sensitivity analysis for each criterion.

Table 19. Material Cost Sensitivity

Criteria	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**
Material Cost	0.15	0.25	0.35	0.45	0.55
Equipment Cost	0.21	0.18	0.15	0.12	0.09
Mixing Method	0.16	0.13	0.1	0.07	0.04
Performance	0.48	0.44	0.4	0.36	0.32

Table 20. Mixing Method Sensitivity

Criteria	(a)	(b)	(c)	(d)	(e)
Material Cost	0.35	0.32	0.29	0.26	0.23
Equipment Cost	0.15	0.12	0.09	0.06	0.03
Mixing Method	0.1	0.2	0.3	0.4	0.5
Performance	0.4	0.36	0.32	0.28	0.24

Table 21. Equipment Cost Sensitivity

Criteria	(a)	(b)	(c)	(d)	(e)
Material Cost	0.38	0.35	0.32	0.29	0.26
Equipment Cost	0.05	0.15	0.25	0.35	0.45
Mixing Method	0.13	0.1	0.07	0.4	0.01
Performance	0.44	0.4	0.36	0.32	0.28

Table 22. Performance Sensitivity

Criteria	(a)	(b)	(c)	(d)	(e)
Material Cost	0.43	0.39	0.35	0.31	0.27
Equipment Cost	0.21	0.18	0.15	0.12	0.09
Mixing Method	0.16	0.13	0.1	0.07	0.04
Performance	0.2	0.3	0.4	0.5	0.6

4.2 Literature Analysis

The literature analysis included 89 articles, as previously stated. Evotherm M1, Zycotherm, hydrated lime, styrene-butadiene-styrene (SBS) polymer, nanoclay, and crumb rubber were the most common additives used in these articles for enhancing moisture resistance (Figure 23). Evotherm M1 and Zycotherm are warm mix additives (WMA) whereas hydrated lime, SBS, nanoclay, and crumb rubber are HMA additives. Since the current study focused on HMA, Evotherm M1 and Zycotherm (Figure 24) were excluded from the MCDA. In the 89 studies analyzed, indirect tensile strength (ITS) and tensile strength ratio (TSR) were the most common metrics used for evaluating moisture resistance of HMA (Figure 25). The most common mixing method for incorporating the additives into the HMA was using mechanical or shear mixers (Figure 26). The placement of the additive in the asphalt mixtures varied by study, however, most mixed the additive with the binder as presented in Figure 27.

Figure 23. Additives Used in the Literature to Improve Resistance of Asphalt to Moisture

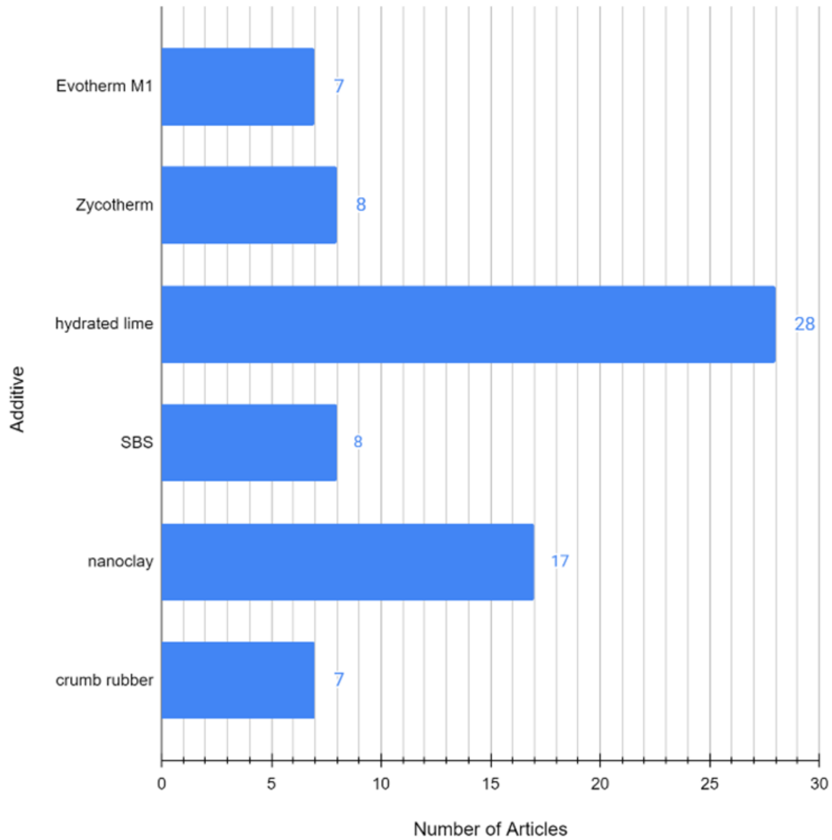


Figure 24. Types of Asphalt Mix Used in the Literature to Study Improvements in Resistance to Moisture-Related Damage

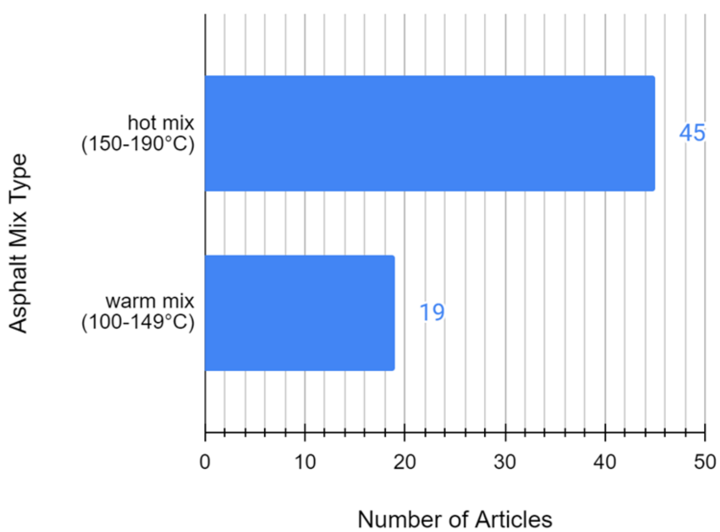


Figure 25. Indicator Parameters Used in the Literature to Evaluate Possible Improvement in Resistance of Asphalt Mixtures to Moisture Damage

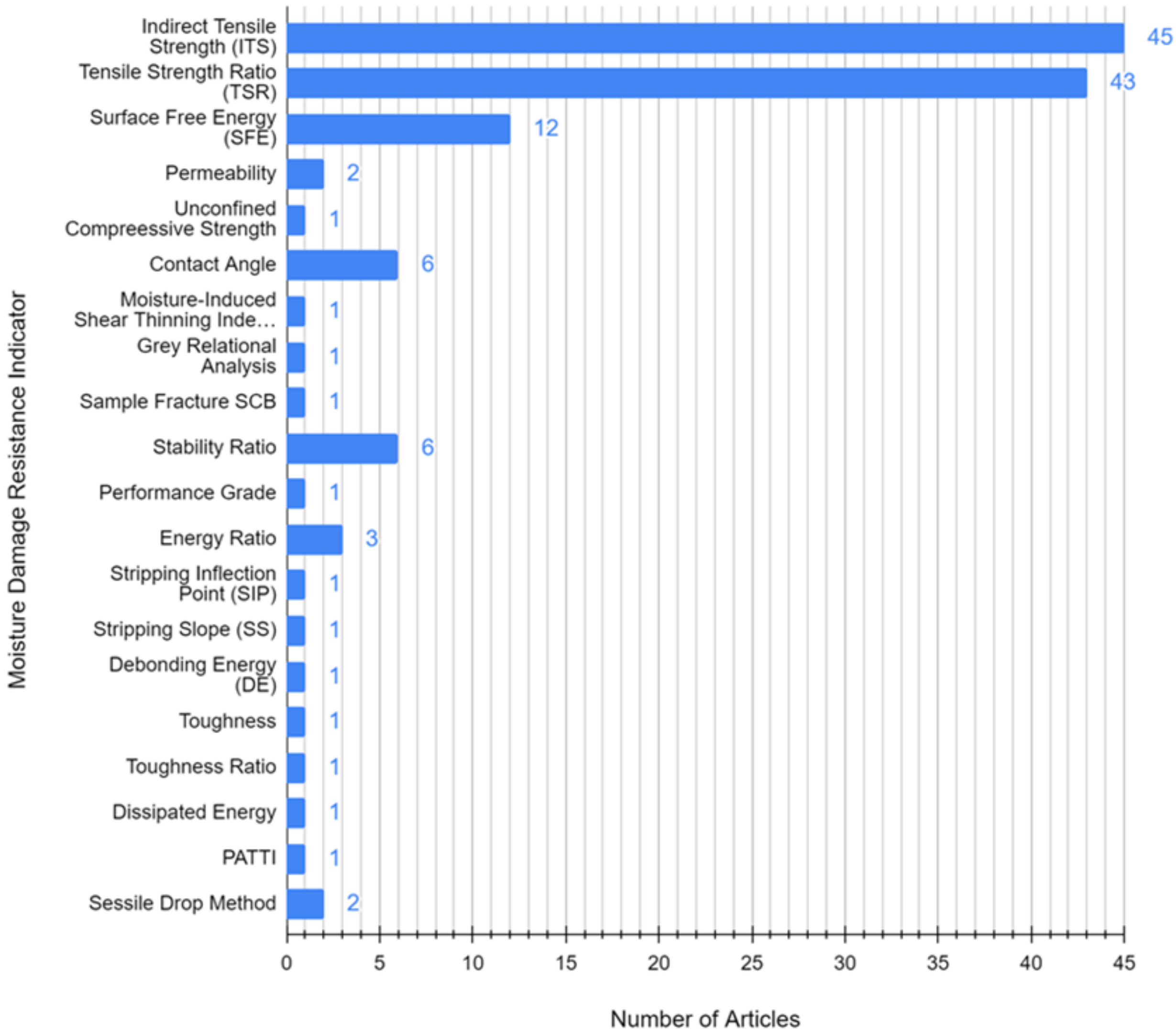


Figure 26. Mixing Methods Used in Literature to Mix the Additives with HMA

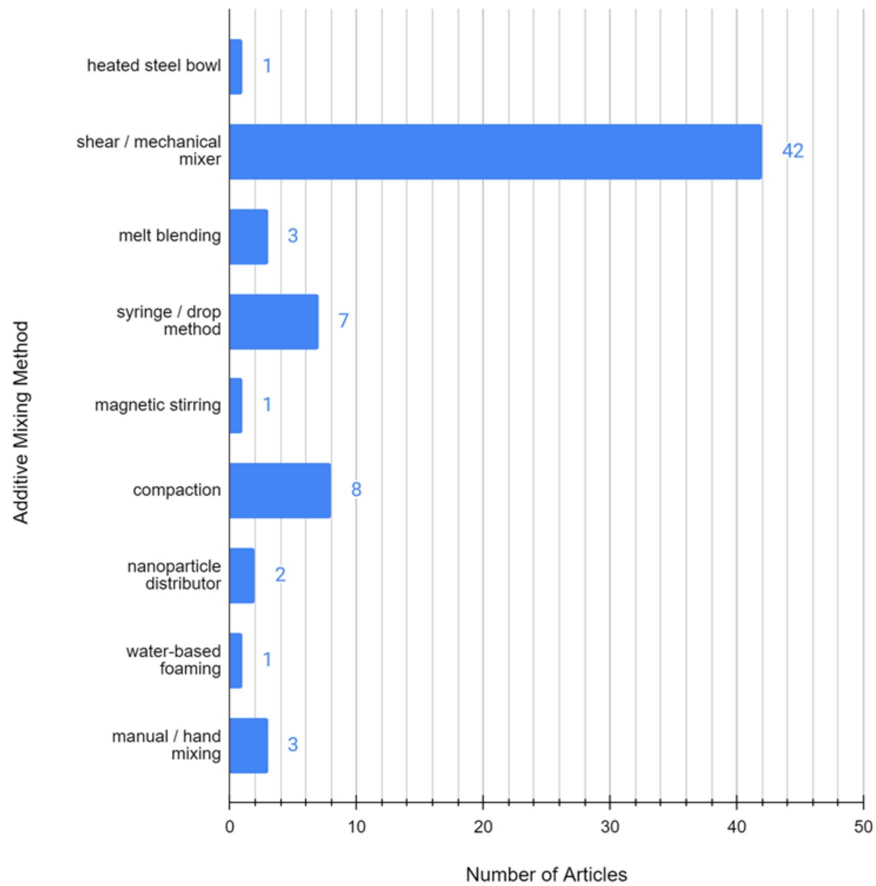
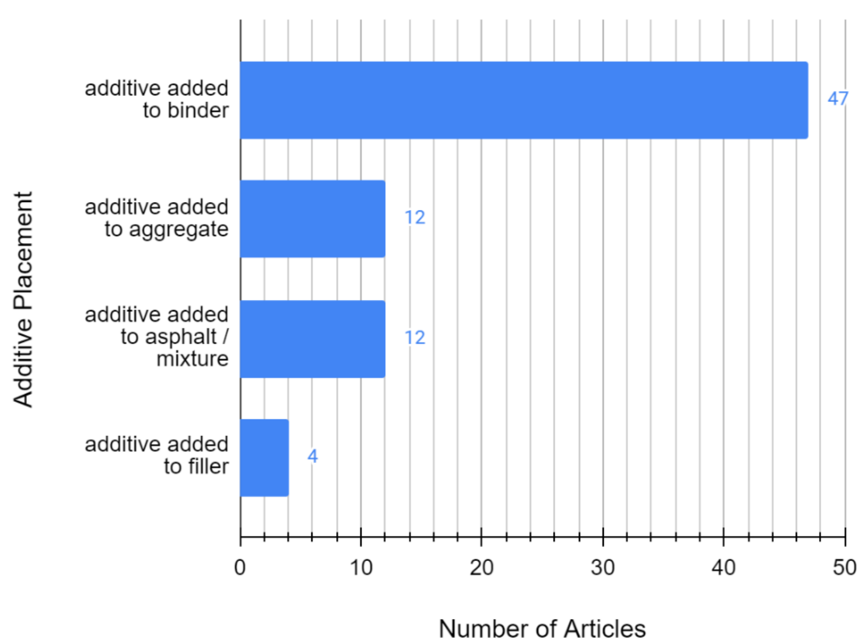


Figure 27. Placement of the Additives in the Asphalt Mixture



4.3 Multi-Criteria Decision Analysis Discussion

Following the scope of the current study, the material additives had to meet the following criteria to be considered in the subsequent MCDA: (a) be used in hot mix asphalt and added to the binder (not the aggregate), (b) the research article included information on the amount of additive and binder used, and (c) the article included TSR and ITS results. From the 89 literature articles analyzed, only 4 additives from 27 articles met these requirements: hydrated lime, SBS, nanoclay, and crumb rubber. The use of hydrated lime in this context includes both nano-hydrated lime and regular hydrated lime. SBS is a thermoplastic elastomer, a type of polymer with high elasticity. Nanoclay includes different forms of cloisite, bentonite, and montmorillonite (MMT). Crumb rubber, also known as ground tire rubber, is recycled rubber from tires. For the analysis of each alternative under each criterion, only the 27 articles that met all the MCDA selection requirements were used. These articles will be referred to as the selected articles throughout the report.

