Monitoring Asphalt Concrete Performance at High Altitudes in the Peruvian Andes

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Thermal cracking in Peru usually occurs in roads with elevations higher than 3,700 meters above sea level (MASL). Asphalt pavements at elevations between 3,700 and 4,300 MASL usually develop thermal cracking, but this type of distress is more severe at even higher altitudes, especially with the combined effects of the large amount of solar radiation, daily temperature cycle, and relatively large amounts of precipitation. The asphalt concrete (AC) thickness of 8 to 12 cm in the La Oroya-Cerro de Pasco Road was designed to carry traffic of approximately 1,000 trucks per day. When the asphalt mixture was designed and constructed according to standard practice and specifications, severe longitudinal cracking appeared 5 to 8 months after completion of construction. In order to reduce this thermal cracking, the following material characteristics and construction procedures were analyzed: (a) engineering properties of the top crude and the asphalt cement; (b) engineering properties of aggregates, particularly those used for fines and filler materials; (c) optimum heating temperature of the asphalt aggregates before mixing; (d) minimum air temperature at which AC can be laid and compacted; (e) measures taken to protect the prime coat and base course; (f) types of asphalt cements used and their respective engineering properties; (g) tensile strength and workability characteristics of the AC mixture; and (h) types and quantities of additives. Preliminary conclusions of specification modification have been adopted by the Peruvian road authorities to improve asphalt performance at high altitudes.

Thermal cracking is the major cause of distress in asphalt concrete (AC) in the higher altitudes of the Peruvian Andes. The main factor causing such cracking is the daily extreme temperature variation that results in repeated tensile stresses and strains, causing rapid thermal fatigue. The Andes cross Peru in a north-south direction at elevations between 2,000 and 5,000 meters above sea level (MASL).

Daily variation in air temperature at altitudes of over 3,700 MASL is between −5°C and +30°C and is accompanied by strong solar radiation. The 120-km asphalt road that connects La Oroya and Cerro de Pasco is located at elevations between 4,100 and 4,350 MASL. Typical hourly and daily air temperature changes at 4,100 MASL are shown in Figures 1 and 2. Figure 1 shows the hourly temperature changes recorded from April 26 to 28, 1982, and indicates that the daily air temperature is above the freezing point for only about 8 to 10 hr, resulting in alternate freezing and thawing.

The AC in the La Oroya-Cerro de Pasco Road was 8 to 12 cm thick. The 12 cm of AC was designed to carry traffic of approximately 1,000 (mostly overloaded) trucks per day. Although the pavement structure and material properties for the road conformed to AASHTO and ASTM standard design procedures and specifications (*1–3*), severe cracking appeared 5 to 8 months after construction. This cracking usually occurs in the form of longitudinal cracks, combined with some transverse cracking. Longitudinal cracks usually appeared after 5 to 6 months, and usually in the lane or road center as shown in Figure 3. This thermal cracking was not associated with traffic stresses. After 3 to 5 months, transverse cracking appeared on the road surface, as shown in Figure 4. Two years after construction, the road surface was severely cracked, as shown in Figure 5. With no modification of the specifications or construction procedures, pavement that was designed for 15 to 20 years was completely cracked after approximately 3 years, as shown in Figure 6. In order to reduce this thermal cracking, the following material characteristics and construction procedures were analyzed:

- Engineering properties of the top crude and asphalt cement;
- Engineering properties of aggregates, particularly those used for fines and filler;
- Optimum heating temperature of the asphalt aggregates before mixing;
- Minimum air temperature at which AC can be laid and compacted;
- Measures taken to protect the prime coat and base course;
- Types of asphalt cements used and their respective engineering properties;
- Tensile strength and workability characteristic of the AC mixture; and
- Types and quantities of additives.

