



## Mechanical and durability characteristics of nanoalumina modified asphalt mixtures for sustainable pavement applications

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### ABSTRACT

Moisture damage is a major factor affecting the durability of hot mix asphalt. This study aimed to investigate the effect of alumina nanoparticles on the physical, mechanical, and moisture-resistant properties of asphalt mixes. Alumina nanoparticles are added to AC (40-50) asphalt binder at 2%, 4%, and 6% of the binder weight. The experimental program included tests of physical properties, Marshall properties, indirect tensile strength, compressive strength, tensile strength ratio, and residual strength index. The results showed that alumina nanoparticles improved the binder properties by reducing penetration and increasing the softening point and flash point. Marshall stability is increased by up to 25.41%, while the modified mixes showed a decrease in air voids and an increase in bulk density. Furthermore, the values for indirect tensile strength, compressive strength, tensile strength ratio, and residual strength index are significantly improved, indicating enhanced moisture resistance and increased bond strength between the binder and aggregate. Optimal performance is achieved using 4% alumina nanoparticles, providing the best balance between mechanical properties and moisture resistance. These results demonstrate the potential of alumina nanoparticles as an effective modifier for improving the durability of asphalt mixtures.

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**Keywords:** Nanoalumina; Moisture susceptibility; Hot mix asphalt; Nanotechnology.

## 1. INTRODUCTION

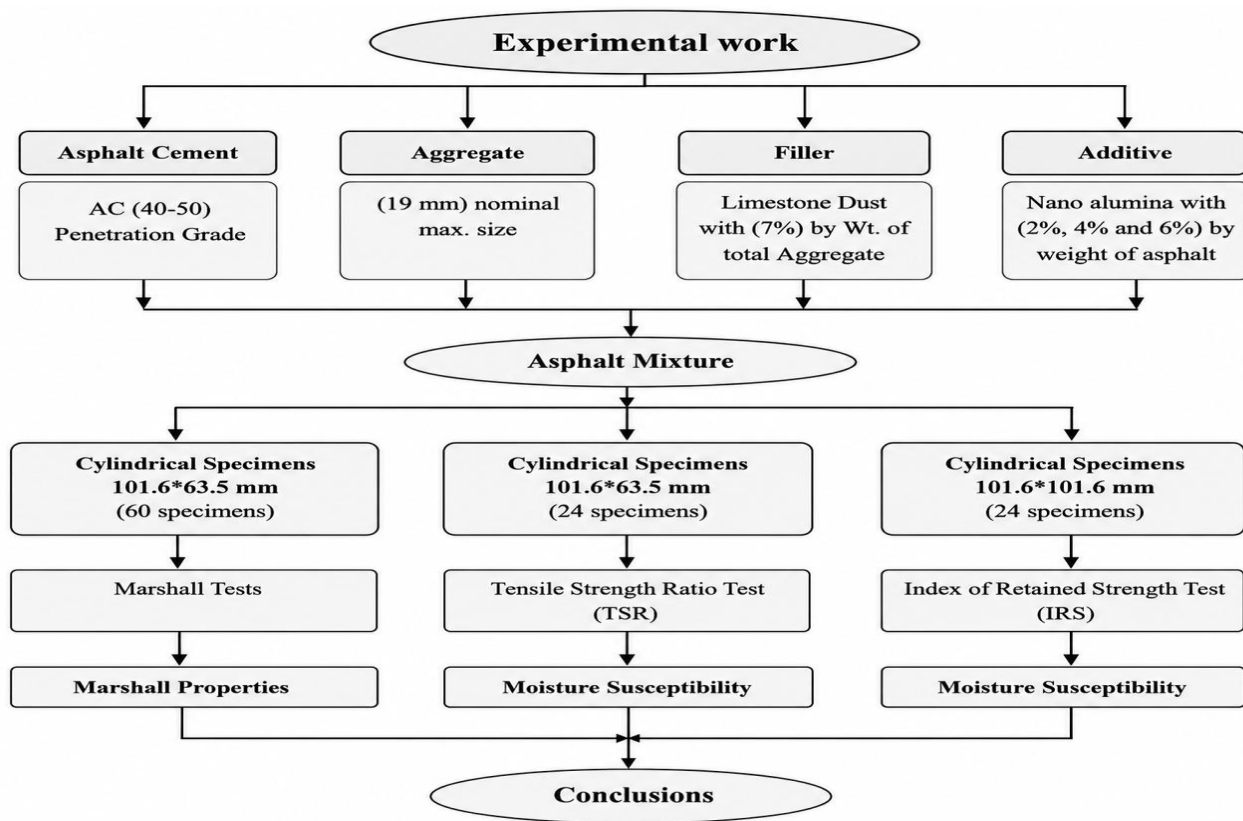
Moisture damage is one of the major causes of premature deterioration in hot mix asphalt pavements. The presence of water within asphalt mixtures weakens both the adhesive bond between asphalt binder and aggregate particles and the cohesive strength of the asphalt binder itself, leading to stripping, raveling, and cracking, which ultimately reduce pavement service life [1]. Under repeated traffic loading, the continuous interaction between water and asphalt mixtures accelerates the deterioration process and significantly affects pavement durability and structural performance [2]. Moreover, a reduction in the stiffness of asphalt mixtures is considered a characteristic of cohesive failure within the asphalt binder matrix. As a result, asphalt pavements may experience various forms of distress, including stripping, raveling, cracking, and rutting [3]. The resistance of asphalt mixtures to moisture damage depends primarily on the quality of adhesion between the asphalt binder and aggregate surfaces. Poor adhesion allows water to penetrate the asphalt film surrounding the aggregates, resulting in gradual separation between the binder and aggregates and consequently reducing the mechanical properties of the asphalt mixtures [4]. In addition, the use of additives, improved asphalt production processes, increased in-place density, reduced permeability, pavement geometry, drainage conditions, and moisture-related delamination are among the factors that influence the moisture susceptibility of asphalt mixtures [5][6][7]. Therefore, enhancing the adhesive and cohesive characteristics of asphalt mixtures has become a major concern in pavement engineering. Traditional additives such as hydrated lime, polymers, and anti-stripping agents have been widely utilized to improve moisture resistance. However, recent advances in nanotechnology have provided more effective approaches for enhancing asphalt performance [8]. Due to several technical advantages, the incorporation of nanomaterials into asphalt mixtures has become one of the most promising modification techniques [9]. Nanomaterials are materials with at least one dimension ranging from 1 to 100 nm. Owing to their extremely small size and large specific surface area, nanomaterials exhibit unique properties that distinguish them from conventional materials, making them attractive additives for asphalt pavement applications [10]. In recent years, nanotechnology has been increasingly applied in asphalt modification, and various nanomaterials have been used as binder modifiers [11]. Numerous studies have investigated the potential benefits of incorporating nanomaterials such as nano-clay (NC) [12], nano-silica (NS) [13], nano-hydrated lime (NHL) [14], nano-sized plastic particles (NPP)[15], nano-carbon fibers (NCF) [16], and nanotubes (NT) [17] into asphalt binders. A considerable number of studies have examined the influence of nanomaterials on the rheological and physical properties of asphalt binders and asphalt mixtures [18]. Recent investigations have shown that nanomaterials can provide asphalt mixtures with higher surface area, improved strain resistance, enhanced functional activity, and superior performance characteristics, thereby addressing several pavement-related problems [19]. Among the various nanomaterials, nano-alumina has attracted significant attention in pavement engineering and is considered a promising asphalt modifier due to its high surface area, thermal stability, and mechanical strength, which improve adhesion, moisture resistance, and the overall performance of asphalt mixtures [20-22].