4.3.1 Material and Equipment Cost Analysis

Cost estimates were taken from accessible online resources. The material cost was calculated as the cost in USD per kg of asphalt mix, so it accounts for the additive amount and binder amount in the asphalt mix. This makes it possible to compare alternatives with regards to cost since the cost per gram of material may be misleading for the amount actually used in the mix. For nanoclay, the cost varied based on the type, so the material cost for each nanoclay article was calculated, and then the average cost for all selected articles was used in the MCDA calculations. Similarly, the equipment cost was the average equipment cost for all selected articles of a certain alternative. The equipment cost was estimated based on the sum of the cost of each piece of equipment used in the mix method in each specific article.

4.3.2 Mixing Method Analysis

The mixing method refers to the method used to mix the additive with the binder. From the 89 articles initially analyzed, the following mixing methods were identified: using a shear/mechanical mixer, melt blending, syringe/drop method, using a magnetic stirrer, compacting, using a nanoparticle distributor, water-based foaming, manual/hand mixing, and ball milling. To convert these mixing methods into a numerical rating, they were given a weight using the AHP method (Table 18). Higher relative importance was given to mixing methods that were more common and/or more efficient. For instance, mechanical mixing is more efficient than hand mixing, so mechanical mixing would have greater relative importance and, thus, a higher rating. The mixing method rating for each alternative is the sum of the weights of the mixing methods used for that alternative.

Table 23. Mixing Method Weights

Using a shear/mechanical mixer	0.42
Melt blending	0.06
Syringe/drop method	0.16
Using a magnetic stirrer	0.02
Compacting	0.20
Using a nanoparticle distributor	0.04
Water-based foaming	0.02
Manual/hand mixing	0.06
Ball milling	0.02

4.3.3 Performance Analysis

Performance in this context refers to the resistance of the asphalt mixture to moisture-related damage. The performance indicators used here were ITS and TSR. The research articles analyzed included ITS results for different conditions, including dry and wet conditions, unconditioned, conditioned, and aged conditions. For consistency, only ITS results presented for dry conditions, wet conditions, and unconditioned were used. For each alternative, the maximum TSR and ITS result for each alternative dose was recorded. The average TSR and ITS results for each alternative was used for MCDA calculations. ITS results were recorded in kPa while TSR results were recorded as a percentage.

4.3.4 MCDA Results

The four additives evaluated using MCDA for improving moisture resistance were hydrated lime, crumb rubber, SBS, and nanoclay. Overall, the MCDA ranked hydrated lime as the top option followed by crumb rubber, SBS, then nanoclay ranked fourth. The multi-criteria used for evaluation were additive material cost, equipment cost, mixing method, and TSR and ITS results. For performance (i.e., enhancing moisture resistance), nanoclay had the best average TSR (~85%) and the best average ITS (~1110 kPa). Although nanoclay had the best performance, it was a relatively expensive alternative, for both materials cost and equipment cost needed for achieving homogenous HMA mixtures. Material cost and equipment cost accounted for 50% of the total weight of the MCDA, so cost-efficiency had a major impact on the ranking of the alternative additives. The cost of nanoclay could reduce in the future provided the widespread use of nanoclay. It is noted that the HP Plus and LOF6500 additives that were experimentally evaluated in this research were not included in the MCDA because of the lack of ITS data to supplement the performance data needed for the MCDA. Nonetheless, according to results presented in this report, based on the experimental testing conditions used herein, the behavior of HP Plus and LOF6500 were comparable to those of nanoclay.

A sensitivity analysis was performed to evaluate the impact of assumptions made as part of the MCDA on the ranking of alternative additives for enhancing resistance to moisture damage of HMA. For each set of weights, two sets of MCDA calculations were performed, one with TSR as the performance metric, and the other with ITS as the performance metric. The weightages of the four criteria were varied in order to evaluate the consistency and validity of the MCDA results. Overall, the ranking remained mostly consistent, hydrated lime was the top among the four alternatives evaluated, with most changes occurring only once throughout the weightage changes.

Summary & Conclusions

This study evaluated the use of different additives (two nanoclay additives, lime slurry, and two liquid antistripping agents) to improve the resistance of HMA against moisture-induced damage. Using standardized testing procedures, aggregate was tested for specific gravity, absorption, abrasion resistance, void content, and gradation. Asphalt binder tests were conducted using a dynamic shear rheometer and a rolling thin film oven to first determine if the virgin binder used would meet Superpave mix design requirements. Second, these tests were used to determine how each additive interacted with the asphalt binder. For nanoclay additives, concentrations of 1%, 2%, 4%, and 6% were tested. One concentration of lime slurry (1.3%) treated aggregate that is typically used on the central coast was supplied by CalPortland. Concentrations of 0.25%, 0.50%, and 0.75% of HP Plus and LOF 6500 liquid antistripping agents were also tested. Overall, the mineral fillers had a stiffening effect on binder, while the liquid anti-stripping additives softened the binder.

The HMA was designed according to Caltrans gradation and Superpave mix design requirements. The optimum binder content was determined to be 5.75% of a medium gradation blend, which gave acceptable air void and specific gravity properties. Moisture sensitivity tests were then conducted on over 100 compacted asphalt specimens. Variations of all the additives were tested for indirect tensile strength before and after moisture conditioning. From these tests, optimum additive content was observed. Most additives were able to reduce moisture damage in the specimens to some degree.

5.1 Conclusions

The following conclusions can be drawn from the test results of this study:

- Nanoclays have a stiffening effect on the asphalt binder according to DSR test results. This was indicated by the increase in both elastic and viscous portions of the complex modulus.

- Higher concentrations of nanoclays further increase stiffness.

- The two types of nanoclays tested in this study exhibited the same effect on binder stiffness.

- The liquid anti-stripping additive had a softening effect on the binder. Generally, increasing the concentration further softened the binder.

- Liquid antistripping additive percentages higher than 0.5% resulted in significant reduction in binder stiffness below the minimum requirement specified by Superpave mix design.

- Additives tested in this study (except HP Plus) resulted in dry tensile strengths that were higher than that for control mix. However, all additives (including HP Plus) resulted in higher wet tensile strength than control mix.

- All mixes tested resulted in dry and wet tensile strengths that were higher than the minimum specified by Caltrans 2018 Standard Specifications (100 psi for dry tensile strength and 70 psi for wet tensile strength).

- Except for the 6% nanoclay02 mix, all HMA modified mixes exhibited TSR higher than 0.80 (the minimum specified by Superpave mix design). Also, all HMA modified mixes resulted in TSRs that were higher than the control mix.

- Optimum additive percentages resulting in maximum TSR were observed.

- TSR for HMA mixes modified using nanoclays were comparable to those for HMA mixes modified using liquid antistripping and lime slurry treated aggregate.

- Overall, liquid antistripping agents tested herein were the least costly additive.

5.2 Recommendations

- Tests were only conducted on one mix design, one type of aggregate, and one type of binder. Performance of anti-stripping additives will vary when any one of these mix components are changed. Investigating the effect any of these have on additive performance is recommended.

- Hydrated lime is currently being used in asphalt pavements on the central coast; however, liquid antistripping and nanoclays outperformed the performance of lime-treated mixes against moisture damage and could be tested in the field. Although the control mix passed Caltrans requirements, it did not pass the 80% TSR specified by the Superpave Mix Design. Future research should also test control mixtures that do not meet Caltrans requirements.

- Development of a testing standard or case studies to evaluate the performance of these additives in the field would further benefit asphalt pavement research.

- Evaluation of HMA that includes Recycled Asphalt Pavement (RAP) is recommended.

- TSR calculated as a ratio of the dry tensile strength of control mix is recommended to be used as an indicator for moisture resistance. $TSR_{normalized}$ compares the conditioned, modified mixes with the unconditioned/unmodified control mix. Normalization using the same denominator for all comparisons makes it a fairer comparison. Because the goal of this work is to improve the control by adding additives, all comparisons should be with the mix that is the target for improvement.

Appendix A

Table 24. Summary of the Literature on Additives for Improving Moisture Resistance of HMA

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Al-Khafaji et al., 2018	binder: 40/50; additives: Portland cement (5-6%), hydrated lime (1% of aggregate weight); nanomaterials: polypropylene fiber (1,2,3% of weight, thickness 18-30 micrometers, length 6-12 mm)	dry hydrated lime, wet polypropylene	ASTM D6927; AASHTO T209; SCRB R9; ASTM D4123	Marshall Test; Indirect Tensile Test (IDT); Immersion Compression Test	5-6% Portland cement by weight; 1% hydrated lime by weight; 1) 1% polypropylene by weight 2) 2% polypropylene by weight 3) 3% polypropylene by weight	1) increased IDT by 12-35% 2) increased IDT by 23-88% 3) increased IDT by 13-14%
Al-Tameemi et al., 2019	binder: 40-50; additives: limestone dust, hydrated lime	dry hydrated lime, dry limestone dust	SCRB R9; ASTM D6926, D1559, D4867; AASHTO T283, T321	Marshall Test; Moisture Susceptibility Test; Fatigue Test	5-7% limestone dust by weight; 1-3% hydrated lime by weight to replace limestone dust at intervals of one-half percent	higher hydrated lime content yields higher splitting tensile strength and greater improvements in tensile strength (both properties generally peaked between 2-2.5% hydrated lime before a decline at 3%)

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Ameli et al., 2020a	binder (AC-85/100), fiber (80% cellulose content, 1.1 mm fiber length, fiber thickness), polymer (SBR, Pasargad oil refinery), ASAs (liquid A: M5000, liquid B: M1, liquid C: LOF-6500), crumb rubber (7% GTR, -40 mesh)	wet mix, heated steel bowl, high shear, ASA blended with binder	National Cooperative Highway Research Pavement (NCHRP) Report No. 425, ASTM D5, ASTM D36, ASTM D113, ASTM D92, ASTM D70, AASHTO T283	Indirect tensile strength (ITS) test	2% SBR, 7% CR, 1) SR: 0% ASA, 2) SRA 0.2: 0.2% liquid A; 3) SRA 0.4: 0.4% liquid A; 4) SRA 0.6: 0.6% liquid A; 5) SRB 0.2: 0.2% liquid B; 6) SRB 0.4: 0.4% liquid B; 7) SRB 0.6: 0.6% liquid B; 8) SRC 0.2: 0.2% liquid C; 9) SRC 0.4: 0.4% liquid C; 10) SRC 0.6: 0.6% liquid C	addition of SBR, CR, and ASA increased ITS values compared to control; 5) highest ITS value
Ameli et al., 2020b	binder: 60-70; additives: cellulose fiber (.5mm thickness, 1mm length) OR styrene-butadiene-styrene (SBS); nanomaterial: montmorillonite nanoclay (1-2nm, 1-2% moisture content)	SMA, binder heated to 160 degrees C, high shear mixer used for 1h @ 5000prm during addition of SBS, MMT added, melt intercalation method at same speed and temperature for 1h, cellulose fiber added to SMA without SBS	National Cooperative Highway Research Program Report No. 425	Multiple Stress Creep Recovery Test	0 and 5% SBS by mass; 0, 2-5% MMT by mass of bitumen, 0.4% cellulose fiber by mass (only in mixture with 0% SBS)	addition of SBS decreased strain across all SMA mixtures; higher montmorillonite content yielded further decreased strain values

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Ameri et al., 2018	binder: 60-70; additives; hydrated lime; nanomaterials: Evonik and/or Zycotherm (both viscous liquids)	150 degrees C with mixer creating 2-3 cm deep vortex, nanomaterials added using syringe over 10min period, aggregates heated at 165 degrees C for 24h, binders added at different dosages	ASTM D1559, D3625, D4123-82; AASHTO T283	Texas Boiling Test; Indirect Tensile Strength modified Lottman test; Dynamic Creep test; Resilient modulus test	4-6% binder by weight of binder-aggregate composite (increasing at interval of one-half percent); 0.1%-0.3% Evonik and/or Zycotherm by weight of binder; 1-2% hydrated lime by weight of aggregates	Evonik and Zycotherm both reduced susceptibility to moisture damage with Zycotherm yielding the greatest reduction in moisture susceptibility; hydrated lime yielded greatest rutting resistance
Arabani et al., 2015	binder: 60-70 supplied by refinery in Tehran; nanomaterial: nanoclay (type unspecified); additives: SBS	short-term aged with thin film oven test, heated for 5h at 163 degrees C; additives and nanoclay added, then mixed at 28000 rpm for 20 minutes at 120-150 degrees C	101 Iranian Issue 10	Static Creep test; Scanning Electron Microscope; Fine Particle Homogeneous Scatter;	nanoclay added at 2, 4, 6, 8% by weight of bitumen; SBS added at 5% by weight of bitumen for all samples	Static creep decreased from 0 to 4% nanoclay, then strain increased from 4 to 8%, fatigue test concluded that nanoclay didn't have very good effect on fatigue performance
Ashish et al., 2016	binder: AC 10; nanomaterial: CLOISITE-30B nanoclay, collected from Southern Clay, Inc.;	CL-30B mixed with binder using high shear mixer, different size doses of nanoclay added at 155 +/- 5 degrees C for 2h period at 4000	ASTM D36, D5, D113, D2170, D92, D1754, D6521	X-ray diffraction; rutting resistivity; surface free energy method	CL-30B at 2, 4 and 6% of asphalt binder	For CL-30B of 2, 4, and 6%, rutting factor value increased by 21%, 108%, and 334% and SFE increased by 5.34%

