Stabilization of Pavement Granular Layer using Foamed and Emulsified Asphalt under Critical Low Temperature Conditions

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Abstract. One of the efficient techniques that is currently used in pavement engineering to improve the stress–strain response conditions of the pavement structure includes the stabilization of its structural layer components. There are several laying techniques that include the usage of stabilizing agents such as emulsified and foamed asphalt. In these technologies, the temperature of the environment is observed to play a critical role. This condition is often considered to be the main factor that encourages the usage of foamed asphalt for stabilization. Further, the aforementioned technique specifies that, at temperatures of approximately 10 °C or lower, the asphalt particles are not effectively inserted in the foamed granular material mastic; they are instead merged with other asphalt particles. This causes an agglomeration of coalesced asphalt, prevents adequate foaming, and hinders the pavement layer from compaction. In such a situation, the pavement will exhibit a structural strength deficiency. Therefore, this study experimentally investigates the environmental temperatures at which an efficient layer that is stabilized using foamed asphalt may be obtained both in the laboratory as well as in the field. Further, this study proposes a new limit. Apart from exceeding this temperature limit, the study also offers an alternative with respect to the usage of asphalt emulsions to stabilize the granular layer. This technique comprises the dispersion of asphalt particles in an aqueous medium; however, when this technique is applied at low temperatures, the low temperatures do not allow the system to reach a critical condition of inapplicability, which is observed when the asphalt foam is used for stabilization. Further, the mechanical behaviors of the foamed pavement at temperatures of lower than 10 °C are discussed. Additionally, this study exhibits the results of stabilized layers that use a slow-setting asphalt emulsion (CSS-1h) as a solution to the temperature problem that is associated with the usage of the foaming technique. The investigation is performed based on a project that is conducted in the extremely low temperature areas of the Peruvian Andean highlands, which are located at an altitude of 4,000 to 5,000 meters above the sea level.

1. Introduction
The usage of foamed asphalt and asphalt emulsions as stabilization techniques for the granular layers of pavements has been increasing. Both foamed asphalt and asphalt emulsions efficiently increase the structural strength of the material that is measured in the compact condition. These methods, which were initially introduced in the United States market during the 1950s, exhibited various advantages such as low energy consumption, reduction in emissions, and improvement in the support capacity of the mixture after compaction [1]. Currently, based on modern techniques, we can observe that both the methods provide excellent stabilization alternatives [2].

Recent studies have denoted that the usage of foamed and emulsified pavements exhibit better resistance to the damage caused due to moisture and fatigue as well as permanent deformation as
compared to that exhibited by the traditional granular base layers [3]. Both stabilizing techniques are observed to add asphalt to the granular material in different manners.

Foamed asphalt is a physical process during which a thermal shock is observed when hot asphalt comes in contact with water, which results in the formation of asphalt bubbles filled with water vapor [4]. These bubbles coming into contact with the aggregates results in expansion. This will be effective if they fall into the mastic, which is a fine fraction that comprises sand, Portland cement, and water, and form connectors that increase the cohesion of the mixture [5].

However, low temperatures cause the optimum asphalt and water temperatures that are required for the occurrence of thermal shock to drop rapidly. This causes the foaming quality indicators, such as expansion ratio and half-life, to exhibit values that are lower than the expected values, thus reducing the foaming quality. Further, these low temperatures cause the aggregates to cool down in such a manner that the asphalt particles are not able to connect in the aforementioned fine fraction, which makes it impossible to form ductile connectors as a consequence of poor foaming [6].

Additionally, emulsions do not require asphalt to be heated to high temperatures of 160 °C–180 °C, which is a temperature range that is similar to that observed in the case of foaming. Further, the asphalt emulsion forms an electrochemical process comprising asphalt, water, and an emulsifying agent. The asphalt particles are dispersed in water because of the temporary effect of the emulsifier. To combine the asphalt particles with the granular material, the breaking and curing processes must be conducted. The first process that can be referred to as emulsion breaking occurs when the water is separated from the asphalt and begins to evaporate. In the second process, or system curing, the water completely evaporates, leaving the asphalt bound in the aggregates [7].

The objective of this study is to define the temperature conditions under which foamed asphalt and asphalt emulsions can be effectively used, which can be further used to validate the application of these techniques with respect to quality parameters such as indirect tensile strength (ITS), loss of stability, and the compaction and deflectometry controls. The experiments that are associated with this study are performed in a construction project that is located between the cities of Tacna and Puno, Peruvian highlands, at very low temperatures. Additionally, the highest sections of this road are observed to be located 4,800 meters above sea level.