Nano-alumina is characterized by its high strength, hardness, thermal stability, and resistance to chemical degradation, which have contributed to its successful application in improving the mechanical performance of cement-based materials. These properties are also desirable in asphalt pavements, particularly for enhancing resistance to deformation and environmental effects [23]. However, despite the growing interest in nanomaterials for pavement applications, the use of nano-alumina in asphalt mixtures remains relatively limited. Therefore, this study investigates the feasibility of incorporating nano-alumina as a modifier in asphalt mixtures through a comprehensive experimental program involving Marshall, indirect tensile strength, moisture susceptibility, and compressive strength tests. The

study also aims to determine the optimum nano-alumina content capable of providing the best overall performance of asphalt mixtures.

**Table 1** Summary of previous studies on asphalt mixtures modified with alumina nanoparticles.

| Authors         | Year | Modifier     | Main Tests                      | Main Findings                                                                     |
|-----------------|------|--------------|---------------------------------|-----------------------------------------------------------------------------------|
| Cao et al.      | 2022 | Nano-Alumina | Rutting, ITS, Marshall, Fatigue | Improved moisture resistance and high temperature performance; optimum content 9% |
| Long et al.     | 2020 | Nano-Alumina | Rheological Tests               | Increased stiffness and thermal stability of asphalt binder                       |
| Razavi& Kavussi | 2020 | Nano-Alumina | Marshall and Moisture Tests     | Enhanced Marshall Stability and durability                                        |
| Broering et al. | 2024 | Nano-Alumina | Mechanical Performance          | Improved binder–aggregate interaction and pavement performance                    |



**Figure 1** Research Methodology Flow Chart.

## 2. MATERIALS

To obtain a true indicator of the behavior of asphalt concrete surface layer pavement when exposed to moisture damage in Iraq, and to study the effect of asphalt mix materials on this phenomenon, all materials (asphalt cement, coarse and fine aggregates, mineral fillers and additives) used in this work are locally available and currently used in road construction in Iraq.

### 2.1 Asphalt Cement

One type of asphalt cement is used in this work, asphalt cement AC (40-50) which is from Al-Daurah Refinery in Baghdad. The Physical properties of this type asphalt cement are listed in Table 2. All tests' results meet the Stat Corporation of Roads and Bridges (SCRB R/9, 2003) specifications.

**Table 2** Physical Properties of Asphalt Cement Grade (40-50).

| Test                                     | Unit    | ASTM<br>Designation No. | Result | SCRB<br>Specification |
|------------------------------------------|---------|-------------------------|--------|-----------------------|
| Penetration (25oC, 100 gm, 5sec)         | 1/10 mm | D-5                     | 44     | 40-50                 |
| Softening Point (Ring & Ball)            | (°C)    | D-36                    | 51     | -----                 |
| Specific Gravity at 25 °C                | -----   | D-70                    | 1.042  | -----                 |
| Ductility ( 25 °C, 5cm/min)              | cm      | D-113                   | 149    | >100                  |
| Flash Point, (Cleveland open Cup)        | (°C)    | D-92                    | 309    | >232                  |
| After Thin-Film Oven Test ASTM D<br>1754 |         |                         |        |                       |
| Retained Penetration of Original         | %       | D-5                     | 61     | 55 (min)              |
| Ductility (25 °C, 5cm/min)               | cm      | D-113                   | 82     | >25                   |

## 2.2. Aggregate

The crushed coarse aggregate is brought from the hot mix plant of Baghdad municipality, The fine aggregate is a part of asphalt mixes that consists of hard grains, free of injurious amount of clay, loam or other deleterious substances. It is also brought from the hot mix plant of municipality Baghdad. According to (SCRB R/9, 2003) specification, the sizes of coarse aggregate ranged from  $\frac{3}{4}$  in (19 mm) to No.4 sieve (4.75mm) for wearing course and the fine aggregate is ranged from passing sieve No.4 (4.75mm) to the retained-on sieve No.200 (0.075 mm). The physical properties of course and fine aggregate are listed in Table 3 and 4.

**Table 3** Physical Properties of Coarse Aggregate.

| Property                   | ASTM Designation No. | Coarse Aggregate | SCRB Specification |
|----------------------------|----------------------|------------------|--------------------|
| Bulk Specific Gravity      | C-127                | 2.584            | -----              |
| Apparent Specific Gravity  | C-127                | 2.608            | -----              |
| Percent Water Absorption % | C-127                | 0.57             | -----              |
| Los Angeles Abrasion %     | C-131                | 13.08            | 30 Max             |

**Table 4** Physical Properties of Fine Aggregate.

| Property                   | ASTM Designation No. | Fine Aggregate | SCRB Specification |
|----------------------------|----------------------|----------------|--------------------|
| Bulk Specific Gravity      | C-128                | 2.604          | -----              |
| Apparent Specific Gravity  | C-128                | 2.664          | -----              |
| Percent Water Absorption % | C-128                | 1.419          | -----              |

### 2.3. Mineral filler

Limestone dust is used as a filler due to its availability and low cost. The mineral filler in asphalt mixture is an important component as it plays an important role in stiffening of asphalt mixture. Filler is a material passing sieve No.200 (0.075 mm). It is brought from lime factory in Karbala governorate. The physical properties of the mineral filler are listed in Table 5.