ENGINEERING PROPERTIES OF TOP CRUDE OIL AND ASPHALT CEMENT

The original design of the AC specifies the use of an 85 to 100 penetration (in 0.1 mm) of asphalt cement. The asphalt cement actually used in the road has a penetration of 90, 2.5 percent of wax, and fulfills the specification requirements of AASHTO M20-70. The AC produced with this cement developed 3- to 4-mm widths of longitudinal and 1- to 2-mm widths of transverse cracking 5 to 8 months after the completion of construction. In order to better understand and identify the reasons for such cracking, the chemical properties of the crude oil were analyzed.

The asphalt cement in Peru is produced by the government's national petroleum company, Petro Peru. A mix of crude oil produced by Petro Peru comes mainly from the Peruvian Amazonian region and is used to produce the asphalt cement. The crude obtained from the primary distillation used for

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the asphalt production for high altitudes has the properties presented in Table 1.

The American Petroleum Institute (API) crude density value of 18.7° presented in Table 1 indicates that the crude is chemically classified as Naftanic (*4*). Because the crude API is less than 35°, it is adequate for production of asphalt cement for normal environmental conditions (*5,6*). Petro Peru also produces crude oil with an API density of over 35° (*7*) that was not used to produce asphalt cement for high altitudes.

The Watson characterization factor K_W (*4,5*) is used to analyze the adequacy of the topped crude to produce the appropriate asphalt cement.

$$K_W = \frac{T_B^{1/3}}{G} \tag{1}$$

where

K_W = Watson characterization factor,
T_B = crude fermenting temperature in °R, and
G = crude specific gravity at 60°F.

Tests by Petro Peru show that T_B = 1,304°R and G = 0.9421 (Table 1); therefore, according to Equation 1, K_W = 11.6, which is less than 11.8, the permissible upper limit (*5,6*). Therefore, the two Peruvian topped crude quality indicators, API < 35° and K_W < 11.8, indicate that this crude is adequate for asphalt cement production (*5,6*). This conclusion was verified in Peru only for asphalt pavement constructed below 3,700 MASL. The asphalt thermal cracking is far less severe at altitudes below 3,700 MASL. Because of the extensive thermal cracking at altitudes higher than 4,100 MASL with this asphalt cement, the Peruvian Road Authority decided to

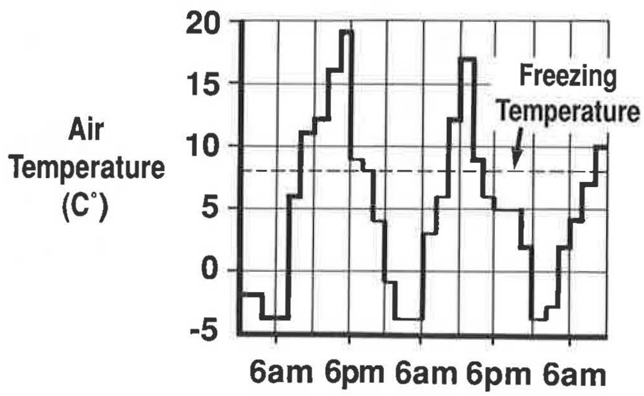

FIGURE 1 Changes of hourly air temperature, Oroya-Cerro de Pasco Road at 4,100 MASL, April 26–28, 1982.

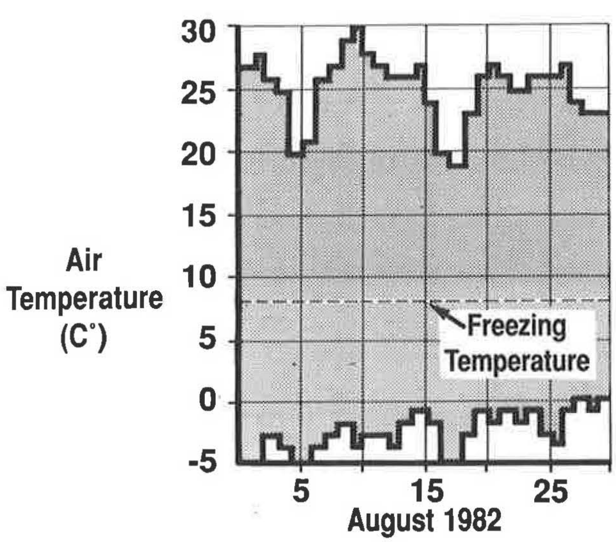

FIGURE 2 Typical changes of daily air temperature, Oroya-Cerro de Pasco Road at 4,100 MASL.