Article	Material	Mixing Method	Standards	Tests	Amount	Results
		rpm; short term aging using Thin Film Oven for 5h at 163 degrees C; long term aging using Pressure Aged vessel for 20h at 2.1 MPa and 100 degrees C				
Behbahani et al., 2020a	binder: 60/70 provided by Isfahan refinery; nanomaterial: nano hydrated lime; aggregate: granite or limestone	hot mix, binder heated to 150 degrees C and then NHL poured slowly at 14000 rpm for 5 minutes	AASHTO T283; ASTM C127, C128, D854, C131, D4791, D5821, C88	AASHTO T283, indirect tensile strength test, SFE	NHL at 0.5 and 1% by weight of binder	Use of the NHL at 1% of binder weight had best increase in moisture resistance, increased the values of indirect tensile strength and tensile strength ratio
Behbahani et al., 2020b	aggregate: limestone; binder: PG 58-22; anti-stripping agent: NHL, SG = 2.24 g/cm3, pH of 12.4; deicing agents: calcium magnesium acetate (CMA), potassium acetate (PA), sodium chloride (NaCl)	Marshall mix design used; binder heated to 150 degrees C, then NHL added over 30-minute period at intervals; mixed at 6000 rpm	AASHTO T283, T245;	indirect tensile strength, indirect tensile fatigue, permeability, SFE	NHL at 0.5, 1, and 1.5% by weight of binder, 4.8% binder content used from Marshall method	CMA, NaCl and PA samples had total average decrease in resistance of 33%, 41%, and 51%; 1.5% NHL had the best improvements in ITS and TSR across all deicing agents and dry samples; CMA had the longest fatigue life, but use of NHL restored

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						fatigue life for other samples, especially NaCl
Chakraborty and Nair, 2018	calcium silicate hydrate; lime-soil slurries; quartz sand (IS 650:1991); bentonite clay	C-S-H samples synthesized in nitrogenous environment, for 3h above 85 degrees C, with magnetic stirring. Precipitates filtered with Whatman filter. Slurries were prepared by dry-mixing soil and lime, then with DI water, then cured at 28 degrees C for 3, 14, 28 and 60 days, then dried at 35 degrees C for 16h.	IS 650:1991; ASTM D6276-99a	unconfined compressive strength	optimum lime content for soil is 5%, 8% also used; soil used 40% bentonite clay and 60% quartz sand; see Table 1 for more precise reagent amounts	The soils with 5% lime showed a compressive strength of around 150 kPa greater than the 8% lime soils after curing periods of 3, 7 and 14 days. After 28 days of curing, the 8% lime soil showed a compressive strength that was about 200 kPa greater than the 5% lime soil, and at 60 days of curing, the 8% lime soil showed a compressive strength of about 4600 kPa, nearly double that of the 5% lime soil.
Chakravartyet al., 2020b	binder: VG-30 grade from Indian Oil, Barauni refinery; nanomaterial: 96% pure	HMA; high speed stirrer used for 30 minutes at 2500 rpm; ball milling used for 18 h at 300 rpm with	ASTM D5, D36; IS 73;	X-ray diffraction; transmission electron microscopy; atomic force	NHL at 5, 10, 15 and 20% by weight of bitumen	particle size of NHL estimated to be 40 nm; average diameter of NHL particles estimated to be 35 nm, agrees

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	hydrated lime from Merck Pvt	BPMR of 10:1 to produce NHL from stock HL;		microscopy		with results from X-ray diffraction
Zhu et al., 2019	binder (60/80, SK Corporation, Korea), crumb rubber (30-40 mesh, 0.55-0.28 mm, Xin-lei Mineral Powder Processing Plant, Hebei Province, China), ASAs (EVOTHERM M1, T9, AD-here LOF-6500)	hot mix; mechanical agitator; crumb rubber and ASAs interfused in virgin asphalt	Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) for AC-13 (Asphalt Concrete-13 Coarse); JTG F40-T 2005 (China Industry Standard 2004); Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-T 0702-2011)	Low temperature indirect tensile strength test (ITS); Freeze-thaw ITS test	12% crumb rubber by weight of virgin asphalt; 1) 0.25% M1 2) 0.50% M1 3) 0.75% M1; 4) 0.25% T9 5) 0.50% T9 6) 0.75% T9; 7) 0.25% LOF-6500 8) 0.50% LOF-6500 9) 0.75% LOF-6500	1-9) enhanced moisture resistance; 1,5,7) highest TSR value
Park et al., 2017	Asphalt binder (PG58-22); liquid ASA K1-7 (silane additive, amine type surfactant, stabilizer; different	powder added to aggregate; liquid added to binder	Tex -242-F	Screening test (boiling water test); indirect tensile strength test (ITS); Hamburg wheel tracking test (conventional	1) 0.5% K-3; 2) 0.5% K-6	1) 6.6% stripping; 2) 8.7% stripping; highest moisture resistance from K-3, K-6, W

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	proportions); commercial ASA W			method and curve fitting method)		
Oldham and Fini, 2020	asphalt binder (Superpave PG 64-22); bio-modified binder (BMB; bio-modifier made through hydrothermal liquefaction process of raw swine manure; hexadecylamide C16NOH33); AD1 (additive of synthetic paraffin wax (C26H54) with C40 to C115 carbon chain lengths); AD2 (additive derived from fatty amines (hexadecylamine C16NH35)); aggregate (Open Road Paving Co. LLC, CM16, FM 20 sand, FM02 sand, limestone	BM, AD1 and AD2 were blended into binder; 4.9% asphalt content; 4.0% air voids; 70 gyrations; control sample - hot mix; 5% BMB samples - warm mix	AASHTO TP 89; AASHTO 283	direct adhesion test (DAT); contact angle measurement; tensile strength ratio test; Hamburg wheel-tracking test	1) 1% paraffin wax (AD1); 2) 1% amine (AD2); 3) 1% amide; 4) 5% BMB; 5) 10% BMB	4) @ 0 hr 27% higher and @ 120 hr 260% higher failure strokes, 38% higher failure load, contact angle 48 degrees lower, improved moisture resistance index of 6.38, higher TSR; 5) @ 0 hr 179% and @ 120 hr 446% higher failure strokes, 38% higher failure load, contact angle 92 degrees lower, improved moisture resistance index of 2.26, higher TSR

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	mineral filler)					
Oldham et al., 2021	asphalt binder (PG58-28; Parco in Athens, New York); polyethylene terephthalate-based additive (PET; obtained from synthesis of waste PET water bottles and benzamide derivatives through an aminolysis process); sodium montmorillonite clay (MMT; Closite-Na+; particle size less than 25 micrometers; BYK USA Inc. in Gonzales, Texas); aggregate (Whitcomb Quarry in Colchester, Vermont)	MMT added to bitumen either by weight of bitumen, by filler weight, or by equivalent surface area of filler; Brunauer, Emmett and Teller (BET) instrument; hot mix with mechanical mixer	Vermont Department of Transportation; AASHTO T-324; AASHTO TP 91	contact angle moisture-susceptibility test; moisture-induced shear thinning index (MISTI); bitumen bond-strength test (BBS); boiling water test (BWT); Hamburg wheel-tracking test	6.0% binder content (5.0% virgin binder and 1.0% RAP); 0.5% WMA additive Rediset; 1) PET; 2) MMT 3) MMTwbf; 4) MMTsaf	1) lower contact angle, pull-off strength moisture-susceptibility index of 52.3%, 31.6% more resistant to change due to water, 88% MITSI; 2) lower contact angle, 21.7% more resistant to change due to water, pull-off strength moisture-susceptibility index of 42.4%, 93% MITSI, SIP value of 14,800; 3) SIP value of 14,100; 4) highest SIP value of 17,800
Das and Singh,	binder: VC-30 grade; additives:	planetary ball mill used for milling	AASHTO T361; ASTM D1754;	BBS test; Grey Relational	fillers at 0, 5, 10, 15 and 20% by	Pull-off tensile strength value of

Article	Material	Mixing Method	Standards	Tests	Amount	Results
2020	basalt stone dust, hydrated lime collected locally in Mumbai; nanomaterial: NHL milled from stock HL	NHL for 6 h at 250 rpm followed by 4 h at 200 rpm, size reduced from 17 microns to 220 nm; fillers first oven-dried at 110 +/- 5 degrees C for 24 hours; manually stirred; preheated filler and binder were mechanically mixed at 2500 rpm for 1 hour at 150 +/- 5 degrees C	IS 73	Analysis (GRA)	mass of binder; binder mixture at 1-2% of weight of dry aggregate	samples containing NHL is higher than samples containing stock HL; greater values of NHL yielded greater increases in POTS
Hesami and Mehdizadeh, 2017	asphalt binder (60-70 grade); ASAs (amidoamine, polyamine)	additives added by weight of binder; laboratory-prepared samples: high shear mechanical mixer; plant production conditions samples: hot mix, mechanical mixer, compaction, oven	AASHTO T11&T27; ASTM-D1559; AASHTO T-96; AASHTO T-176; ASTM D5821; AASHTO T-89; AASHTO T-104; AASHTO T182; AASHTO T228; AASHTO T49; AASHTO T53; AASHTO T51; AASHTO T48; AASHTO T201; AASHTO T44; AASHTO	AASHTO T283 test; indirect tensile strength ratio (ITS); sample fracture SCB	4.7% binder content; 1) 0.4% polyamine; 2) 0.6% polyamine; 3) 0.4% amidoamine; 4) 0.6% amidoamine; 5) 0-3 hrs storing mixture and 3-6 hrs storing modified asphalt at production temp	1) 82 TSR, 838.3 highest SCB, best case 16% reduction additive effect, best option when dosage pumps are used; 2) 87 TSR, 875.4 highest SCB, best case 22% reduction additive effect; 3) 64 TSR, 690.2 highest SCB, best case 31% reduction additive effect; 4) 68 TSR, 692.3 highest SCB, best case 41% reduction additive effect; 5) additives

Article	Material	Mixing Method	Standards	Tests	Amount	Results
			T283			had highest effects
Iskender, 2016	stone mastic asphalt gradation; aggregate (19 mm max size, basalt); asphalt binder (AC 50-70 PG); cellulose fiber (preventive filtration material for SMA design characteristics); nanoclays (used bentonite clays: nano-clay A; nano-clay B; nano-clay C; from Eskisehir-Kutahya, Eskisehir and Canakkale regions)	filler content was decreased by weight of total dry aggregate @ 2%, 3.5%, 5% ratios and nanoclays were added as 2%, 3.5%, 5% proportions in dry aggregate mixtures; Marshall Design	Turkish Board; AASHTO T283	Tensile Strength Ratio (TSR), stability ratio, indirect tensile strength ratio (ITS)	1) 2% nanoclay A; 2) 3.5% nanoclay A; 3) 5% nanoclay A; 4) 2% nanoclay B; 5) 3.5% nanoclay B; 6) 5% nanoclay B; 7) 2% nanoclay C; 8) 3.5% nanoclay C; 9) 5% nanoclay C	1) 0.96 stability ratio, 1.13 cond. 1 TSR [56.8% increase], 0.75 cond. 2 TSR [11.2% increase]; 2) 0.95 stability ratio, 0.94 cond. 1 TSR [18.8% percent increase], 0.83 cond. 2 TSR [4.9% increase]; 3) 0.91 stability ratio, 0.78 cond. 1 TSR [1.1% increase], 0.89 cond. 2 TSR [2.2% decrease]; 4) 0.88 stability ratio, 0.85 cond. 1 TSR [30.8% increase], 0.76 cond. 2 TSR [1.2% increase]; 5) 0.88 stability ratio, 0.85 cond. 1 TSR [18.3% increase], 0.84 cond. 2 TSR [5.5% decrease]; 6) 0.72 stability ratio, 0.68 cond. 1 TSR [24.1% decrease], 0.87 cond. 2 TSR [25.4% decrease]; 7)

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						0.88 stability ratio, 0.73 cond. 1 TSR [8.7% increase], 0.72 cond. 2 TSR [12.7% increase]; 8) 0.84 stability ratio, 0.55 cond. 1 TSR [6.0% decrease], 0.70 cond. 2 TSR [0.0% increase]; 9) 0.78 stability ratio, 0.55 cond. 1 TSR [24.2% decrease], 0.88 cond. 2 TSR [5.9% increase]
Ezzat et al., 2020	nanomaterials: nanoclay with active mineral montmorillonite (NMMT), nano silicon dioxide (NSD); binder: PG 52-xx from Al Nasr Oil, Suez; aggregate: limestone CA, sand FA; additive: limestone	HMA blended with 3, 5, 7% of each nanomaterial with mechanical mixer at 1500 rpm and 145 +/- 5 degrees C for 1h, short-term aged in a rolling thin film oven;	ASTM D2872	changes in binder performance grade due to addition of nanomaterials	optimum binder content found to be 5.5%, air void content was about 7%; 3, 5, and 7% of each nanomaterial	Optimum quantity of various nanomaterials was 3% for NMMT (performance grade increased to PG 64-xx, but decreased again after increasing NMMT content to 5%) and 7% for NSD (performance grade increased to PG 70-xx)
Mansour and Vahid, 2016	bitumen (PG 85/100); aggregate (max	Not mentioned directly	ASTM D3625; AASHTO T 283	Boiling water test; indirect	1) 2% hydrated lime; 2) 0.1% zycosoil; 3) 0.3%	1) 79.03 TSR; 2) 80.11 TSR; 97% coating retained; 3)

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	size 19 mm; Hamedan city mines in Iran); zycosoil (organo-silicon combination for hydrophobic surface); hydrated lime			tensile strength	zycosoil; 4) 0.5% zycosoil	82.66 TSR; 98.5% coating retained; 4) 90.73 TSR; 99% coating retained
Gedafa et al., 2019	binder: PG 58-28, PG 64-28; aggregate: Reclaimed Asphalt Pavement from Grand Forks County by Strata Company (PG 58-28) and from Knife River materials (PG 64-28); nanomaterials: Cloisite 20 nanoclay and Nanoalumina	HMA based off AASHTO MP2; mixed using Superpave Gyratory Compactor following AASHTO T312; air void content determined using trial and error	AASHTO MP2; AASHTO T312; AASHTO T340; ASTM D7313	Asphalt Pavement Analyzer for rutting behavior, Semi-Circular Bending for fatigue cracking potential, Disk-shaped Compact Tension for low-temperature cracking potential	PG 58-28 5.8% by aggregate weight, PG 64-28 5.4% by aggregate weight. See table 1 for percents of aggregates; target air void percentage was 7 +/- 0.5%; HMA specimen height was 75 mm. Nanomaterials present in 0, 1, 5, and 7% quantities	For both PG grades, nanoclay decreased rutting depth as quantity of nanoclay increased. Nanoalumina decreased rutting depth up to 5%, but then increased rutting depth from 5-7%. Nanomaterial content did not have a significant change in fatigue crasking performance. For Low-temperature cracking performance test, results were inconclusive due to limited number of specimens.