**Table 5** Physical Properties of Limestone Dust.

| Property              | Result |
|-----------------------|--------|
| % Passing No.200      | 99     |
| Bulk Specific Gravity | 2.67   |

### 2.4 Nano-alumina

| Nano alumina Index            | Value        |  |
|-------------------------------|--------------|--------------------------------------------------------------------------------------|
| Exterior                      | White powder |                                                                                      |
| Particle size /nm             | ≤80          |                                                                                      |
| Density (gm/cm <sup>3</sup> ) | 0.9          |                                                                                      |
| Solubility%                   | 99           |                                                                                      |

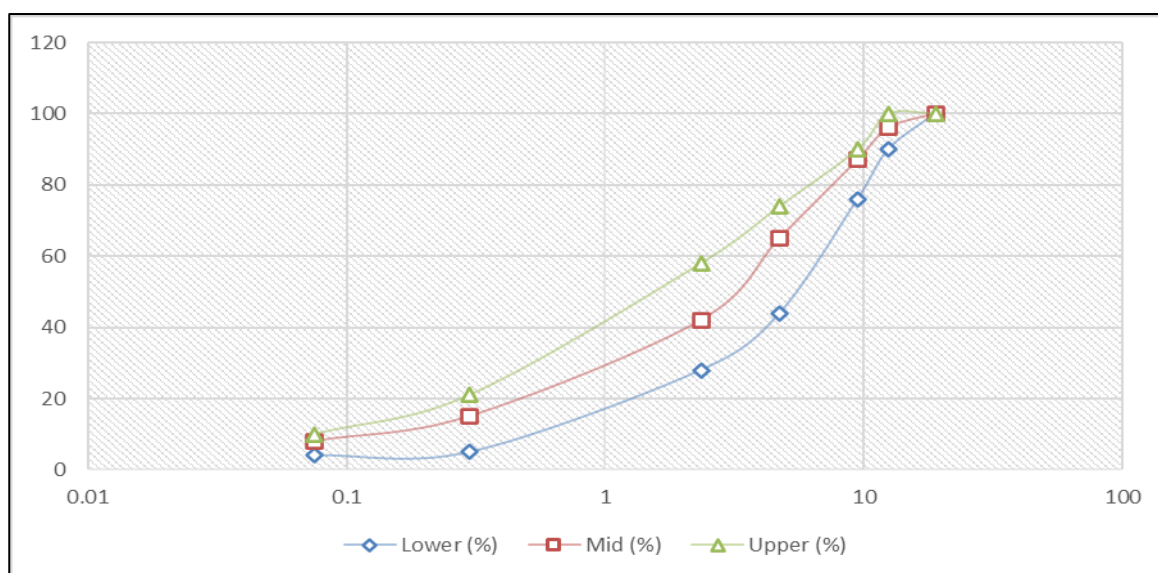
**Figure 2** Nano alumina characteristics.

## 2.5 Selection of aggregate and gradations

According to (SCRB/R9, 2003) specification, the nominal maximum size of aggregate is 12.5 mm for wearing course. The selected aggregate gradation is shown in Table 6 and Figure 3.

**Table 6** Gradation of Combined Aggregate for Wearing Course According to (SCRB/R9- 2003).

| Sieve Size | Sieve Size (mm) | Specification Passing Range (%) | Mid-limit Gradation (%) |
|------------|-----------------|---------------------------------|-------------------------|
| 3/4"       | 19              | 100                             | 100                     |
| 1/2"       | 12.5            | 90-100                          | 95                      |
| 3/8"       | 9.5             | 76-90                           | 83                      |
| No.4       | 4.75            | 44-74                           | 59                      |
| No.8       | 2.36            | 28-58                           | 43                      |
| No.50      | 0.3             | 5-21                            | 13                      |
| No.200     | 0.075           | 4-10                            | 7                       |



**Figure 3** Aggregate gradation of the wearing layer according to SCRBS, [24].

## 3. EXPERIMENTAL

### 3.1 Physical properties of asphalt cement

In this study, conventional asphalt cement with an AC penetration grade (40-50) is used. The binder is modified using varying proportions of Nano alumina to investigate its effect on the asphalt cement's physical properties. Laboratory tests, including penetration, softening point, ductility, and flash point,

are conducted according to ASTM specifications to evaluate the effectiveness of the alumina nanoparticle modification. The results are compared with those of the unmodified cementitious binder to assess the improvement in binder performance and its suitability for paving applications under load and environmental conditions.

### 3.2 Asphalt mixtures tests

The asphalt binder is initially heated to  $150 \pm 5$  °C to achieve sufficient fluidity before modification. Nano-alumina particles are then added to the asphalt binder at 2%, 4%, and 6% by weight as shown in Figure4 During the mixing process, a small amount of kerosene is added to improve workability and enhance the dispersion of the aluminum oxide Nano alumina within the asphalt matrix. The modified binder is prepared using a high-shear mechanical mixer operating at 3500–4000 rpm for 40 minutes under controlled heating conditions to ensure uniform nanoparticle distribution throughout the binder, following procedures established in previous studies [20] to determine the optimal asphalt content, asphalt mix samples are prepared using five asphalt levels: 4%, 4.5%, 5%, 5.5%, and 6% by weight. To improve the accuracy and reliability of the experimental results, three identical samples are prepared for each asphalt grade. After compaction, the samples are allowed to cool at room temperature for approximately 24 hours before testing. The experimental evaluation program included Marshall stability, fluidity, bulk density, and volumetric properties analysis according to ASTM D6927 specifications. The optimal asphalt ratio is selected based on Marshall mix design criteria corresponding to a target air void ratio of approximately 4%. The asphalt mixes are prepared using a particle size gradation with a nominal maximum particle size of 19 mm, while limestone dust is used as a mineral filler at 7% of the total aggregate weight.



**Figure 4** Samples of Asphalt Mixture by Marshall Test.

### 3.3. Tensile strength ratio (TSR) test

The Tensile Strength Ratio (TSR) test is performed in accordance with ASTM D4867 to evaluate the moisture susceptibility and stripping resistance of the asphalt mixtures. Marshall specimens with a diameter of 101.6 mm and a height of  $63.5 \pm 2.5$  mm are prepared at the optimum asphalt content for both the control mixture and the modified asphalt mixtures. The compaction effort is selected to achieve an air void content of approximately  $7 \pm 1\%$ , as required by the standard specification. For each mixture, the prepared specimens are divided into two groups: conditioned and unconditioned specimens. The

unconditioned group is immersed in a water bath at 25 °C for 30 min before conducting the Indirect Tensile Strength (ITS) test. The conditioned group is first partially saturated under vacuum with distilled water to achieve the required saturation level. The specimens are then subjected to a freeze–thaw cycle by placing them in a freezer at –18 °C for 16 h, followed by immersion in a water bath at 60 °C for 24 h. After conditioning, the specimens are maintained in a water bath at 25 °C for 1 h prior to testing.