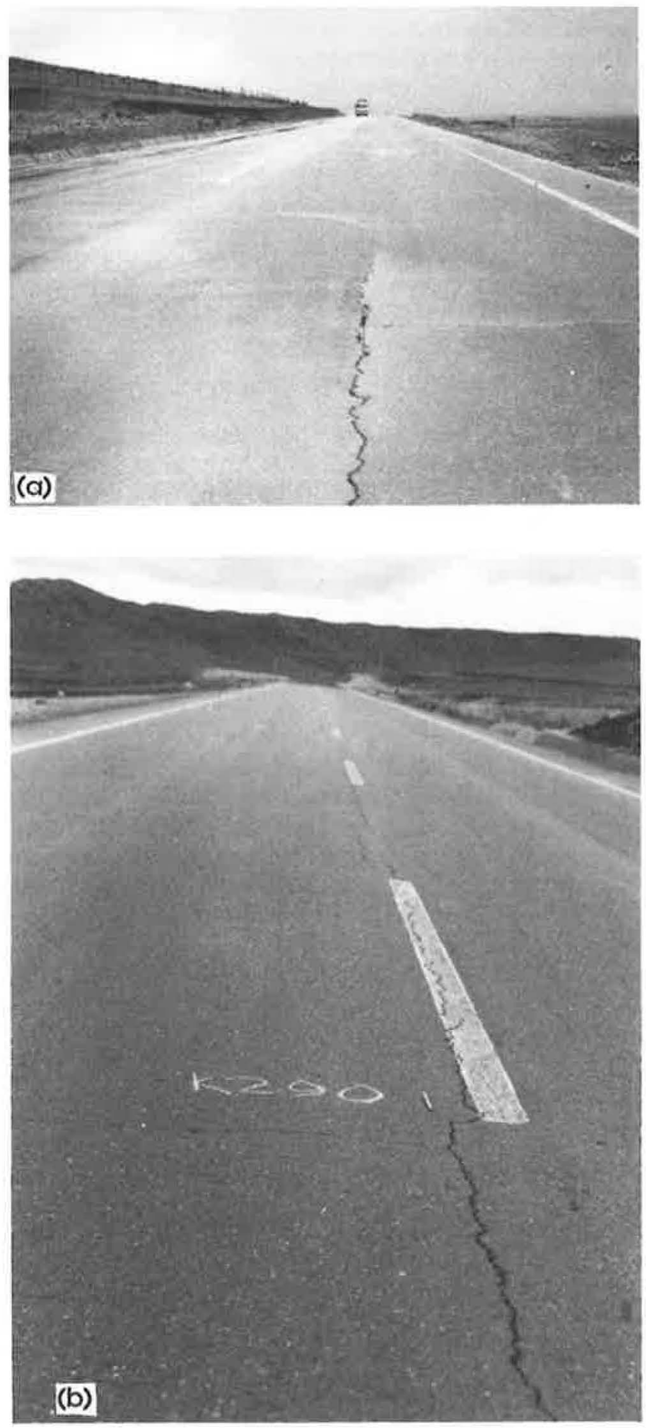

FIGURE 3 a, Typical longitudinal cracking; b, typical longitudinal joint cracking.

FIGURE 4 Typical transverse cracking.

FIGURE 5 Typical pavement cracking, 2 years after completion of construction.