2. Background: design of a mixture stabilized with foamed asphalt
This study began using the initial laboratory test results that were obtained for the foamed asphalt design based on the specifications from the Wirtgen Manual. Because the granular material that was to be stabilized did not exhibit a plasticity index, 1% of the Portland cement was used as the active filler. Based on the foaming laboratory design, it can be determined that the factors that achieved the most efficient foaming, in terms of both expansion ratio and half-life, corresponded to the usage of asphalt cement 85/100 penetration grade at a temperature of 160 °C and in the presence of 2% water. Using this combination, samples were manufactured with 1.5%, 2%, and 2.5% asphalt content to evaluate the combination that provided the optimal stabilization conditions for the granular material. The specimens in a compact condition were subjected to the Marshall press to determine their ITS in dry and saturated conditions, establishing 2% of residual asphalt as the optimum value for the foamed mixture.

However, despite the fact that the design of the mixture that was stabilized with foamed asphalt was successful in the laboratory during the early stages, progressive difficulties were reported in preparing and laying the foamed mixture during the construction process in the field. The conditions of the construction work increased in altitude and decreased in temperature; thus, unfavorable temperature conditions were achieved, and these results were further verified in the laboratory. While achieving a temperature of 7 °C or lower, which is characteristic of the Peruvian highlands in this sector at which large extensions are observed at an altitude of 4,000 meters above the sea level, the foaming quality was observed to be considerably diminished by the adverse climate. Thus, during the foaming process, water and asphalt entered the expansion chamber, which further resulted in the production of thermal shock at lower temperatures than those recommended in the design. Further, asphalt bubbles were dispersed over very cold aggregates, which caused poor foaming and stabilization.
Figure 1. (a) Asphalt particles coalesced in the field. (b) Specimens manufactured using the foamed material with coalesced asphalt connectors.

Such circumstances caused the inefficient insertion of asphalt particles as connectors in the mastic. This resulted in the formation of coalescing asphalt masses, which are colloquially referred to as gummy asphalt, as depicted in figure 1a.

In figure 1b, the base foaming material is taken to the laboratory, where it was compacted and subjected to the Marshall press to determine its ITS using the ITS test. The obtained ITS values were observed to be lower than those recommended for the technique: 200 kPa, 100 kPa, and 50% ITS in dry, saturated, and retained strength, respectively.

| Table 1. Structural strength of the foamed mixture in a compact condition. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Sector km                      | Density (g/cm³) | Humidity (%)    | Strength (kPa)  | Retained Strength (%) |
| 126+000 to 127+000             | 2,116           | 7.9             | 180.9           | 45.4             |
|                                | 2,016           | 7.0             | 171.3           |                  |
|                                | 2,073           | 7.9             | 187.3           |                  |
|                                | 2,106           | 7.4             | 80.3            |                  |
|                                | 2,093           | 7.0             | 88.0            |                  |
|                                | 2,011           | 8.2             | 76.8            |                  |
| Average                        | 2,069           | 7.5             | 179.8           | 81.7             |

3. Method: design of the stabilized mixture with asphalt emulsions
In the first stage, the quality control of the granular material that was to be stabilized was performed. Aggregates were procured from the Tasabaya Quarry, which is located 86 km away from Tacna, Peru. The results of the laboratory tests that were performed on aggregates, as presented in table 2, were obtained based on the specifications of the ASTM (American Society for Testing and Materials) and the Ministry of Transport and Communications [8].
Table 2. The results of the granular material laboratory tests.

| Test                                      | Standard          | Result | MTC Specification |
|-------------------------------------------|-------------------|--------|-------------------|
| Fine Material (%)                         | ASTM D 6913 / MTC E 202 | 8.70   | Maximum 10%       |
| Liquid Limit (%)                          | ASTM D 4318 / MTC E 110 | 18.0   |                   |
| Plasticity Index (%)                      | ASTM D 4318 / MTC E 111 | NP     | Maximum 9%        |
| Sand Equivalent (%)                       | ASTM D 2419 / MTC E 114 | 34.0   |                   |
| Los Angeles Abrasion (%)                  | ASTM D 131 / MTC E 207 | 31.5   | Maximum 50%       |
| Loss with Magnesium Sulphate for Coarse Aggregate (%) | ASTM D 88 / MTC E 209 | 14.96  | Maximum 18%       |
| Loss with Magnesium Sulphate for Fine Aggregate (%) | ASTM D 88 / MTC E 209 | 2.90   | Maximum 15%       |