The indirect tensile strength test is conducted using a universal testing machine by applying a compressive load along the vertical diametrical plane of the specimen at a loading rate of 50 mm/min until failure occurred. The ITS values for conditioned and unconditioned specimens are calculated using Eq. (1), while the TSR value is determined using Eq. (2).

$$ITS = \frac{2000 P}{\pi t D} \quad (1)$$

$$TSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}} \quad (2)$$

where P is maximum applied load at failure (N), t is specimen thickness (mm), D is specimen diameter (mm). Con., ITS is conditioned indirect tensile stress (kPa) and uncon. ITS is unconditioned indirect tensile stress (kPa). According to ASTM D4867, asphalt mixtures are considered resistant to moisture damage when the TSR value is not less than 80%.

### 3.4 The compressive strength test

The compression strength test is conducted to evaluate the moisture sensitivity and durability of asphalt mixtures, according to ASTM D1075-07 specifications. Cylindrical specimens measuring 101.6 mm in diameter and 101.6 mm in height are prepared by compressing the asphalt mixtures to the required dimensions. Four sets of specimens are produced for this study, including one reference mix free of Nano alumina and three modified mixes containing 2%, 4%, and 6% Nano alumina (relative to the weight of the asphalt binder). Each set consisted of six specimens.

For conditioning purposes, three specimens from each set are stored in air at 25°C for approximately four hours prior to the dry compression strength test. The remaining three specimens are immersed in a water bath at 60°C for 24 hours to simulate moisture exposure. After immersion, the specimens are transferred to another water bath at 25°C for two hours prior to the test.

The compressive strength performance of asphalt mixtures is evaluated using the Residual Strength Index (IRS), which represents the ratio of the compressive strength of the cured samples to the compressive strength of the uncured samples. Higher IRS values indicate better resistance to moisture damage and improved bonding between the asphalt binder and the aggregate particles. According to SCRB/R9 (2003), the acceptable IRS value for asphalt mixtures should not be less than 70%.

$$IRS = (S2/S1) \times 100 \quad (3)$$

Where S1 is compressive strength of dry samples (kPa) and S2 is compressive strength of cured or immersed samples (kPa) 80%.

## 4. RESULTS AND DISCUSSION

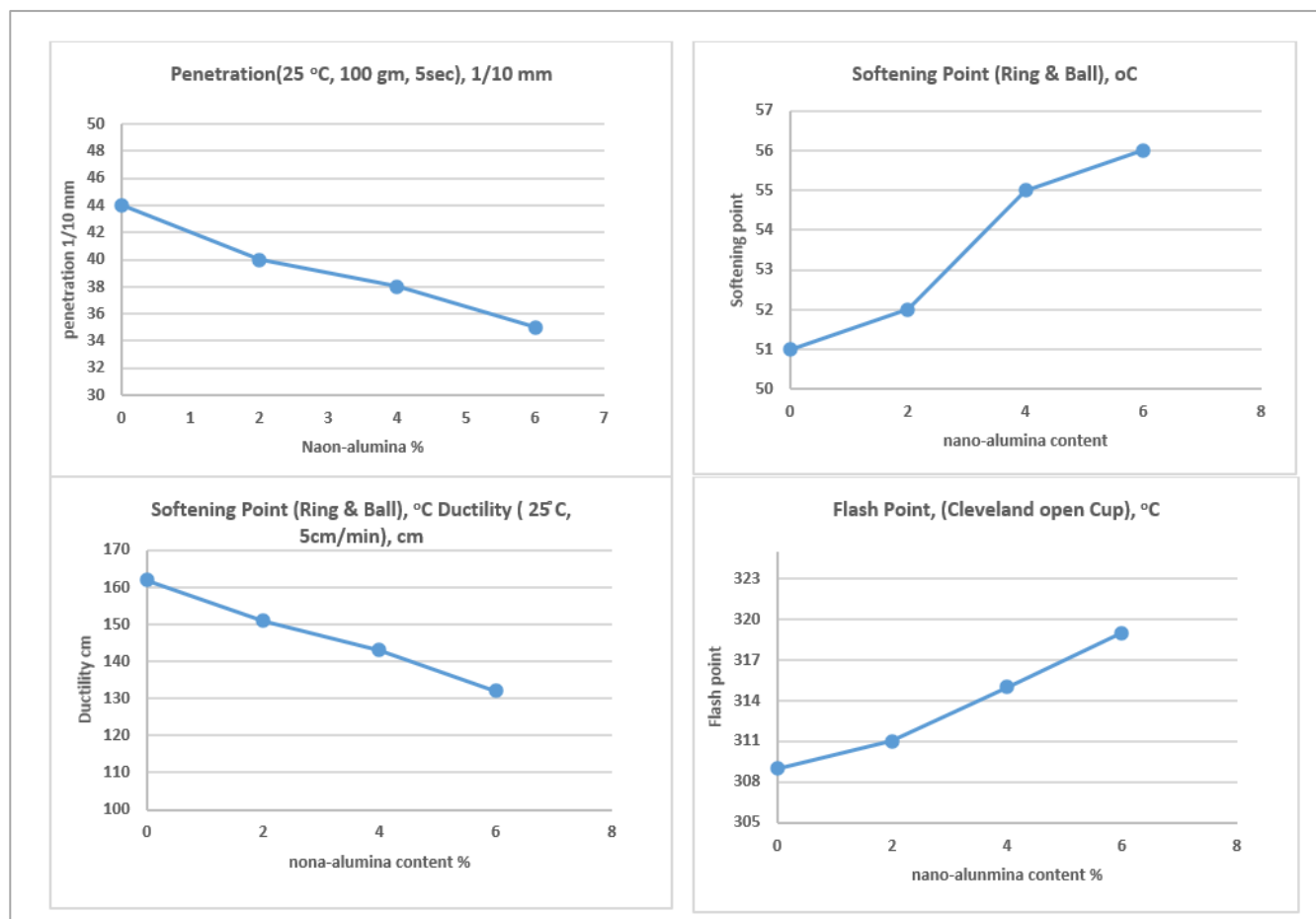
### 4.1 Physical properties of asphalt cement