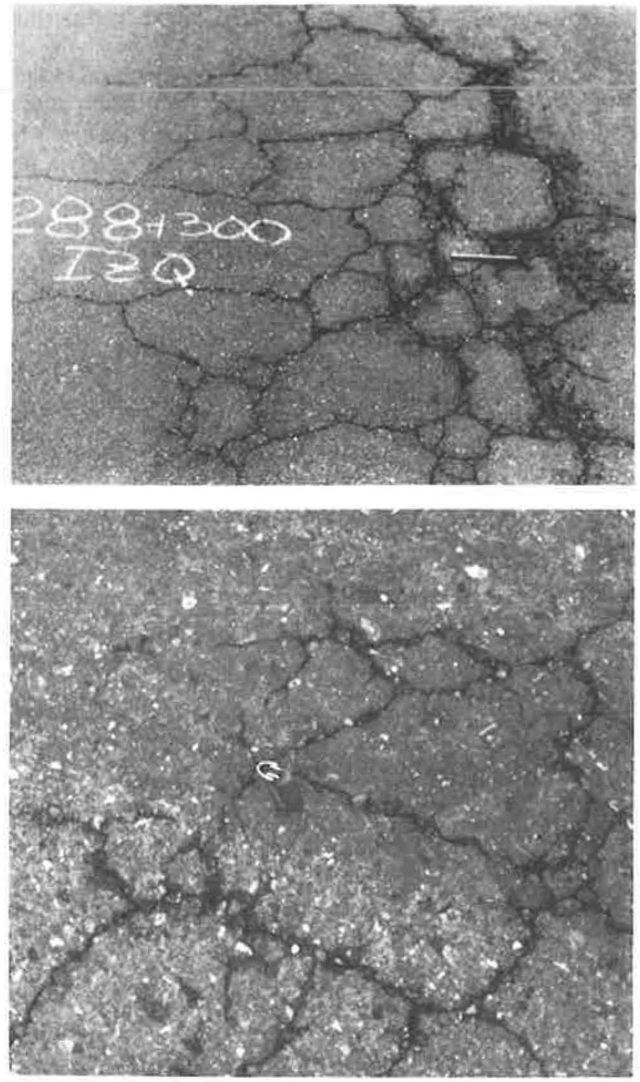

FIGURE 6 Typical pavement cracking, 3 years after completion of construction.

use a combination of mix crude with $K_W < 11$, and preferably $K_W = 10.0$ to 10.5. This crude contains mainly pure aromatic ($K_W = 10$) or Naftanic ($K_W = 10.5$). The road authority also decided that although trucks in Peru are usually overloaded, 120–150 penetration (in 0.1 mm) asphalt was more appropriate than 85–100 AC for reducing thermal cracking with no significant increases in surface rutting. Implementation and monitoring of these conclusions are scheduled after new asphalt road and highway projects are completed in the Peruvian high-altitude region.

ANALYSIS OF THERMAL CRACKING

Severe temperature variations that cause stiffness changes in the asphalt layers are known to develop thermal cracking (*8–12*). In order to analyze the relationship between thermal cracking occurring after the completion of some road sections and asphalt properties, the relationship between the asphalt stiffness changes in the road and its penetration index were investigated. The penetration index (PI) is used as an indicator of the asphalt cement's elastic viscous properties. The investigation in Peru was carried out with three 85–100 penetration (in 0.1 mm) asphalt cements with penetration index values of −0.15, −0.50, and +0.90. The extreme asphalt stiffness changes occurring in high altitudes were calculated using the extreme representative temperatures of −5°C and +20°C for maximum and minimum asphalt stiffness in the La Oroya-Cerro de Pasco Road. The stiffnesses of both the original asphalt cement and the residue after the thin-film oven test (TFOT) were determined (*8–10*). For all three asphalts, the maximum and minimum stiffnesses were determined for loading periods of 0.01 and 0.1 sec, respectively. Table 2 presents the relationship between the asphalt penetration index, asphalt stiffness changes, and actual road surface cracking.