The Illinois methodology was used to design the granular material that was stabilized using emulsions with an objective of determining the optimum content of residual asphalt using a slow-setting cationic emulsion (CSS-1H), which exhibited a penetration of 75 mm at 25 °C. The product was observed to be compliant with the ASTM D2397-13 specifications. The initial step was to evaluate the theoretical residual asphalt content, which was 2%. Using this value, Marshall briquettes were prepared at 75 strokes per face at different moisture contents to determine the optimum water content for compaction, which was 8.6%. Briquettes were prepared again with an optimum moisture content and at different residual asphalt contents of 1%, 2%, and 3%. Half of these samples were subjected to the Marshall press under dry conditions, and the other half under saturated conditions. The Marshall dry and wet stability values were found, which are demonstrated in figure 2 (a). Therefore, an optimum residual asphalt content of 2% was selected, because the highest Wet Marshall Stability of 1052.5 kgf and a loss of stability of 49.4% was achieved with this value. Also, the highest Dry Bulk Density of 2,162 g / cm3 was obtained, which is demonstrated in figure 2 (b) with a percentage of air voids of 13.55%. These results allowed the stabilization of the granular layer of the pavement with asphalt emulsion to have the highest resistance under critical conditions of the environment to which it would be subjected.

![Figure 2](image_url)

Figure 2. (a) Dry (top line) and wet (bottom line) Marshall stabilities. (b) The dry bulk density at different contents of residual asphalt.

4. Results
The laboratory design of the granular layer that was stabilized with asphalt emulsions at 2% residual asphalt was observed to be efficient at low temperature climate conditions, since this technique was not incidentally dependent on the climatic conditions that were observed at temperatures of 10 °C and more. This was similar to that observed in the case of the foamed asphalt, which required adequate foaming and adequate insertion of the connectors in the foamed mastic with aggregates at equally controlled temperatures. Further, the asphalt was temporarily dispersed in water due to an emulsifying
agent to ensure stabilization with emulsions. This aqueous solution was maintained at a temperature of 30 °C.

This can be verified using field results that involved compaction degree controls that were performed every 50 meters, accepting a minimum compaction of 98% Maximum Dry Density. This was completed with the results of the deflectometry, using the Benkelman Beam every 25 meters alternating lane, to determine if the deflection was recoverable at the passage of the load, compared to the admissible deflection value of 0.95mm. These controls can be observed in figure 3 (a) and (b).

![Figure 3. (a) Degree of compaction of the layer stabilized with asphalt emulsions. (b) Pavement deflections measured with the Benkelman beam.](image)

Similarly, the stock material that was emulsified in the field can be taken to the laboratory to verify whether the production complied with stability losses of less than 50%, as depicted in table 3.

**Table 3. The results of the granular material laboratory tests.**

| Nmbr | Dry density (g/cm³) | Dry load (kgf) | Wet load (kgf) | Loss of Stability (%) |
|------|---------------------|----------------|----------------|-----------------------|
| 1    | 1,832               | 2181.47        | 1444.35        | 33.8                 |
| 2    | 1,867               | 1731.59        | 988.14         | 42.9                 |
| 3    | 1,921               | 1375.50        | 926.90         | 32.6                 |
| 4    | 1,821               | 1443.47        | 975.55         | 32.4                 |
| 5    | 1,941               | 1302.53        | 781.40         | 40.0                 |

Finally, the versatility of the stabilization of granular materials with asphalt emulsions as compared to the stabilization of granular materials with foamed asphalt was demonstrated in low temperature conditions (5 °C). This can be verified when the quality parameters of the finished product are satisfied from 126 + 000 km to 146 + 000 km, when compaction grades are greater than 98%, deflections are less than 0.95 mm, and loss of stability is less than 50% are observed.

**5. Conclusions**

The climate temperatures are fundamental in stabilizing the pavement granular materials with foamed asphalt, since proper foaming is not achieved at low temperatures. In the case of the project analyzed in this study in the Peruvian Puno highlands (one of the few places in the world where large extensions, not only steps, are located at an altitude of more than 4,000 meters above the sea level), efficiently foamed asphalt mixtures could be achieved at a temperature of 7 °C. The quality of the foaming was poor below this temperature. Further, stabilization with foamed asphalt could not be achieved along with cold aggregates, which generated massive coalesced asphalt agglomerations that were immersed
in the foamed granular mass, as evidenced in both the laboratory and the field.

Before this thermodynamic environmental issue was observed, the stabilization of granular layers with asphalt emulsions achieved a structural contribution that was equal to the results obtained using granular layers that were stabilized with foamed asphalt. Further, no changes were observed in the thickness of the stabilized layer, and the dosage of the asphalt cement that was required to stabilize the granular material was not affected, which ensured that the residual asphalt would remain 2% in both the techniques. The important factor was the variation that was observed during the construction procedure; the emulsions worked and managed the asphalt in a manner that effectively controlled the adversities encountered at low temperatures, thereby facilitating the stabilization of the granular layer with asphalt emulsions.

Both techniques exhibited discontinuous ductile ligament stabilizations, which further provided higher structural capacity, less deterioration from fatigue and less failure due to permanent deformation, thus creating a new group of efficient materials in the stabilization of pavements.

6. References
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