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Hamedi and Tahami, 2018	aggregate (limestone; granite); bitumen (60/70 PG); zycosoil (additive; 45-50 specific gravity; pale yellow color; 0.2-0.8 Pa.s viscosity @ 25 degrees C)	zycosoil added by weight of bitumen; Marshall mix design	ASTM D1559; MS-2 Asphalt Institute; AASHTO T283	Modified Lottman test; surface free energy (SFE)	1) 2% zycosoil; 2) 4% zycosoil	1) high 80 TSR/low 50 TSR w/ limestone aggregate, high 75 TSR/low 49 TSR w/ granite aggregate, 21.91 ergs/cm2 total component; 2) high 90 TSR/low 55 TSR w/ limestone aggregate, high 76 TSR/low 63 TSR w/ granite aggregate, 23.35 ergs/cm2 total component (overall 4% had better results)
Ghabchi et al., 2021	binders: PG 70-28 and PG 76-28 (modified with SBS), PG 58-28 and PG 64-22 (unmodified); aggregates: limestone, granite, sandstone (locally collected); fillers: chemical WMA additive (amine-based), ASA (amine-based),	binders mixed between 145 and 175 degrees C depending on binder grade. Mixed with a High Shear Mixer at 1000 rpm for 45 minutes, aged using a rolling thin-film oven; long-term aged with pressure aging vessel;	AASHTO M 323, R35, T240, R28, T315, T313, T324, T283	dynamic shear rheometer used for determining Superpave temperature, rutting factor at high temperature, fatigue factor; bending beam rheometer used for flexural stiffness and creep compliance; Hamburg Wheel Tracking; Tensile	.5% WMA additive; .5, 1, 1.5, 2% PPA; .5% ASA;	rutting factor of PG 58-28 increased with WMA additive and by increasing PPA content across all testing temperatures

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	PPA (75.9% of P2O5)			Strength Ratio		
Behbahani et al., 2015	aggregate (continuous type IV scale); asphalt binder (60/70 PG, Isfahan mineral oil refinery); glass cullet (glass aggregate; waste glass of a glass industrial production company; max size 4.75 mm); nanotechnology zycosoil (ASA; organosilane compound that forms silanols groups which form siloxane bonds with surface silanol groups of inorganic surface)	hot mix (oil bath heated by a hot plate); zycosoil added by weight of binder (manual blended then mixed with mechanical stirrer); glass particles added by weight of aggregate	AASHTO; ASTM C 127; ASTM C 128; ASTM D854; ASTM C 131; ASTM D 4791; ASTM C 88; ASTM D2726; ASTM D1559; ASTM D2041; EN 12697-26 Annex C; ASTM D4123	indirect tensile modulus test (ISTM); creep test, modified Lottman test	5.5% binder content for conventional mix; 5.1% binder content for glasphalt mix; 10% glass particle content; 1) 0.5% zycosoil; 2) 2.5% zycosoil; 3) 4.5% zycosoil	1) @ 5 degrees C 5000 MPa [0.4% increase], @ 25 degrees C 1700 MPa [42.3% increase], @40 degrees C 800 MPa [18.6% increase], @ 200 KPa 0.012 mm/mm, @ 500 KPa 0.039 mm/mm, 71.00 TSR; 2) @ 5 degrees C 5400 MPa [8.1% increase], @ 25 degrees C 1900 MPa [63.8% increase], @40 degrees C 1000 MPa [59.2% increase], @ 200 KPa 0.007 mm/mm, @ 500 KPa 0.018 mm/mm, 80.00 TSR [8.6% increase]; 3) @ 5 degrees C 5900 MPa [16.9% increase], @ 25

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						degrees C 2100 MPa [91.4% increase], @40 degrees C 1400 MPa [114.5% increase], @ 200 KPa 0.004 mm/mm, @ 500 KPa 0.008 mm/mm, 89.00 TSR [21.3% increase]
Sanij et al., 2019	aggregate (continuous gradation No. 4); filler (from used aggregates passing sieve number #200 0.075 mm); bitumen (60-70 PG); crushed glass (waste of glass production factory; max size 4.75 mm); zycotherm (nanotechnoogy product)	warm mix; zycotherm added by weight of bitumen (mixed with bitumen in mechanical stirrer using 1-ml syringe); glass added by weight of aggregates (Los Angeles abrasion machine used to crush glass)	Iran highway asphalt paving code for Topeka layer; ASTM C127; ASTM C128; ASTM C88; ASTM C131; ASTM T176; BS-812; ASTM D5; ASTM D113; ASTM D70; ASTM D36; ASTM D92; ASTM D4402: ASTM D2726; ASTM D1559; ASTM D2041	resilient modulus test, creep test, moisture susceptibilty (modified Lottman) test	10% glass content; 1) 0.05% zycotherm/5.20% binder content; 2) 0.10% zycotherm/5.14% binder content; 3) 0.15% zycotherm/5.11% binder content; 4) 0.20% zycotherm/5.0% binder content	1) 71 TSR, 1645 MPa, 829 flow [34.3% decrease]; 2) 76 TSR, 2012 MPa, 1192 flow [5.6% decrease]; 3) 81 TSR [10.95% increase], 2411 MPa, 1443 flow [14.2% increase]; 4) 84 TSR [15.06% increase], 2440 MPa, 1420 flow [12.4% increase]
Hamedi, 2019	binder: 60-70 from Isfahan	binders mixed in a mixer at 600 rpm	AASHTO T283,	rutting potential test, moisture	optimum bitumen content	both types of anti-stripping liquids

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	refinery; aggregates: limestone and granite; additives: antri stripping liquids (additive A - alkyl amine family with polar properties, additive B - amido-amines famile with non-polar properties)	for 20 minutes while adding additives in .1% and .2% quantities by mass of binder. binder is heated to 150 degrees C before mixing	T269	damage sensitivity (AASHTO T283), fatigue test	was 5.5% for granite aggregates and 5.7% for limestone aggregate. Additives at .1% and .2% of mass of binder, 7% air voids	increased indirect tensile strength and tensile strength ratio; using 0.2 additive B by mass of binder yielded the highest increase in indirect tensile strength
Hamedi and Tahami, 2018	nanomaterials: organic montmorillonite A (OMMT A), organic montmorillonite B (OMMT B), calcined-layered double hydrotalcite (LDH)		Marshall method to determine optimum asphalt ratio; JTGE20-2011; JTGF40-2004	Surface free energy test; atomic force microscopy; freeze-thaw splitting test		
Nejad et al., 2016	aggregates: limestone and granite sources from Makadam and Ghiam Dasht mines of Tehran; binder: 60/70 from	binders mixed using a "nano particle distributor" device that rotated at 14000 rpm for 4-5 minutes at 130-140 degrees C for a batch with	ASTM C88, C127, C128, C131, C1252, D854, D4791; AASHTO T283	tensile strength ratio	optimum asphalt binder content was 5.6 and 5.1% for limestone and granite, respectively; Nano ZnO added at 2 and	The use of nano Zinc Oxide decreased the acidity of the asphalt binder, which increased the adhesion between binder and

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	Isfahan refinery; nanomaterial: nano Zinc Oxide	diameter and height of 15cm and 30 cm respectively.			4% by weight of asphalt binder. Air void content of compacted specimens should be between 6.5 and 7.5%	aggregate, especially in wet conditions; significant improvements in indirect tensile strength; limestone aggregate samples had better resistance to moisture damage than granite samples
Hamedi et al., 2015	binder: 60/70 from Isfahan refinery; limestone and granite aggregates; nanomaterial: nano Calcium Carbonate	nanoparticle distributor used for 4-5 minutes at 14000 rpm from 140-150 degrees C,	ASTM D1559; AASHTO T283	modified Lottman test, surface free energy test	optimum asphalt binder content was 5.6 and 5.1% for limestone and granite, respectively; nano CaCO3 added at 2, 4 and 6% of binder weight.	greater addition of nano CaCO3 resulted in greater increases in tensile strength ratio;
Ziari et al., 2019	aggregate (limestone); bitumen (PG 60-70); Ground Tire Rubber (GTR; additive; passing sive No. 100); amorphous carbon power (ACP; paraffin wastes; filler;	hot mix; rubber powder mixed with bitumen using low shear mixer then high shear mixer (GTR added by weight of bitumen); ACP added by weight of filler; Superpave	ASTM D1559; AASHTO T96; ASTM D5821; AASHTO T182; BS-812; AASHTO T176; AASHTO T84	resilient modulus test; indirect tensile strength; modified lottman test; wheel tracking test	1) 8GTR + 25ACP (5.1OBC); 2) 8GTR + 50ACP (5.1OBC); 3) 8GTR + 75ACP (5.1OBC); 4) 12GTR + 25ACP (5.2OBC); 5) 12GTR +	1) 3000 MPa, 860 TSR ; 2) 3750 MPa, 1020 TSR; 3) 3600 MPa, 660 TSR; 4) 4100 MPa, 650 TSR; 5) 4950 MPa, 750 TSR; 6) 4800 MPa, 390 TSR; 7) 4500 MPa, 450 TSR; 8) 5550 MPa, 550 TSR; 9)

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	passing through sive No. 200; nano-roughness texture w/ hydrophobic property)	gyratory compactor			50ACP (5.2OBC); 6) 12GTR + 75ACP (5.2OBC); 7) 16GTR + 25ACP (5.4OBC); 8) 16GTR + 50ACP (5.4OBC); 9) 16GTR + 75ACP (5.4OBC)	5525 MPa, 200 TSR
Omar et al., 2018	binder (60/70 PG); nanoclay (halloysite nano-tube composed of double layers of alumina, silicon, hydrogen, and oxygen; outer diameter of 30-70 nm; length of 460-640 nm); aggregate (Cenco Sains Company in Malaysia; granite is hydrophilic; mix design D-5; max size of 19.00	nanoclay added by weight of bitumen; hot mix; mechanical mixer; bitumen poured into can and heated to 150 degrees C for 1 hr until fluid; additive heated at 100 degrees C for 4 hrs to dehydrate; additive gradually added at 500 rpm until blended for 3-5 min then raised at 2000 rpm for 2 hrs	ASTM D2872; ASTM D6521; ASTM D3515; AASHTO T312; PP-28-200; AASHTO R 35; ASTM D5; ASTM D36; ASTM D4402; ASTM C: 131-81; BS 812; AASHTO T33; AASHTO 176; ASTM C88; ASTM D3625; EN 12272-3	boiling water test; vialit adhesion of the bitumen; surface free energy; contact angles of the binders; indirect tensile strength (ITS); energy ratio	200 +/- 10 g bitumen; 1) 2% nanoclay (2NCMB); 2) 4% nanoclay (4NCMB)	1) less stripping than both control and 4%, 2 days 92% aggregate retention, 5 days 96% aggregate retention, 18 days 95% aggregate retention, unaged 1.58 energy ratio, STA 1.61 energy ratio, LTA 1.61 energy ratio, unaged 86 TSR, STA 90 TSR, LTA 97 TSR; 2) less stripping than control, 2 days 83% aggregate retention, 5 days 95%

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	mm)					aggregate retention, 18 days 91% aggregate retention, unaged 1.16 energy ratio, STA 1.60 energy ratio, LTA 1.70 energy ratio, unaged 79 TSR, STA 98 TSR, LTA 99 TSR
Hesami and Mehdizadeh, 2017	binder: 60-70 grade (4.7% optimum); anti-stripping additives: amine-based liquids (polyamine and amidoamine)	additives were mixed with asphalt binder using a high shear mechanical mixer around 30 minutes before mixing the asphalt samples	AASHTO T283; ASTM D1559; BS 812; AASHTO T96; AASHTO T176; AASHTO T89; ASTM D5821; AASHTO T104; AASHTO T182; AASHTO T228; AASHTO T49; AASHTO T53; AASHTO T51; AASHTO T48; AASHTO T201; AASHTO T44	AASHTO T283 (Tensile strength ratio)	.4% and .6% of both additives tested as a percent of weight of binder; optimum binder content determined to be 4.7% from Marshall test	TSR results: Control - 51; 0.4% amidoamine - 64; 0.6% amidoamine - 68; 0.4% polyamine - 82; 0.6% polyamine - 87