Modifying asphalt cement with Nano alumina significantly altered its physical properties compared to standard cement. Penetration values decreased progressively with increasing alumina content, registering reductions of 9%, 13.6%, and 20.5% for AC (40-50) asphalt cement at 2%, 4%, and 6%

alumina contents, respectively. This decrease in penetration indicates increased cement stiffness and resistance to deformation due to the presence of Nano alumina within the asphalt matrix. Conversely, softening increased progressively with increasing nano alumina content, reaching 1.96%, 7.84%, and 9.8% for AC (40-50) asphalt cement at 2%, 4%, and 6% alumina contents, respectively. This behavior reflects the improved thermal stability of the modified cement and its increased resistance to softening at elevated temperatures. The ductility values decreased by 6.79%, 11.72%, and 15.5% with the addition of 2%, 4%, and 6% of oxide Nano alumina, respectively. This decrease in ductility is attributed to the hardening effect of the aluminum oxide Nano alumina, which reduces the elasticity of the asphalt binder while improving its structural strength and cohesion. However, the resulting ductility values remained within acceptable specifications for paving applications. Furthermore, the flash point gradually increased with the addition of Nano alumina, with increases of 0.65%, 1.94%, and 3.24% observed with the addition of 2%, 4%, and 6% of Nano alumina, respectively. The increase in flash point indicates improved thermal resistance and reduced volatility of the modified asphalt binder during heating processes. Overall, the addition of Nano alumina increased the density and viscosity of the asphalt cement, contributing to lower penetration and plasticity values while increasing the softening point and flash point. These results demonstrate that Nano alumina can effectively improve the physical and thermal performance of asphalt cement, particularly under high-temperature operating conditions. The changes in values of physical properties of asphalt cement with addition of these percentages of nano alumina are shown in Table 7 and Figure 5.

**Table 7** Physical Properties of Asphalt Cement AC(40-50) modified by Nano-alumina.

| Nano-alumina<br>(%) of AC | Penetration<br>(1/10 mm) | Softening Point<br>(°C) | Ductility (cm) | Flash Point<br>°C |
|---------------------------|--------------------------|-------------------------|----------------|-------------------|
| 0                         | 44                       | 51                      | 162            | 309               |
| 2                         | 40                       | 52                      | 151            | 311               |
| 4                         | 38                       | 55                      | 143            | 315               |
| 6                         | 35                       | 56                      | 132            | 319               |



**Figure 5** Effect of Nano-alumina on Physical Properties of Asphalt Cement.

#### 4.2 Marshall test results

##### *Effect of nano-alumina on optimum asphalt content (O.A.C)*

The results showed a gradual increase in the Optimum Asphalt Content (O.A.C) with increasing nano-alumina content. The O.A.C increased from 4.85% for the control mixture to 5.15%, 5.27%, and 5.41% for mixtures modified with 2%, 4%, and 6% nano-alumina, respectively. These increases correspond to approximately 6.19%, 8.66%, and 11.55% compared with the control mixture. The increase in asphalt demand can be attributed to the high specific surface area of nano-alumina particles, which requires additional asphalt binder to provide adequate coating for aggregate particles and maintain mixture workability. Furthermore, nano-particles tend to absorb part of the asphalt binder because of their high surface activity, reducing the effective binder content within the mixture. The obtained asphalt content for mix design of asphalt mixtures for the wearing course meets the design criteria established by the Iraqi Specification (SCRB, 2003).

##### *Effect of nano-alumina on bulk density*

The bulk density values increased from 2.301 g/cm<sup>3</sup> for the control mixture to 2.316, 2.321, and 2.314 g/cm<sup>3</sup> for mixtures modified with 2%, 4%, and 6% nano-alumina, respectively. The corresponding

increases are approximately 0.65%, 0.87%, and 0.57% compared with the control mixture. The increase in density up to 4% nano-alumina indicates an improvement in the compactness and internal structure of the asphalt mixture. Nano-alumina particles act as ultra-fine fillers capable of filling micro-voids between aggregate particles, leading to better particle packing and reduced internal air spaces. However, a slight reduction in density at 6% nano-alumina may be related to increased binder viscosity and reduced workability during compaction.

#### *Effect of nano-alumina on marshall stability*

Marshall Stability increased significantly with increasing nano-alumina content. The stability values increased from 9.13 kN for the control mixture to 9.78, 10.73, and 11.45 kN for mixtures modified with 2%, 4%, and 6% nano-alumina, respectively. These increases correspond to approximately 7.12%, 17.52%, and 25.41% compared with the control mixture. The improvement in stability can be attributed to the enhanced cohesion within the asphalt matrix and the stronger adhesion between asphalt binder and aggregate particles resulting from nano-alumina addition. Moreover, nano-alumina increases binder stiffness and improves stress distribution within the mixture, thereby increasing resistance to deformation and shear failure under loading conditions.

#### *Effect of nano-alumina on flow values*

The Flow values decreased from 3.58 mm for the control mixture to 3.41 mm and 3.52 mm for mixtures modified with 2% and 4% nano-alumina, corresponding to reductions of approximately 4.75% and 1.68%, respectively. However, the Flow value increased slightly to 3.69 mm at 6% nano-alumina, representing an increase of approximately 3.07% compared with the control mixture. The initial reduction in Flow values indicates improved stiffness and resistance to plastic deformation due to nano-alumina modification. On the other hand, the slight increase observed at 6% nano-alumina may be associated with the higher optimum asphalt content and increased binder viscosity, which could increase the plastic behavior of the mixture. In addition, excessive nano-particle concentration may reduce the efficiency of nano-particle dispersion within the asphalt matrix.

#### *Effect of nano-alumina on air voids*

The Air Void values decreased from 4.42% for the control mixture to 4.19%, 4.03%, and 4.11% for mixtures modified with 2%, 4%, and 6% nano-alumina, respectively. These reductions correspond to approximately 5.20%, 8.82%, and 7.01% compared with the control mixture. The reduction in air voids indicates improved compactness and denser internal structure resulting from the ability of nano-alumina particles to occupy micro-scale voids within the asphalt mixture. Additionally, improved asphalt coating and higher binder viscosity reduced air entrapment during compaction.

#### *Effect of Nano-alumina on VMA*

The VMA values remained relatively stable, varying between 16.48% and 16.87% for all mixtures. Compared with the control mixture (16.72%), the modified mixtures showed changes of approximately -1.44%, -0.54%, and +0.90% for 2%, 4%, and 6% nano-alumina, respectively. The relatively stable VMA values indicate that nano-alumina did not significantly alter the aggregate skeleton structure of the