Table 2 indicates that surface cracking in high altitudes occurs earlier and more severely when (a) the value of the penetration index is 0.9, and (b) the calculated stiffness changes after TFOT are greater than 4,000 kg/cm^2. Significantly less cracking occurred when the stiffness changes after TFOT were less than 3,000 kg/cm^2. This conclusion was verified in mountainous areas, below 3,700 MASL. In these lower altitudes, stiffness changes in residue from TFOT were less than 3,000 kg/cm^2. No thermal cracking occurred at altitudes below 3,700 MASL.

The relative inferiority of asphalt with the higher penetration index of 0.9 was also determined by testing asphalt samples extracted from the La Oroya-Cerro de Pasco Road pavement at an elevation of 4,100 MASL after 11 months of service. The asphalt properties are presented in Table 3. The conclusion from this study adopted by the Peruvian Road Authority was that for high altitudes the asphalt stiffness changes and the penetration index should be limited. The absolute value of the penetration index was limited to 0.5 or less. The Peruvian findings and conclusions are equivalent to the finding of Marks et al. (*11*) that the use of a highly temperature-susceptible asphalt cement produced severe transverse cracking. Marks et al. analyzed the relationship between temperature susceptibility of asphalt, its stiffness, and the frequency of transverse cracking, by using the Pen-Vis number (PVN) developed by McLeod (*12*). PVN values represent the rela-

TABLE 1 PROPERTIES OF THE PERUVIAN TOPPED CRUDE

Test Description	Crude Test Result	ASTM Designation	ASTM Specification Minimum	ASTM Specification Maximum
API Gravity (°API)	+ 18.7	D 287	15	35
Specific Gravity (60°F)	+ 0.9421	D3142	0.865	0.996
Viscosity, Saybolt Furol (210° F)	+ 99	E 102	-	-
Kinematic Viscosity (210° F)	+ 25	D2170	-	-
Universal Saybolt Viscosity (210° F)	+ 122	D2161	-	-
Draining Point (°F)	+70	D 97	14	-
Salts (lb/1,000 barrels)	50	D 3220	5	150
η - Heptane Insoluble (%)	0.96	D 3279	0.9	16
Solubility in Trichloroethylene (%)	99.7	D2042	99	-
Index of Acidity (mg KOH/yr)	0.175	D 664	-	1.0

TABLE 2 RELATIONSHIP BETWEEN ASPHALT STIFFNESS CHANGES, PENETRATION INDEX, AND SURFACE CRACKING (AC: 85–100)

Asphalt Penetration Index	Stiffness Changes (kg/cm) - 5° C, 0.01 sec + 20° C, 0.1 sec	Period After Completion of Construction with Minor or No Cracking
-0.15, - 0.50	1. Original AC: less than 2,000 2. AC After TFOT: less than 3,000	3 years
+ 0.9	1. Original AC: over 3,000 2. AC After TFOT: over 4,000	5 - 8 months

TABLE 3 ASPHALT PROPERTIES BEFORE AND AFTER USE IN THE ROAD AFTER 11 MONTHS ON THE ROAD

Asphalt Property	Original Value (Before Use)	Penetration Index +0.9	Penetration Index -0.15-0.5
Penetration	90	28-41	50-60
Softening Point	49°C	75-100°C	-
Penetration Index	+0.90 -0.15-0.50	5.2-6.6 -	- 2.0-2.5

tionship between the asphalt viscosity at 140°F and the penetration at 77°F. McLeod established that PVN = 0 represents an excellent AC with low temperature susceptibility. PVN = 0 is equivalent to the penetration index's being zero; PVN = 1.5 represents an AC with high temperature susceptibility.