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Abandansari and Modarres, 2017	aggregates (limestone; granite; nominal gradation size 19.0 mm); polymer-clay nano-composite (SBS polymer nano-composite); bitumen (60-70% penetration, PG 64-22, Isfahan Refinery Plant)	Marshall mix design; SBS added by weight of bitumen; hot mix; mechanical mixer; bitumen first heated to 160 degrees C then SBS mixed in at 8000 rpm for 6 min	ASTM D1559; ASTM C 127; ASTM C 128; ASTM D854; ASTM C 131; ASTM D 4791; ASTM C 88; ASTM C 1252; AASHTO T283; AASHTO T269	indirect tensie-strength (ITS) test; surface free energy (SFE); contact angle	5.5% binder content for limestone; 5% binder content for granite; 1) 2% SBS; 2) 4% SBS	1) granite [uncond 1050 kPa, 1 cycle 850 kPa, 3 cycle 810 kPa, 5 cycle 725 kPa], limestone [uncond 1150 kPa, 1 cycle 1025 kPa, 3 cycle 975 kPa, 5 cycle 875 kPa], 96.74 contact angle w/ water, 21.94 total SFE; 2) granite [uncond 1250 kPa, 1 cycle 1100 kPa, 3 cycle 1090 kPa, 5 cycle 1000 kPa], limestone [uncond 1210 kPa, 1 cycle 1125 kPa, 3 cycle 1075 kPa, 5 cycle 1000 kPa], 92.61 contact angle w/ water, 26.77 total SFE
Iwanski, 2020	binder: 50/70 PG; additive: fatty acid amine-based SAA; aggregate: AC-8 graded mineral mixture	Marshall hammer used to determine air void content; binder foamed using water-based foaming	AASHTO T283; WT-2; EN 13108-1; EN 12697-8	Tensile Strength Ratio	air voids: 6-8%; SAA added in 0.6% by weight of binder; foaming water contents: 1.5, 2, 2.5, 3, 3.5% by weight; foamed	1A: ITSd 1122.4 kPa, ITSw 1074.0 kPa; 2A: ITSd 1102.6 kPa, ITSw 1065.3 kPa; 3A: ITSd 1060.4 kPa, ITSw 1041.7 kPa; 4A: ITSd 1016.9

Article	Material	Mixing Method	Standards	Tests	Amount	Results
					bitumen added in 5.6 (1), 5.9 (2), 6.2 (3), and 6.5% (4) by weight; hydrated lime added at 0% (A), 15% (B), 30% (C), and 45% (D) as filler to replace lime	kPa, ITSw 1018.6 kPa; 1B: ITSd 1185.7 kPa, ITSw 1143.1 kPa; 2B; ITSd 1143.6 kPa, ITSw 1124.3 kPa; 3B: ITSd 1091.9 kPa, ITSw 1102.8 kPa; 4B: ITSd 1048.8 kPa, ITSw 1086.9 kPa; 1C: ITSd 1109.1 kPa, ITSw 1076.1 kPa; 2C: ITSd 1173.1 kPa, ITSw 1243.9 kPa; 3C: ITSd 1124.1 kPa, ITSw 1200.2 kPa; 4C: ITSd 1072.6 kPa, ITSw 1172.0 kPa; 1D: ITSd 1058.0 kPa, ITSw 1007.9 kPa; 2D: ITSd 1154.1 kPa, ITSw 1136.5 kPa; 3D: ITSd 1087.8 kPa, ITSw 1081.6 kPa; 4D: ITSd 1051.7 kPa, ITSw 1072.6 kPa
Wang et al., 2018	aggregates (AC-20 Dense Grade Asphalt	PE added by weight of mixture; warm mix and hot	AASHTO T 313-12; AASHTO T	wheel tracking test; indirect tensile strength	4.2% asphalt binder content; 1) SMA-13; 2)	1) LMLC: dry 1.30 MPa, cond 1.10 MPa, 90% TSR,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	Concrete; SMA-13 Stone Matrix Asphalt Concrete); ASA Portland cement P.O 42.5); binder (PG 76-22 SBS modified); PE additive (Polyurethane fiber); ARA additive (anit-rutting agent); Evotherm M1 (WMA technology to reduce energy consumption and GHG emission)	mix; mechanical mixer; Evotherm M1 added by weight of mixture; Marshall design method; Laboratory-mixed and Laboratory-Compacted (LMLC); Plant-mixed and Laboratory-compacted (PMLC); Plant-mixed and Field-compacted (PMFC); ARA and PE were mixed with SBS at 180 degrees C and 25000 rpm for 1 hr then stored at 150 degrees C for 1 hr	240-13; AASHTO R 28-12; T 0625-2011; T 0705-2011; T 0709-2011; AASHTO T 324; T 0729-2000; T 0715-2011; AASHTO T 315-12	(ITS) test; 3-point bending test; permeability coefficient test	AC-20	PMLC: dry 1.05 MPa, cond 0.90 MPa, 95% TSR, PMFC: dry 2.20 MPa, cond 1.60 MPa, 75% TSR; 2) LMLC: dry 1.75 MPa, cond 1.50 MPa, 80% TSR, PMLC: dry 1.60 MPa, cond 1.45 MPa, 90% TSR, PMFC: dry 1.80 MPa, cond 1.75 MPa, 100% TSR
Li et al., 2021	binder (PG 64-22); aggregates (J: quartz and potassium feldspar; L: metamorphic rock; South Carolina; nominal max size 12.5 mm);	Superpave Gyratory Compactor (SGC); mixing temp 153 degrees C; compaction temp 145 degrees C	South Carolina Department of Transportation (SCDOT); AASHTO T 378; AASHTO R 83; AASHTO T 324	Hamburg Wheel-Track (HWT); Stripping Inflection Point (SIP); Stripping Slope (SS)	Surface Type B: 23% RAP, 20% natural sand, 1% ASA; Surface Type C: 27% RAP, 20% natural sand, 1% ASA; 1) BJA0; 2) BJA1; 3) BJA2; 4) BLA0;	1) post-compaction rut depth 0.308 mm, HWT max rut depth 1.0345 mm; 2) post-compaction rut depth 0.208 mm, HWT max rut depth 0.885 mm; 3) post-compaction rut depth 0.220 mm,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	natural sand source; RAP materials; ASAs (A0: hydrated lime; A1: liquid ASA, fatty amidoamine; A2: liquid ASA, polyamines, alkyl amines)				5) BLA1; 6) BLA2; 7) CJA0; 8) CJA1; 9) CJA2; 10) CLA0; 11) CLA1; 12) CLA2	HWT max rut depth 0.9545 mm; 4)post-compaction rut depth 0.365 mm, HWT max rut depth 1.175 mm; 5) post-compaction rut depth 0.311 mm, HWT max rut depth 1.4125 mm; 6) post-compaction rut depth 0.340 mm, HWT max rut depth 0.8655 mm; 7) post-compaction rut depth 0.616 mm, HWT max rut depth 1.249 mm; 8) post-compaction rut depth 0.592 mm, HWT max rut depth 1.1095 mm; 9) post-compaction rut depth 0.698 mm, HWT max rut depth 6.517 mm, SIP 14863 passes, SS 72.92*10^-5 mm/passes; 10) post-compaction rut depth 0.863 mm, HWT max rut depth 1.9705 mm; 11) post-

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						compaction rut depth 0.680 mm, HWT max rut depth 2.8965 mm; 12) post-compaction rut depth 0.861 mm, HWT max rut depth 3.0275 mm, SIP 16,756 passes, SS 35.45*10^-5 mm/passes
de Melo et al., 2018	asphalt binder (58-22 PG); organophilic nanoclay (500 nm); aggregrate (basaltic mineral origin; nominal size 19 mm); hydrated lime (CH-I; dolomitic)	nanoclay added by weight f binder; high shear mixer at 5000 rpm	AASHTO M 303	Lottman test; wheel tracking test	4.35% binder content; 1) 3% nanoclay	1) 100% TSR, 0.675 MPa average dry strength, 0.68 MPa average wet strength, 5.6% rutting at 30,000 cycles, 39% reduction in permanent deformation
Bindu, et al. 2020	binder: NRMB-70; aggregates: 20, 10 and 6mm; filler: passing through 0.075mm Indian Standard sieve; additive: cashew nut shell liquid	both HMA and WMA prepared; binder contents and mixing temperatures are 5.27 and 5.2% and 160 and 140 degrees C respectively; air	AASHTO T283	ITS test	5.27% and 5.2% of RHMA and RWMA binders	RHMA avg TSR: 85.9%; RWMA avg TSR: 97.5%

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	(CNSL)	void content is 7 +/- 0.5%				
Tang et al., 2019	base asphalt (Inman PG 64-22 from southeast area of USA); ASAs (MORLIE 5000 [M5000]; EVOTHERM M1 [M1]; AD-here LOF-65-00 [LOF-6500]); crumb rubber (40 mesh; 0.425 mm; processed under ambient conditions)	melt blending method; 1st: base asphalt heated until flowing; 2nd: crumb rubber and ASA added with mechanical mixer, 177 degrees C, 1000 rpm, 30 min; 3rd: aged in rolling thin film oven (RTFO) and pressure aging vessel (PAV)	ASTM D 2872; ASTM D 6521; ASTM D 4402; ASTM D 7175; ASTM D 7405; ASTM D 6648			N/A
Khedaywi and Al Kofahi, 2019	binder: 60/70 from Jordan Petroleum Refinery Company; aggregate: valley gravel (uncrushed) from Jordan Valley quarries, limestone (crushed) from Shatana quarries, basalt (crushed)	aggregate oven dried, then mixed with binder and then cooled at room temperature for 24 hours	ASTM D3625, Rolling Bottle test standard,	boiling water test, rolling bottle test	boiling water: 100g aggregate, binder 5% by weight of aggregate; rolling bottle: 150g aggregate, binder 3.5% by weight of aggregate	limestone is a strip-resistant aggregate; additives all reduced stripping within every mixture; lime additive was a stronger anti-stripping agent than polyamine liquid

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	from Wadi Al-Mojib quarries; additives: hydrated lime (local), polyamine (Morelife); moderate or high saturation conditioning					
Lopez-Montero et al., 2018	aggregate: granite; filler: limestone; binder: 35/50; nanomaterials: hydrophilic bentonite and iron nanoparticles	high speed stirrer used to mix nanomaterials with binder at 4% by weight of modified binder. samples aged using TEAGE and LTOA	EN 12697-12; EN 12697-30; EN 12697-6; EN 12697-5	indirect tensile strength	nanomaterials added to binder at 4.5% by weight of binder-nanomaterial mixture; binder content 4.5% by weight of mixture	nano-Fe samples had highest tensile strength ratios by around 20% minimum increase
Dalhat, 2021	SBS modified asphalt substrate (PG 76-10); recycled polypropylene (RPP; collected based on recycled label #5; less than 3 mm size; two mesh sizes: #80 177 micrometers, #100 149	hot blend radial-type-SBS with 64-16 fresh asphalt binder at 180 degrees C for 1 hr at 3000 rpm high shear mixing; molten asphalt at 165 degrees C was thoroughly stired with metallic spatula for 3 min, then poured in to 2	ASTM D113; ISO 25178; ASTM D7334	water contact angle (WCA); work of adhesion (WA)	4% radial-type-SBS; 1) Mesh #80; 2) Mesh #100	1) 25 min curing [152.7 degrees, max 156.6 degrees, 129.2 degrees after 12 months, 8.15 +/- 1.22 nM.m^-1 before, 26.76 +/- 1.66 nM.m^-1 after], 40 min curing [154.6 degrees, max 162.1 degrees, 143.5 degrees after 12

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	micrometers)	mm thick silicon mold to form asphalt substrate; asphalt substrate treatment with milled and sieved RPP then placed in 100 degrees C oven				months, 7.24 +/- 2.18 nM.m^-1 before, 14.37 +/- 0.26 nM.m^-1 after], 55 min [156.0 degrees, max 165.1 degrees, 153.8 degrees after 12 months, 6.50 +/- 2.15 before, 7.45 +/- 0.29 nM.m^-1]; 2) 25 min curing [150.3 degrees, max 152.7 degrees, 139.0 degrees after 12 months, 9.57 +/- 1.03 nM.m^-1 before, 17.87 +/- 1.37 nM.m^-1 after], 40 min [150.5 degrees, max 153.4 degrees, 144.5 degrees after 12 months, 9.55 +/- 1.93 nM.m^-1 before, 13.60 +/- 0.80 nM.m^-1 after], 55 min [152.5 degrees, max 154.4 degrees, 149.0 degrees after 12 months, 8.28 +/- 1.14 nM.m^-1 before, 10.47 +/-