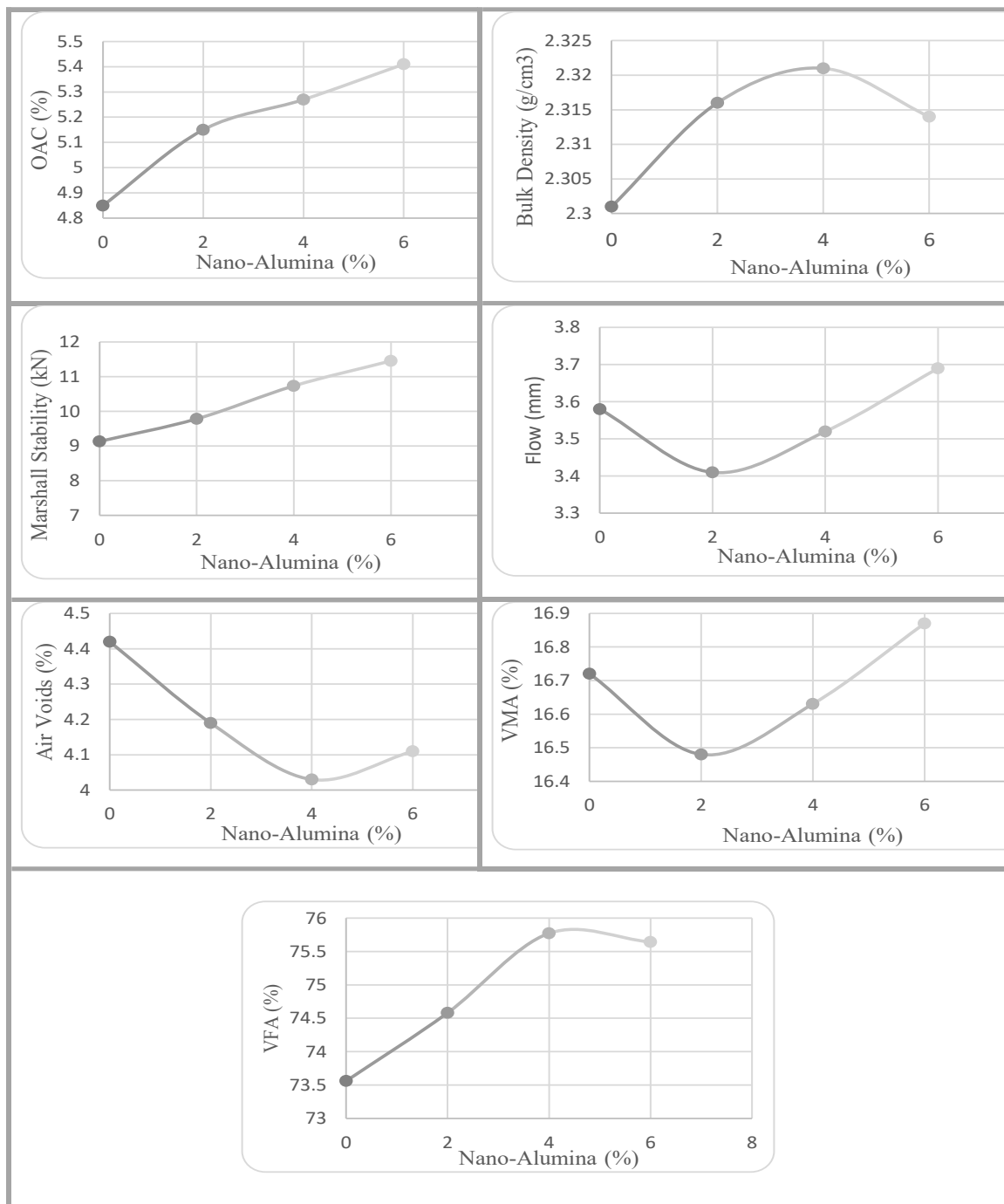
asphalt mixture. Instead, its influence is mainly related to improving binder distribution and filling micro-voids within the mixture. Maintaining stable VMA values is important to ensure sufficient space for asphalt binder while preserving mixture durability and resistance to deformation.

#### *Effect of nano-alumina on VFA*

The VFA values increased gradually from 73.56% for the control mixture to 74.58%, 75.77%, and 75.64% for mixtures modified with 2%, 4%, and 6% nano-alumina, respectively. These increases correspond to approximately 1.39%, 3.00%, and 2.83% compared with the control mixture. The increase in VFA is mainly associated with the increase in optimum asphalt content and the reduction in air voids, resulting in a greater portion of aggregate voids being filled with asphalt binder. Higher VFA values improve mixture cohesion and reduce permeability, thereby enhancing resistance to moisture damage and improving long-term durability. Similar propensities are reported by Cao et al. (2022), who found that nano-alumina improves binder efficiency and increases the percentage of voids filled with asphalt all results are shown below in Table 8 and Figure 6.

**Table 8** Effect of Nano-alumina on Marshall Properties of Asphalt Mixture.

| Nano alumina<br>(%) of AC                          | O.A.C<br>(%) | Bulk<br>Density<br>(gm/cm3) | Stability<br>(kN) | Flow<br>(mm) | Air<br>Voids<br>(%) | VMA<br>(%) | VFA<br>(%) |
|----------------------------------------------------|--------------|-----------------------------|-------------------|--------------|---------------------|------------|------------|
| 0                                                  | 4.85         | 2.301                       | 9.13              | 3.58         | 4.42                | 16.72      | 73.56      |
| 2                                                  | 5.15         | 2.316                       | 9.78              | 3.41         | 4.19                | 16.48      | 74.58      |
| 4                                                  | 5.27         | 2.321                       | 10.73             | 3.52         | 4.03                | 16.63      | 75.77      |
| 6                                                  | 5.41         | 2.314                       | 11.45             | 3.69         | 4.11                | 16.87      | 75.64      |
| <b>SCRB (R/9) Specification for Wearing Course</b> |              |                             |                   |              |                     |            |            |
| -----                                              | 4-6          | -----                       | 8 Min             | 2-4          | 3-5                 | 14 Min     | -----      |