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						1.53 nM.m^-1 after]
Ameri et al., 2018	asphalt binder (60-70 PG); ASA (Zycotherm nanomaterial; Evonik which is an acid-based polyamine fatty material in liquid form; hydrated lime comprised of calcium hydroxide)	mechanical mixer at temp 150 degrees C; nanomaterials added to binder in drops using syringe for 10 min; limestone filler used in fabrication of control mixtures and ASA mixtuers; hydrated lime used partly as substitution of limestone filler in certain mixtures; Evonik and Zycotherm added by weight of bitumen; hydrated lime added by weight of aggregate	Iranian Pavement Design Code No. 234; AASHTO T96; ASTM D5821; AASHTO T85; AASHTO T84; ASTM C127; BS 812; ASTM D 1559; AASHTO 3625; AASHTO T283; ASTM D-4123-82	Texas boiling test; indirect tensile strength (ITS) modified Lottman test	for hydrated lime: 4.9% binder content; for Zycotherm: 4.8% binder content; for Evotherm: 4.9% binder content; 1) 0.1% Zycotherm; 2) 0.3% Zycotherm; 3) 0.1% Evonik; 4) 0.3% Evonik; 5) 1% hydrated lime; 6) 2% hydrated lime	1) glossier than 2-6, dry 850 KPa, wet 810 KPa, 95 TSR; 2) dry 760 KPa, wet 610 KPa, 82 TSR; 3) dry 775 KPa, wet 625 KPa, 83 TSR; 4) glossier than 3-6, dry 825 KPa, wet 760 KPa, 90 TSR; 5) dry 775 KPa, wet 650 KPa, 85 TSR; 6) glossier than 1% hydrated lime, dry 820 KPa, wet 725 KPa, 88 TSR
Nazirizad et al., 2015	binder (85/100 PG; Tabriz Refinery); ASA (Iterlene In/400-S; dense liquid); hydrated lime filler; aggregate (sand stone from	ASA added by weight of bitumen; ASA blended with binder before mixing	ASTM T96; ASTM D5821; AASHTO T182; BS-812; AASHTO T176; AASHTO T104; AASHTO T85; AASHTO T84;	Boiling water test; Modified Lottman Test	1) 0.2% ASA; 2) 0.3% ASA; 3) 0.4% ASA; 4) 1% hydrated lime; 5) 1.5% hydrated lime; 6) 2% hydrated lime	1) MATLAB 94% coating, AUTOCAD 96% coating, cond 452 kPa, uncond 550 kPa, 82 TSR; 2) MATLAB 96% coating,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	Ojan Chai Quarry near Bostan abad city in East Azerbaijan, Iran)		AASHTO T100; AASHTO T283; ASTM C25; Type 3 wearing coarse gradation of Iran code of practice			AUTOCAD 97% coating, cond 502 kPa, uncond 590 kPa, 85 TSR; 3) MATLAB 97% coating, AUTOCAD 98% coating, cond 557 kPa, uncond 612 kPa, 91 TSR; 4) MATLAB 95% coating, AUTOCAD 96% coating, cond 440 kPa, uncond 524 kPa, 84 TSR; 5) MATLAB 96% coating, AUTOLAB 98% coating, cond 537 kPa, uncond 610 kPa, 88 TSR; 6) better coverage than 3, MATLAB 99% coating, AUTOLAB 99% coating, cond 540 kPa, uncond 651 kPa, 83 TSR
Arabani et al., 2021	aggregates (limestone; granite; max size 19 mm; nominal	high-speed mixer (4000 rpm); base asphalt cement heated to 160	ASTM D3515; AASHTO T283; AASHTO T48; AASHTO T315;	indirect tensile strength (ITS) test; surface free energy (SFE);	for limestone: 5.8% binder content; for granite: 5.5%	LIMESTONE: 1) pH=5.5 [743.09 kPa, 74 TSR], pH=6 [786.80 kPa,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	max size 12.5 mm); asphalt cement (PG 64-16); zeolite	degrees C; zeolite slowly and gradually added to heated asphalt cement for 20 min until homogenous	AASHTO R28; AASHTO T313	debonding energy (DE)	binder content; 1) 1% Zeolite; 2) 2% Zeolite	78 TSR], pH=6.5 [845.79 kPa, 84 TSR], pH=7 [931 kPa, 92 TSR], pH=7.5 [894.43 kPa, 89 TSR], pH=8 [845.28 kPa, 84 TSR], pH=8.5 [810.20 kPa, 80 TSR]; 2) pH=5.5 [783.09 kPa, 75 TSR], pH=6 [826.84 kPa, 80 TSR], pH=6.5 [895.79 kPa, 86 TSR], pH=7 [978.00 kPa, 94 TSR], pH=7.5 [944.43 kPa, 91 TSR], pH=8 [899.28 kPa, 86 TSR], pH=8.5 [880.02 kPa, 85 TSR]; GRANITE: 1) pH=5.5 [713.42 kPa, 62 TSR], pH=6 [740.30 kPa, 64 TSR], pH=6.5 [840.58 kPa, 73 TSR], pH=7 [930.12 kPa, 80 TSR], pH=7.5 [874.36 kPa, 75 TSR], pH=8

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						[830.83 kPa, 72 TSR], pH=8.5 [778.24 kPa, 67 TSR]; 2) pH=5.5 [771.42 kPa, 64 TSR], pH=6 [800.30 kPa, 66 TSR], pH=6.5 [890.58 kPa, 74 TSR], pH=7 [990.12 kPa, 82 TSR], pH=7.5 [930.36 kPa, 76 TSR], pH=8 [880.83 kPa, 73 TSR], pH=8.5 [830.24 kPa, 69 TSR]; BINDER: 1) 19.28 ergs/cm^2, 38.56 cohesion free energy; 2) 22.08 ergs/cm^2, 44.16 cohesion free energy
Mamun and Arifuzzaman, 2018	additives: polymer styrene-butadiene, polymer styrene-butadiene-styrene; nanomaterial: single walled carbon nanotubes;	HMA binder heated to 163 degrees C. After 30-40 minutes, additives and nanomaterials added and stirred with mixer at 190 degrees C at 60	ASTM D6373; ASTM D4402; ASTM D70	AFM	SB and SBS added at 4 and 5% by weight of binder, CNT added at .5, 1, 1.5% by weight of binder,	4% SB and 1% SWCNT is less susceptible to moisture damage than 4% SB; 1.5% SWCNT and 5% SB outperformed all binders with 5% SB; use of SWCNT with 4% SBS did

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	binder: PG 66-22	rpm				not have significant effect on moisture damage resistance; 1.5% SWCNT and 5% SBS offered good resistance to moisture damage
Fakhri et al., 2019	bitumen (85/100 PG); aggregate (crushed dolomite; filler size 0.075 mm); recycled crumb rubber (RCR; gradations: passing 3 mm and retained on 1 mm, passing 1 mm and retained on 0.4 mm, passing 0.4 mm and retained on 0.075 mm); Sasobit; ASA (produced by Evonik company, liquid bitumen additive based on fatty acid polyamines); deicing agents (solutions of chloridic salts;	warm mix; partial aggregate gradation (retained on 0.075 mm, 0.3 mm, 2.36 mm) replaced by RCR particle; RCR added by mass of the accumulated weight of three sieves or Replaced Aggregate (RA); Sasobit blended into bitumen by weight of bitumen (application rate of 1.5%); for adding RCR (wet process: crumb rubber powder blended with bitumen; dry process: natural aggregate partially replaced by crumb rubber); ASA added by mass of	ASTM D70; ASTM D5; ASTM D36; ASTM D113; ASTM D92; AASHTO T96; BS 812; ASTM D5821; AASHTO T85; AASHTO T84; ASTM C127; ASTM C128; ASTM D1559; ASTM D3625; AASHTO T283; ASTM D4541	boiling water test, indirect tensile strength (ITS) test, pull-off adhesion test	1.5% Sasobit; 5.2% binder content; 1) 5% RCR; 2) 5% RCR + ASA; 3) 3% RCR; 4) 3% RCR + ASA; 5) 1% RCR; 6) 1% RCR + ASA	1) 87.8% coating retained, water: 50.49 TSR (pull-off test 59.89 TSR), NaCl: 74.63 TSR (pull-off test 79.10 TSR), MgCl2: 47.89 TSR (pull-off test 33.90 TSR), CaCl2: 76.83 TSR (pull-off test 81.92 TSR); 2) 94.1% coating retained, water: 72.64 TSR (pull-off test 61.50 TSR), NaCl: 76.42 TSR (pull-off test 80.71 TSR), MgCl2: 75.18 TSR (pull-off test 74.33 TSR), CaCl2: 79.65 TSR (pull-off test 85.56 TSR); 3) 88.7% coating retained, water: 51.04% TSR (pull-

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	Calcium Chloride; Maagnesium Chloride, Sodium Chloride)	bitumen (application rate of 0.35); RCR blended with hot aggregate (150 degrees C) and hot bitumen (130 degrees C) to gain uniform mix				off test 67.82 TSR), NaCl: 75.94 TSR (pull-off test 79.70 TSR), MgCl2: 70.07 TSR (pull-off test 89.11 TSR), CaCl2: 90.40 TSR (pull-off test 77.72 TSR); 4) 94.4% coating retained, water: 82.22 TSR (pull-off test 71.09 TSR), NaCl: 80.86 TSR (pull-off test 80.57 TSR), MgCl2: 74.52 TSR (pull-off test 89.57 TSR), CaCl2: 90.96 TSR (pull-off test 85.31 TSR); 5) 89.7% coating retained, water: 49.83 TSR (pull-off test 75.21 TSR), NaCl: 82.03 TSR (pull-off test 71.01 TSR), MgCl2: 75.78 TSR (pull-off test 81.51 TSR), CaCl2: 90.63 TSR (pull-off test 84.87 TSR); 6) 95% coating retained; water: 78.92 TSR

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						(pull-off test 75.58 TSR), NaCl: 87.44 TSR (pull-off test 75.97 TSR), MgCl2: 85.86 TSR (pull-off test 83.33 TSR), CaCl2: 97.74 TSR (pull-off test 87.21 TSR)
Fakhri and Mottahed, 2021	aggregates (from asphalt plant named Asbcheran located in Tehran, Iran); reclaimed asphalt pavement (RAP; obtained from Yassini highway in eastern part of Tehran, Iran; passed through a 4-mesh sieve); bitumen (60/70 PG; from Pasargad corporation); sasobit (organic additive); Montmorillonite (nanoclay, from company in Iran that sells	WMA; sasobit blended with bitumen or mixture since it dissolves at about 100 degrees C; sasobit added by weight of binder; nanoclay added by weight of bitumen; nanoclay mixed with binder using high shear mixer	ASTM C127; ASTM C128; ASTM C131; ASTM D2419; ASTM D5821; ASTM D70; ASTM D5; ASTM D36; ASTM D113; ASTM D92; ASTM D2170; Iran Highway Asphalt Paving Code (Code 234); Natural Cooperative Highway Research Program (NCHRP); ASTM D6927	tensile strength ratio; indirect tensile strength	2% sasobit; 1) 3% nanoclay; 2) 6% nanoclay 3) 20% RAP; 4) 20% RAP + 3% nanoclay; 5) 20% RAP + 6% nanoclay; 6) 30% RAP; 7) 30% RAP + 3% nanoclay; 8) 30% RAP + 6% nanoclay; 9) 40% RAP; 10) 40% RAP + 3% nanoclay; 11) 40% RAP + 6% nanoclay	1) ITS dry: 718 Kpa, ITS wet: 615 Ka, 85 TSR; 2) ITS dry: 770 Kpa, ITS wet: 641 Kpa, 83 TSR; 3) ITS dry: 821 Kpa, ITS wet: 692 Kpa, 84 TSR; 4) ITS dry: 923 Kpa, ITS wet: 821 Kpa, 88 TSR; 5) ITS dry: 987 Kpa, ITS wet: 898 Kpa, 90 TSR; 6) ITS dry: 898 Kpa, ITS wet: 795 Kpa, 88 TSR; 7) ITS dry: 1077 Kpa, ITS wet: 975 Kpa, 90 TSR; 8) ITS dry: 1151 Kpa, ITS wet: 1016 Kpa, 88 TSR; 9) ITS dry: 1004 Kpa, ITS wet: 898 Kpa, 89 TSR;

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	products of an American biotech company)					10) ITS dry: 1186 Kpa, ITS wet: 1082 Kpa, 91 TSR; 11) ITS dry: 1206 Kpa, ITS wet: 1130 Kpa, 93 TSR
Faramarzi et al., 2017	binder (PG 94-22); filler material (grinded limestone); googas (produced by compounding neat sulfur, plasticizer, etc; from Zenit Company (R&D unit) in granular shape (solid pellet)); nanotechnology zychotherm (NZ; from Zydex Company, Gujarat, India; ASA)	WMA; NZ added by weight of asphalt; mechanical stirrer (300 rom) to mix NZ in molten asphalt (150 degrees C); NZ added in 10 drops/min for about 2 min; mixed for 10 min for homogeneous blend; Googas added by weight of asphalt; Googas heated to 60 degrees C before added to asphalt mix; ASA-modified aspalt mixed with hot aggregates (120 degrees C); blend mixed at 120 degrees C to melt/diffuse Googas throughout	Superpave mix desiign; AASHTO T283; ASTM D113; ASTM D4402; ASTM D36; ASTM D5	Indirect Tensile Strength (ITS); Modified Lottman test; Loaded-Wheel Tracking (LWT) test	convential mix: 5.5% binder content; SEA mix: 4.3% binder content; 0.15% NZ; 35% Googas; 1) ASA-modified WMA mix (AWMA); 2) Sulfur-extended WMA mix (SWMA); 3) ASA-modified and sulfur extended WMA mix (ASWMA)	1) uncond ITS: 875 KPa, cond ITS: 790 KPa, 90 TSR; 2) uncond ITS: 690 KPa, cond ITS: 475 KPa, 68 TSR; 3) uncond ITS: 750 KPa, cond ITS: 625 KPa, 85 TSR

Article	Material	Mixing Method	Standards	Tests	Amount	Results
		mix				
Alam and Agrawal, 2020	aggregate (10 mm, 6mm, stone dust); bitumen (VG 30 grade); ASAs (silicon-based: ZycoTherm, WETBOND-S, WETBOND-ES; amine-based: Super Bond A-99, Bitubuild)	dry mix set and wet mix set of specimens; hot mix (aggregate heated 150-160 degrees C; bitumen heated 155-165 degrees C; mixture mixed to 145-165 degrees C); ASA added by weight of bitumen	BC(G-II)l Ministry of Road Transport and Highways (MORTH-2013); Bureau of Indian Standards; IS:2386 Part III; IS:2386 Part IV; IS:2386 Part I; IS 1203; IS 1208; IS 1205; IS 1209; IS 1202: IS 1206 (Part II); IS 1206 (Part III); IS: 73:2013; ASTM D1559 (Marshall method of mix design); AASHTO T283; ASTM D3625; AASHTO T 269	Modified Lottman Test; Texas Boiling Test; SFE	5.4% bitumen content; 1) 0.05% WETBOND-S; 2) 0.50% Bitubuild; 3) 0.10% Super Bond A-99; 4) 0.05% WETBOND-ES; 5) 0.05% Zycotherm	1) dry ITS: 1387 kpa, wet ITS: 1192 kpa, 85.9 TSR, 13% strip; 2) dry ITS: 1381 kpa, wet ITS: 1200 kpa, 86.9 TSR, 11% strip; 3) dry ITS: 1306 kpa, wet ITS: 1140 kpa, 87.3 TSR, 5% strip; 4) dry ITS: 1358 kpa, wet ITS: 1251 kpa, 92.1 TSR, 7% strip; 5) dry ITS: 1299 kpa, wet ITS: 1233 kpa, 94.9 TSR, 3% strip
Mirzababaei, 2016	binder: 60/70; additive: zycotherm;	both HMA and WMA used; zycotherm prepared by diluting with 10ml of water for 1 ml of zycotherm, added to binder at .1% by weight of binder. mechanical	ASTM D1559; AASHTO T283; ASTM D5; ASTM D113; ASTM D70; ASTM D2042; ASTM D1754; ASTM D92; ASTM D36;	Fourier Transformed Infrared Spectroscopy; AASHTO T283; Resilient Modulus Ratio; Marshall Stability Ratio; Fracture	zycotherm .1% by weight of binder; optimum binder content measured to be 4.9 and 5.1% for lime aggregates and 5.4 and 5.6% for siliceous	across the board, warm mix asphalt generally performed significantly better than hot mix; RMR of WMA was about 6% higher than HMA in lime aggregates and