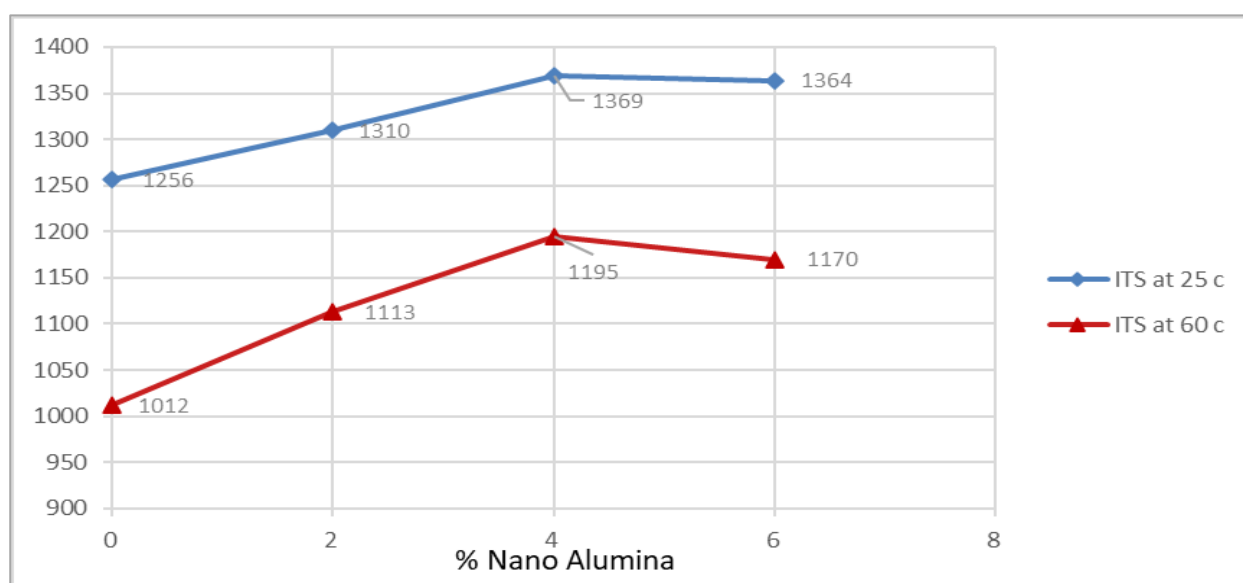


**Figure 6** Marshall Test Property Curves.

#### 4.3 Indirect tensile strength test results

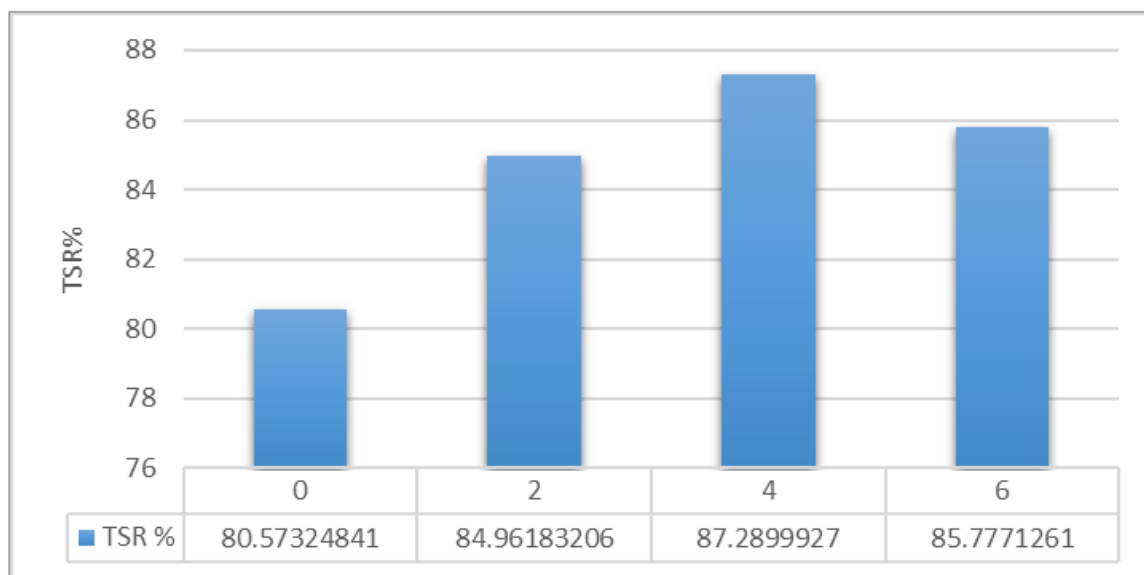
The dry indirect tensile strength (ITS) values increased with the addition of Nano alumina compared to the standard mix. The dry ITS increased from 1256 kPa for the standard mix to 1310, 1369, and 1364 kPa for the mixes modified with 2%, 4%, and 6% Nano alumina, respectively. These increases represent

approximately 4.30%, 8.99%, and 8.60% compared to the standard mix. This improvement in dry ITS indicates that the Nano alumina enhanced cohesion within the asphalt matrix and improved the bonding between the asphalt binder and the aggregate particles. However, a slight decrease is observed at 6% alumina nanoparticle content compared to the 4% content. This is likely due to particle agglomeration and increased viscosity of the binder at higher nanoparticle concentrations, which reduces the efficiency of nanoparticle dispersion within the mixture. Similarly, the wet indirect tensile strength (ITS) values increased significantly with the addition of Nano alumina. It is increased from 1012 kPa for the standard mixture to 1113, 1195, and 1170 kPa for the mixtures containing 2%, 4%, and 6% nano-alumina, respectively as shown in Figure 7. These increases represent approximately 9.98%, 18.08%, and 15.61% compared to the standard mixture. The greater improvement in wet ITS compared to dry ITS indicates that Nano alumina played a significant role in enhancing moisture resistance and mitigating the erosion effect caused by water infiltration. Nano alumina possesses a high specific surface area, which improves the asphalt layer around the aggregate particles and strengthens the adhesive bond within the mix.



**Figure 7** Effect of Nano alumina on Indirect Tensile Strength.

The tensile strength ratio (TSR) is also improved with the addition of Nano alumina to the mix. The TSR values increased from 80.57% for the standard mix to 84.96%, 87.29%, and 85.78% for the mixes modified with 2%, 4%, and 6% Nano alumina, respectively as shown in Figure 8. These increases represent approximately 5.45%, 8.34%, and 6.46% compared to the standard mix. This higher TSR value confirms the positive effect of Nano alumina on moisture resistance. The improved TSR values indicate that the modified mixtures retained a greater portion of their tensile strength after moisture curing, reflecting stronger bonding between the asphalt binder and aggregate particles, and improved mix durability under moisture conditions. Overall, the results show that the addition of Nano alumina significantly improved the tensile and moisture-resistant properties of the asphalt mixtures, particularly at a 4% nano alumina concentration, which exhibited the highest values for indirect tensile strength (ITS) and total tensile strength (TSR). These findings are consistent with previous studies published by [20] who confirmed that Nano alumina improves the cohesion of asphalt mixtures, reduces moisture susceptibility, and enhances tensile performance due to its filler effect and improved interaction between the binder and aggregate.