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		stirrer used, 20-30mm deep vortex, zycotherm added at 10 drops per minute to center of vortex	ASTM D2170; ASTM D2041; ASTM D2726	Energy Ratio	aggregates	about 22-24% higher in siliceous aggregates; MSR of WMA was about the same as HMA for lime aggregate samples, but was about 20% greater than HMA in siliceous aggregates; FER values of WMA were about 17% greater than HMA in lime aggregate and about 24% greater than HMA in siliceous aggregates
Hasan et al., 2015	binder: PG 58-34; additives: .25% Advera, 3% Sasobit, .35% Cecabase RT; filler: hydrated lime	HMA used as control, mixed and compacted at 165 degrees C and 155 degrees C respectively. WMA samples mixed and compacted at 130 degrees C. hydrated lime added as snti-stripping agent. multiple freeze-thaw procedure	5E3 Superpave mix design	moisture susceptibility test (TSR), AASHTO T283	HL added at 1% of weight of mixture; Advera, Sasobit and Cecabase RT added at .25%, 3%, and .35% by weight of binder, respectively.	TSR of control HMA: .4 without HL, 1.14 with HL; TSR of Advera WMA: .33 without HL, 1.08 with HL; TSR of Sasobit WMA: .38 without HL, 1.08 with HL; TSR of Cecabase WMA: .36 without HL, 1.21 with HL

Article	Material	Mixing Method	Standards	Tests	Amount	Results
		used				
Nakhaei et al., 2018	bitumen (PG 64-22; commonly used in Iran); aggregate (limestone; siliceous); EBS (ethylene-bis-stearamide; synthetic wax and an organic compound); PE-wax (polyethylene-wax)	EBS added by weight of asphalt; PE-wax added by weight of asphalt	ASTM D36; ASTM D5; ASTM D113; AASHTO M 323; AASHTO T316; ASTM D2171; ASTM D938; ASTM D1321; ASTM D2126; ASTM D792; Superpave mix design; AASHTO R35; AASHTO T312	Tensile strength ratio (TSR)	for limestone: 5.5% binder content; for siliceous: 5.1% binder content; 1) 2% EBS; 2) 3% EBS; 3) 2% PE-wax; 4) 3% PE-wax	LIMESTONE: 1) 145 degrees C 84 TSR, 115 degrees C 72 TSR; 2) 145 degrees C 86 TSR, 115 degrees C 75 TSR; 3) 145 degrees C 80 TSR, 115 degrees C 73 TSR; 4) 145 degrees C 79 TSR, 115 degrees C 70 TSR; SILICEOUS: 1) 145 degrees C 57 TSR, 115 degrees C 46 TSR; 2) 145 degrees C 66 TSR, 115 degrees C 49 TSR; 3) 145 degrees C 52 TSR, 115 degrees C 48 TSR; 4) 145 degrees C 49 TSR, 115 degrees C 44 TSR
Kakar et al., 2016	bitumen (PG-64 and PG-76; from Shell Bitumen Singapore); CECABASE RT 975	bitumen/additive blends prepared using lab overhead mechanical blender for 15 min; used Rolling Thin Film	N/A	Sessile drop method; contact angle; surface free energy (SFE)	1) 0.2% Cecabase; 2) 0.3% Cecabase; 3) 0.4% Cecabase	PG-64: 1) unaged (contact angle 98.20, total SFE 16.84 ergs/cm^2) RTFO (contact angle 103.54, total

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	(manufactured by CECA; surfactant-based chemical additive)	Oven (RTFO) for short-term aging; used Pressure Aging Vessel (PAV) for long-term aging; additive added by weight of bitumen; PG-64 blending temp at 120-130 degrees C; PG-76 blending temp at 170-180 degrees C				SFE 17.81 ergs/cm^2) PAV (contact angle 108.86, total SFE 14.25 ergs/cm^2); 2) unaged (contact angle 98.70, total SFE 16.72 ergs/cm^2) RTFO (contact angle 104.21, total SFE 17.29 ergs/cm^2) PAV (contact angle 109.24, total SFE 14.01 ergs/cm^2); 3) unaged (contact angle 98.81, total SFE 16.69 ergs/cm^2) RTFO (contact angle 104.85, total SFE 17.20 ergs/cm^2) PAV (contact angle 109.24, total SFE 13.97 ergs/cm^2); PG-76: 1) unaged (contact angle 104.90, total SFE 13.49 ergs/cm^2) RTFO (contact angle 105.3, total SFE 14.58 ergs/cm^2) PAV (contact angle

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						111.20, total SFE 11.56 ergs/cm^2); 2) unaged (contact angle 105.30, total SFE 13.22 ergs/cm^2) RTFO (contact angle 108.60, total SFE 13.33 ergs/cm^2) PAV (contact angle 114.30, total SFE 11.58 ergs/cm^2); 3) unaged (contact angle 105.60, total SFE 12.95 ergs/cm^2) RTFO (contact angle 109.30, total SFE 13.25 ergs/cm^2) PAV (contact angle 115.60, total SFE 12.14 ergs/cm^2)
Nabizadeh et al., 2017	additives: Sasobit; binder: PG 64-22 from Tehran refinery; filler: hydrated lime	binder modified by melting Sasobit at 120 degrees C and then adding to binder in low shear mixer at 350 rpm at 135 degrees C for 10 minutes. Aggregates treated with hydrated lime slurry and then	AASHTO M320; AASHTO T312; AASHTO MP 2; ASTM C127; ASTM C128; ASTM C131; ASTM D5821; ASTM D4791; NCHRP Report 691; AASHTO	AASHTO T283; Indirect tensile strength, tensile strength ratio, toughness, toughness ratio	HMA optimum binder content was 5.5% by weight of aggregate and 5.3% by weight of aggregate for WMA; addition of HL lowered binder content to	Control HMA with 0% HL, 1% HL, 1.5% HL, and 2% HL: 74%, 89%, 92%, 94.5%; WMA with 1.5% Sasobit, 2.5% Sasobit, 3.5% Sasobit, and 1.5% Sasobit + 1.5% HL: 79.5%, 82%, 83.5%,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
		marinated for 24 hours	R35; AASHTO T283;		5%	94.3%
Gilani et al., 2020	aggregate: limestone; binder: PG 85-100 from Jey oil refinery; additive: nano HL	NHL and binder mixed by heating bitumen to 150 degrees C and then pouring nanoparticles slowly into mixture over 30 minute period	AASHTO T283; ASTM D3625; ASTM D5581	Indirect tensile strength test, boiling water test	NHL added to binder at .5%, 1%, and 1.5% by weight of binder; optimum binder content 4.8% by weight of aggregate; air voids 4%	boiling water: modification of samples with .5%, 1%, and 1.5% NHL reduced moisture sensitivity by 2.37%, 4.63%, and 8.27% respectively; ITS: values of ITS of .5%, 1%, and 1.5% NHL-modified samples increased by 12.1%, 20.4%, and 37.8% respectively.
Alam and Aggarwal, 2020	aggregate: 10mm and 6mm CA, stone dust fines; binder: VG 30; ASA's: silicon-based (Zycotherm, WETBOND-S, WETBOND-ES) or amine-based (Super Bond A-99, Bitubuild)	aggregates heated, then bitumen added at increments of .1% by weight of aggregates	Ministry of Road Transport and Highways; Bureau of Indian Standards; IS 2386; IS 1203; IS 1202; IS 1205; IS 1209; IS 1206; IS 1208; AASHTO T283; ASTM D3625; ASTM D1559;	AASHTO T283; Texas Boiling Test; SFE	optimum binder content is 5.3-5.6%	Control TSR: 83.2%; .05% WETBOND-S: 85.9%; .5% Bitubit: 86.9%; .1% Superbond A-99: 87.3%; .05% WETBOND-ES: 92.1%; .05% Zycotherm: 94.9%

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Nataadmadja et al., 2020	binder: 60/70; additive: hydrated lime	not stated	Standar Nasional Indonesia	Marshall test, Cantabro Loss test, Indirect Tensile Test	HL added at 1%, 1.5%, 2%	TSR of Aggregate A with 0% HL, 1% HL, 1.5% HL, 2% HL: 79.9%, 80%, 82.8%, 84.2%; TSR of Aggregate B with 0% HL, 1% HL, 1.5% HL, 2% HL: 80.5%; 80.5%; 81.6%; 81.5%
Nazirizad et al., 2015	binder: 85/100 from Tabriz Refinery; additive: Iterlene In/400-S anti-stripping liquid; aggregate: sandstone from Ojan Chai quarry	mix methods not directly stated	ASTM D3625; AASHTO T283	boiling water test, AASHTO T283	250g of aggregate particles for boiling water test; Iterlene at .2%, .3%, .4%; HL added at 1%, 1.5%, 2%	TSR of control, Iterlene at .2%, .3%, .4%, HL at 1%, 1.5%, 2%: 75%, 82%, 85%, 91%, 84%, 88%, 83%
Park et al., 2017	binder: PG 58-22; several liquid anti-stripping agents; hydrated lime	mix methods not directly stated	ASTM D3625; KS F 2398; AASHTO T283	boiling water test, AASHTO T283	powdered HL added at 2% by weight of aggregates, liquid additives added at .5% by weight of binder	Control TSR: 53%; TSR of first ASA: 90%; TSR of second ASA: 81%; TSR of HL sample: 82%; TSR of third ASA: 98%
Jitsanigam et al., 2018	aggregate (from quarries around Perth); binder (C170 and C320); hydrated	HMA	Standard Australia; Western Australia Mainroads	Rolling Bottle Test (RBT)	1) 10% LKD; 2) 20% LKD; 3) 30% LKD; 4) 40% LKD; 5)	C320: 1) 21% bitumen coverage; 2) 15% bitumen coverage; 3) 40% bitumen coverage;

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	lime (HL; active filler; indutrial HL used); LKD (active filler; dust collected by baghouse filters in a lime kiln during calcination; from Cockburn Cement Western Australia)		(MRWA); EN 12697-11:2012; ISO14040-44		50% LKD	4) 33% bitumen coverage; 5) 58% bitumen coverage; C170: 1) 25% bitumen coverage; 2) 19% bitumen coverage; 3) 35% bitumen coverage; 4) 35% bitumen coverage; 5) 53% bitumen coverage
Mirzababaei, 2016	binder (60/70 PG); zycotherm (silane-based technology); aggregate (siliceous and calcareous)	WMA and HMA; 1 mL zycotherm diluted with 10 mL to add 10 drops/min into center of vortex of binder; molten asphalt in mechanical stirrer at 120 degrees C; stirring kept for extra 10 min to complete mix; rotator used; mix was placed in aluminum pan and put in oven at mix temp for 2 hr while stirred every 30 min	ASTM D1559 (standard Marshall Test method); ASTM D2726; ASTM D2041; AASHTO T283; ASTM C127; ASTM C128; ASTM C131; ASTM C88; ASTM T176; BS-812	Modified Lottman test; Resilient Modulus Ratio (RMR); Marshall Stability Ratio (MSR); Fracture Energy Ratio (FER); ITS; TSR	for No. 4 calcareous: 4.9% binder content; for No. 5 calcareous: 5.1% binder content; for No. 4 siliceous: 5.4% binder content; No. 5 siliceous: 5.6% binder content; 0.1% zycotherm; 1) No. 4 limestone; 2) No. 5 limestone; 3) No. 4 siliceous; 4) No. 5 siliceous	HMA: 1) dry ITS 624 Kpa, wet ITS 519 Kpa, 83.19 TSR, 87.42 RMR, 81.85 MSR, 81.18 FER; 2) dry ITS 634 Kpa, wet ITS 514 Kpa, 81.08 TSR, 89.30 RMR, 83.56 MSR, 82.97 FER; 3) dry ITS 693 Kpa, wet ITS 403 Kpa, 58.17 TSR, 68.90 RMR, 61.71 MSR, 79.55 FER; 4) dry ITS 705 Kpa, wet ITS 399 Kpa, 56.59 TSR, 72.66 RMR, 63.41 MSR, 74.48 FER; WMA: 1) dry

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						ITS 589 KPa, wet ITS 516 Kpa, 87.63 TSR, 93.33 RMR, 82.22 MSR, 96.63 FER; 2) dry ITS 594 Kpa, wet ITS 508 Kpa, 85.59 TSR, 95.51 RMR, 84.24 MSR, 98.95 FER; 3) dry ITS 689 Kpa, wet ITS 516 Kpa, 74.89 TSR, 90.21 RMR, 80.24 MSR, 97.02 FER; 4) dry ITS 691 Kpa, wet ITS 511 Kpa, 73.95 TSR, 98.10 RMR, 87.82 MSR, 98.72 FER
Ashish et al., 2016	AC-10 grade asphalt binder; Basalt, Limestone, Granite and Sandstone; CLOISITE-30B (CL-30B) (Southern clay Inc.)	CL-30B was mixed with virgin binder (AC-10) using a high shear mixer; hot mix; different doses of CL-30B (2, 4 and 6% by weight of asphalt binder) with virgin binder	ASTM:D 1754; ASTM:D 6521; ASTM: D 7175; AASHTO: TP 101	Dispersion characterization using X-ray diffraction (XRD); Rutting resistivity; SFE of asphalt binders using Wilhelmy plate method	CL-30B (2, 4 and 6% by weight of asphalt binder); virgin binder; sandstone aggregate, granite, limestone and basalt aggregates	1) The PG grade of the control binder increases by 1 PG and 2 PG with addition of 4% and 6% of CL-30B 2) The total SFE of asphalt binder increases with an increase in CL-30B content. 3) The highest value of work of adhesion

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						was observed for sandstone aggregate followed by granite, limestone and basalt aggregates. 4) The LVE range of asphalt binder decreases with addition of CL30B, indicating a stiffer binder with addition of nanoclay.
Dong et al., 2018	70# asphalt; 0# diesel; Basalt aggregate and limestone mineral filler; Stone Matrix Asphalt (SMA)	Mix aggregate; cement and bentonite for 60s; Add cutback asphalt and mix for 60s; hot mix; shear mix	ASTM D6927; ASTM D4867	The Marshall stability ratio (MSR); freeze-thaw cycling in accordance with ASTM D4867	Asphalt content, 79.2%; the percentage of aggregate between 0.3 and 2.36 mm, 7.7%; the percentage of aggregate between 0.075 and 0.3 mm, 4.1%; the percentage of aggregate passing 0.075 mm, 9%	1) Marshall stability after 24 h soaking, the MSR was improved from 70% to around 100%. 2) 40% cement content group had the highest unconditioned IDT strength while the 20% group had the highest unconditioned Marshall stability. 3) Only the 20% cement content group improved cracking resistance at low temperature

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Ravi Shankar et al., 2017	additives: hydrated lime, Zycosoil; filler: stone dust; aggregate: crushed locally obtained granite; binder: VG-30	Marshall mix design used for bitumen content	Ministry of Road Transport and Highways; IS:2386; AASHTO T283	AASHTO T283; Retained Stability	Mix 1 (control) used 5.57% binder, Mix 2 used 5.63% binder, 2% lime and 3% stone dust filler, Mix 3 used 5.62% binder and 1% Zycosoil by weight of binder	TSR and Retained Stability value of Mix 1, Mix 2 and Mix 3: 88.93% and 89.58%, 93.54% and 93.28%, 96.48 and 96.75%
Razavi and Kavussi, 2020	binder: 60/70 from Tehran refinery; aggregate: siliceous aggregate with size 12.5mm; additives: CaCO3, HL, NHL, nano-CaCO3, nano-SiO2, bentonite nanoclay	HMA, Marshall method	AASHTO T283, ASTM standards for grading of aggregates	AASHTO T283	optimum binder content 5.1%; HL at 5, 10, 20%; NHL at 2%, 4%; CaCO3 at 5, 10, 20%; NCaCO3 at 2%, 4%; bentonite at 2 and 4%; NSiO2 at 2 and 4%	NHL and NCaCO3 showed significant increases in TSR with 4% samples having slightly higher TSR than 2% samples; HL showed steady increases in TSR with increased dosage; CaCO3 showed decreasing increases in TSR with increasing dosage; bentonite didn't increase TSR as much as other samples, with NSiO2 showing smallest increases in TSR

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Saedi, et al., 2020	aggregates: limestone, granite and quartzite; binder: AC 60-70; additives: glass cullet; nanomaterials: NHL and NCC	Marshall method used to mix asphalt	AASHTO T283	AASHTO T283	nanomaterials present at 2% of bitumen mass; glass cullet at 2.025% of aggregates	TSR was greatest with no glass cullet and 2% NHL, then control, then glass cullet with 2% NHL, then no glass cullet and 2% NCC, then glass cullet only, then glass cullet and 2% NCC; significant deterioration occurred to all samples after full 5 freeze-thaw cycles
The and Hamzah, 2019	binder: unmodified PG-64, SBS-modified PG-76; aggregate: granite supplied by Kuad Sdn Bhd in Penang, limestone supplied by Pens Industries Sdn Bhd in Perlis; filler: Pavement Modifier (NSL Chemicals LTS, Ipoh, Perak) and HL; Evotherm	binders heated, mixed with preheated high shear mixer; long-term aged for 120h	AASHTO R30, ASTM D4551;	Pneumatic adhesion tensile test	Evotherm added at .5% by binder mass;	Limestone aggregate specimens failed at a lower rate than granite, regardless of binder type or additives

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	3G					
Razavi et al., 2019	60–70 penetration grade bitumen (Refinery of Tehran); siliceous aggregate type, with nominal maximum size of 12.5 mm; A calcium carbonate filler; A hydrated lime filler; Nano-hydrated lime; bentonite	Optimum asphalt binder content of the mixture was determined based on Marshall Method with 75 blows on each side; hot mix; wet mix	ASTM D3515-01; ASTM D1559-89; ASTM D4123-82; AASHTO T283	Modified Lottman test; ITSM test	control asphalt binder at 2% and 4% by weight of bitumen; calcium carbonate (CaCO3) and hydrated lime (Ca(OH2)), amounts of 5, 10 and 20% (by weight of asphalt binder)	1) At the optimum condition, minimum particle sizes of nano-hydrated lime were 125 and 208 nm when SEM and DLS tests were performed, respectively. 2) The optimum conditions for producing nano-hydrated lime were consisted of 5 h of milling 3) The addition of 20% hydrated lime filler and 4% nano-hydrated lime to the binder promoted TSR values of bituminous mixes by 60 and 61%, respectively. 4) By adding 20% hydrated lime filler and 4% nanohydrated lime to bitumen, IRM values of mixes enhanced by 56% and 60%,

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						respectively.
Singh et al., 2020	asphalt binder, CRMB60; CRMB60 was modified with rubber granulates having gradation of 100% and 80%; antistripping agents, amine and silane.	Mixing temperature of 150°C–165°C; additives were added in the form of drops over a span of 10 min; mixing was prolonged for 20 min to ensure parity; portion of blended binder was short-term aged in accordance with ASTM D2872 and thereafter, the short-term aged binder was long-term aged as per ASTM D6521	AASHTO MP19; AASHTO TP101; ASTM D2872; ASTM D5/D5M; ASTM D36/D36M; ASTM D7405; ASTM D4402/D4402M; ASTM D6648-08; ASTM D6521; ASTM D6084/D6084M; ASTM D92			1) Both the amine and silane antistripping agents caused a decrease in apparent viscosity of CRMB60. 2) Addition of the silane antistripping agent caused a bump in the high-temperature PG of CRMB60, from 88°C to 94°C. 3) Decrease in R was observed after addition of the amine antistripping agent to CRMB60, whereas it increased on addition of the silane antistripping agent. 4) A severe decrease in fatigue life of CRMB60 was observed on addition of the amine and silane antistripping agents. 5) The effect of the amine and silane antistripping agents on lowtemperature

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						cracking resistance was minor up to the temperature of −12°C.
Teh and Hamzah, 2019	binder: unmodified PG-64; aggregates: granite (Kuad Sdn Bhd Perlis); fillers: PMD and HL; surfactant-WMA (EV)	Marshall mix design used for HMA and WMA	ASTM D1559; ASTM D4867;	indirect tensile test;	binder contents for HMA and WMA were 5% and 5.2%; surfactant EV added at .5% by mass of binder	PMD samples had higher moisture resistance than those containing HL. EV surfactant addition further reduced failure percentage of all samples
Lopez-Montero et al., 2018	asphalt concrete mixture with a maximum aggregate size of 14 mm (AC14); conventional one (35/50), a nanoclay	impact compactor (Marshall hammer); hot mix; wet mix	EN 12697-12; ASTM STP 1322; ASTM D1075-11; AASHTO T245-15	The indirect tensile strength test; Specimens have been conditioned according to EN 12697-12 related to the water	conventional specimen (35/50), a nanoclay modified specimen and a nanoiron modified one;	1) tensile strength of the mixtures increases by modifying the binder with nanoparticles. 2) When the mixtures are subjected to

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	modified one and a nanoiron modified one; nanoclay is a hydrophilic bentonite			sensitivity analysis of asphalt mixtures.	binder content was 4.5% by the weight of the mixture; nanoparticles content was 4% by weight of modified binder	moisture damage, their indirect tensile strength tends to decrease considerably. 3) The values of the indirect tensile strength significantly increase with ageing due to the hardening of the binder.
Gilani et al., 2020	Limestone aggregates; bitumen with a penetration grade of 85–100 (the oil refinery Jey);	Marshall mix design method; hot mix; dry mix; shear mix	AASHTO T283; ASTM D3625; ASTM PS 129–0; ASTM D5581;	The boiling water testing; The indirect tensile strength (ITS) test; MVR, GMDH and GP to determine the best model	the highest specific gravity and 4% air void; optimum bitumen content of the mixtures was calculated to be 4.8%; . Nano hydrated lime (NHL) with weight percentages of 0.5%, 1.0% and 1.5%; nominal and maximum size of the aggregates is 12.5 mm and 19 mm	1) ITS values of the modified specimens with 0.5%, 1% and 1.5% NHL in the dry condition compared to the unmodified specimens, increased by 12.1%, 20.4% and 37.8%, respectively. 2) NHL in dry condition compared to the unmodified specimens, increased by 19%, 55% and 31%. 3) the R2 value of the GMDH model for

Article	Material	Mixing Method	Standards	Tests	Amount	Results
						TSR and NFR was 93.9% and 86.9%, respectively
Vishal et al., 2020	WMA binder; viscosity grade (VG) 30 bitumen as a base binder; surfactant based warm mix additive of 0.4% by weight of asphalt was added to VG30; blended at 500 rpm; blending at 150°C.	hot mix; binders were mixed with dense graded aggregate; shear box compactor	AASHTO T321; AASHTO T283; ASTM D7460; ASTM D7981; IS (Indian Standard)	freeze-thaw conditioning process in accordance with AASHTO T283; Lottman Test	WMA binder; viscosity grade (VG) 30 bitumen as a base binder; surfactant based warm mix additive of 0.4% by weight of asphalt was added to VG30	1) Fatigue life estimated from the flexural stiffness was found to be consistently lower than the fatigue life estimated using the energy ratio method 2) The number of cycle corresponding to 50% of initial flexural stiffness coincided with the point of change of slope. 3) Addition of warm mix additive slightly increased the fatigue life at 400 microstrain and decreased the fatigue life at 600 and 800 microstrain.

Article	Material	Mixing Method	Standards	Tests	Amount	Results
Xiao et al., 2016	P1 is an ethene homo-polymer white powder material, P2 is a combination of P1 and SBS, and P3 is an oxidized polyethylene wax-like powder;	warm mix; blended with virgin PG 64-22 binders at a temperature of 150˚C; wet and dry mix; blend was performed at 800 rpm for up to 20 min to produce the PG 76-22 binder	AASHTO TP 62; AASHTO T 269	indirect tensile strength (ITS); tensile strength ratio (TSR); dissipated energy; permanent deformation; volumetric properties of three alternative polymers and SBS.	2.5% P1, 1%P1 + 2%SBS P2, and 2.5% P3 by weight of asphalt binder were blended with virgin PG 64-22 binders	1) The optimized binder contents of various polymerized mixtures were very similar. 2) All of the polymers used in this study produced wet ITS values higher than 448 kPa. 3) TSR values of all mixtures were greater than 80% 4) The average rut depths of all mixtures generally were less than 3 mm 5) The mixture containing SBS had the highest phase angle values at varying frequencies 6) Flow number results indicated that the mixtures containing A2 might have the weakest resistance to permanent deformation
Zaidi et al., 2021	aggregate: granite and limestone; additives:	bitumen heated to 160 degrees C, stirred by hand as fillers added,	BS EN 12697-2012;	SFE, Rolling bottle test, PATTI test	300g bitumen per batch; fillers at 50% by weight	SFE: surface free energy values for granite aggregate mixtures increased

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	limestone, granite and hydrated lime; binder: 40/60 Neat;	stirring mainained until mixture becomes homogeneous and cooled off enough to prevent the filler from settling out of the mixture.				9.5% with addition of 10% HL and 56% with addition of 20% HL, work of debonding decreased 9% and 51% respectively.
Zhang and Luo, 2019	#70 asphalt; a gravel aggregate; additive materials - including a WMA additive (Sasobit® wax (SW)) (AkzoNobel,China), two nano-materials (nano SiO_2 and nano ZnO) (Jingbei Company, China), a hydrated lime (HL) (Xingyinhe Chemical Company, China), a Portland cement (PC) (Wuhan Wuganghuaxin Cement Co., Ltd., China), and a non-amine	shearing method is utilized to add the additive into the neat asphalt with the aid of a high-shear mixer (JRJ 300-S, Shanghai, China); the neat asphalt is heated at 150 °C for 30 min in the mixer; hot mix	ASTM D6927; ASTM D4867; ASTM D3625	Modified boiling water test; Indirect tensile strength (ITS) test;	Sodium oxide, Na_2O (%), 2.077; Silicon dioxide, SiO_2 (%), 87.495; Aluminium oxide, Al_2O_3 (%), 6.096; Ferric oxide, Fe_2O_3 (%), 1.621; Sulphur trioxide, SO_3 (%), 0.061; Calcium oxide, CaO (%), 0.276; Magnesium oxide, MgO (%), 0.032; Insoluble residue (%), 0.882; SW, 0.5%; SiO_2, 5%; ZnO, 4%; HL, 5%; PC, 5%; NA, 0.4%	1) This validates that the proposed SFE method can be used to accurately quantify the effects of additives on the moisture susceptibility of asphalt mixtures. 2) From the perspective of SFE theory, lowering the ratio of $+\gamma/A$ / $-\gamma/A$ of asphalt binder may be helpful towards the enhancement of the moisture damage resistance of asphalt mixtures containing a given type of aggregates.

Article	Material	Mixing Method	Standards	Tests	Amount	Results
	liquid asphalt anti-stripping agent (NA) (Chongqing Haimu Traffic Technology Co., Ltd., China)					

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