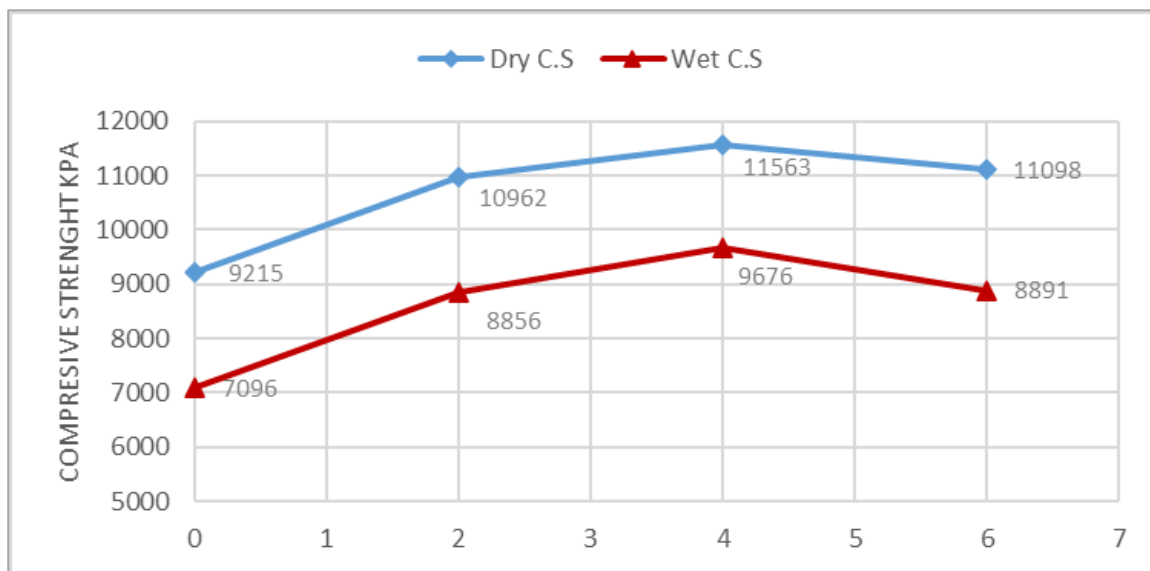


**Figure 8** Effect of nano alumina on the Tensile Strength ratio (TSR).

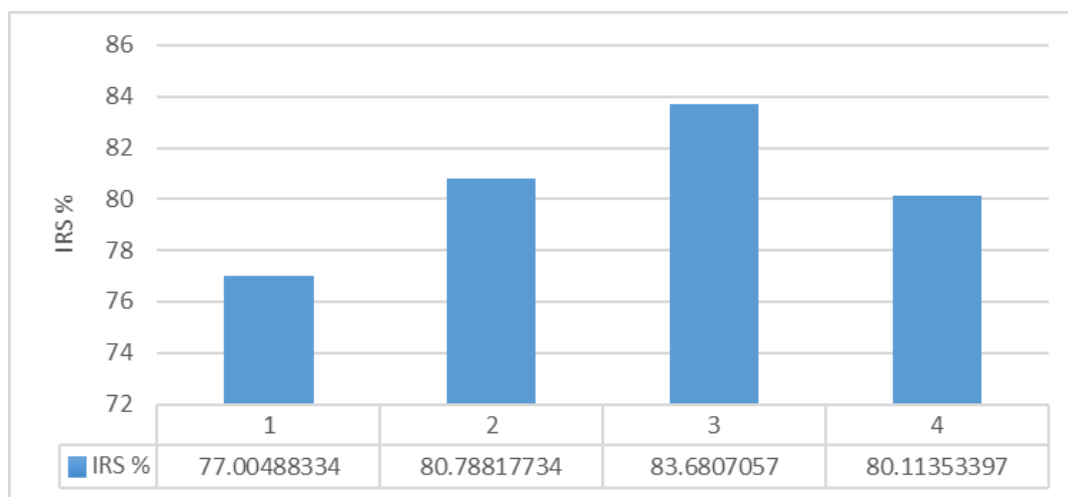
#### 4.4 Compressive strength test results

The dry compressive strength values increased with the addition of Nano alumina compared to the standard mix. The dry compressive strength rose from 9215 kPa for the standard mix to 10962, 11563, and 11098 kPa for the mixes modified with 2%, 4%, and 6% Nano alumina, respectively. The corresponding increases are approximately 18.96%, 25.48%, and 20.43% compared to the standard mix. This improvement in dry compressive strength indicates that the Nano alumina enhanced the internal cohesion of the asphalt mix and improved the bonding efficiency between the asphalt binder and the aggregate particles. However, a slight decrease is observed at 6% Nano alumina compared to 4%, which may be attributed to particle agglomeration and increased binder viscosity at higher nanoparticle concentrations, thus reducing the effective distribution of the Nano alumina within the mix. Similarly, wet compressive strength values increased significantly with increasing nano alumina content. The wet compressive strength increased from 7096 kPa for the standard mix to 8856, 9676, and 8891 kPa for mixes containing 2%, 4%, and 6% Nano alumina, respectively. These increases represent approximately 24.80%, 36.36%, and 25.30% compared to the standard mix. This marked improvement under wet conditions indicates that Nano alumina significantly enhanced the moisture resistance of the asphalt mixes and reduced the erosion effect caused by water seepage. The Nano alumina possess high surface activity, which strengthens the asphalt layer around the aggregate particles and reinforces the adhesive bonds within the mix. The residual resistance index (IRS) values also improved with the modification of the mix using Nano alumina. The internal compressive strength (IRS) increased from 77.00% for the standard mix to 80.79%, 83.68%, and 80.11% for the mixes modified with 2%, 4%, and 6% Nano alumina, respectively as shown in Fig 9 and 10. The higher IRS values indicate that the modified mixes retained a greater portion of their compressive strength after moisture curing, reflecting improved bonding between the asphalt binder and aggregate particles, and enhanced durability performance under moisture exposure. Overall, the results show that Nano alumina significantly improved the compressive and moisture-resistant properties of asphalt mixes, particularly at a 4% content, which exhibited the highest values for dry compressive strength, wet compressive strength, and internal compressive

strength. These results indicate that a moderate alumina nanoparticle content provides an optimal balance between stiffness, cohesion, and moisture resistance in hot asphalt mixes.



**Figure 9** Effect of Nano alumina on Compressive strength.



**Figure 10** Effect of Nano-alumina on IRS.

## 5. CONCLUSIONS

1. Nano-alumina modification significantly enhanced the rheological and thermal properties of asphalt cement AC (40–50). The reduction in penetration and ductility values, accompanied by increases in softening and flash points, indicates improved binder stiffness and higher resistance to temperature susceptibility.

2. The incorporation of nano-alumina improved the Marshall characteristics of asphalt mixtures through increasing Marshall Stability, bulk density, and optimum asphalt content, while reducing air void content. These improvements reflect better aggregate packing, enhanced binder–aggregate adhesion, and improved internal structure of the mixtures.
3. The modified asphalt mixtures exhibited higher indirect tensile strength, compressive strength, and retained strength under moisture conditioning compared with the control mixture. The improvement in ITS, compressive strength, TSR, and IRS values confirms the positive role of nano-alumina in enhancing moisture damage resistance and long-term durability of asphalt mixtures.
4. Based on the overall experimental evaluation, the asphalt mixture containing 4% nano-alumina demonstrated the optimum overall performance by achieving the best balance between mechanical strength, volumetric properties, and moisture resistance characteristics.

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