AGGREGATE AND MATERIAL PROPERTIES

The aggregates commonly used both for base course and AC are partially crushed gravel that meets AASHTO and ASTM standard specifications for road construction. The aggregate chemical analysis had the following composition: $CaCO_3$ (60 percent), $MgCO_3$ (6 percent), SiO_2 (29 percent), and other materials (5 percent). The aggregate absorption to water and asphalt was 1.0 to 1.6 percent and 0.3 to 0.5 percent, respectively. When thermal cracking commenced 5 to 8 months after construction, the road authorities started to monitor and compare the asphalt surface conditions with the construction and quality control records. These records indicated that less thermal cracking occurs when the base course and AC materials have the following two properties:

1. The base course is open-graded nonplastic that was prime coated immediately after compaction. Proper coating was defined when the prime coat penetrated 20 mm or more into the base course materials. With good pavement drainage and proper surface sealing, less humidity was present in the base course and the daily freeze and thaw were reduced. Because it is almost economically impossible in the Peruvian mountain area to construct an open base course that meets a minimum California bearing ratio (CBR) of 80, zero plastic index, and zero passing sieve 200, the road authority decided to limit the plastic index and the percentage passing sieve 200 to 2 and 5 percent, respectively.
2. The AC fine aggregate material passing sieves 40 and 200 is nonplastic. The construction record shows that this conclusion is less significant if an additive in the form of hydrated lime is added to the AC mix.

CONSTRUCTION CONSIDERATIONS

Heating Temperature

The temperature range for heating the AC in Peru followed standard practice that specifies Sabolt Furol viscosity of 75 to 150 SSF to achieve proper coating. This criterion has been appropriate for achieving adequate aggregate coating at altitudes below 3,700 MASL. At altitudes above 4,100 MASL, where the air pressure is about 0.6 atmospheres, relatively poor coating was achieved when asphalt viscosity during standard mixing procedures in the asphalt plant was 120 SSF or more. Better aggregate coating was achieved when the asphalt viscosity range during mixing was narrowed to 75 to 100 SSF. These viscosity limits occur at temperatures of 145°C and 140°C, respectively. Because reducing the heating temperature in the high altitude also reduces asphalt oxidation, for better control the asphalt heating temperature should be established at 140°C to achieve adequate coating at viscosity of 100 SSF.

Compaction of AC

The standard practice in Peru of compacting AC mixtures permits breakdown at 100°C to 110°C, and compaction is completed before the mix temperature drops to 70°C. This compaction temperature control permits the achievement of adequate density. The air voids in the compacted mixture range between 3 and 6 percent. Implementation of this temperature compaction control in high altitudes resulted in lower density and significantly higher air voids in the compacted mix, mainly between 8 and 11 percent. Only a slight reduction in air voids in the compacted mix, with no significant reduction in stability, was obtained when the amount of asphalt cement in the mixture was increased beyond the optimum determined according to the Marshall design procedure. From the experience obtained on the La Oroya-Cerro de Pasco road project, it was concluded that proper density and air voids can be achieved only if the compaction breakdown is done when the mix temperature is 115°C to 130°C and compaction is completed before the asphalt mixture temperature in the road drops to 90°C or 85°C. Difficulties in obtaining the proper density and percentage of air voids were recorded when the ambient air temperature dropped to 15°C or less. Road sections where the AC mixture was laid when the ambient air temperature was between 12°C and 15°C show relatively lower densities or higher air voids of approximately 5 to 8 percent and were associated with accelerated surface cracking. Severe surface cracking occurred when compaction was carried out in an ambient air temperature below 12°C. On the basis of this experience, the Peruvian Road Authority specified that in high altitudes the AC can be laid when the ambient air temperature is above 12°C as it rises and above 15°C as it drops. This severe requirement significantly limits the daily AC construction period to about 5 to 6 hr, which naturally increases construction costs.

Longitudinal Joint Construction

Standard construction procedures such as sawing, tack coating, or heating, failed to prevent joint cracking along the La Oroya-Cerro de Pasco Road, as shown in Figure 3b. This type of distress can be reduced when the full asphalt road width is constructed simultaneously.

In the Juliaca Airport asphalt pavement project constructed at an elevation of 3,890 MASL, thermal cracking had not developed 2 years after construction. In this project (see Figure 7), the conclusions obtained from the La Oroya-Cerro de Pasco highway were implemented.

AC MIXTURE ADDITIVES

In order to improve asphalt pavement performance, the Peruvian Road Authority studied the use of different additives for asphalt mixes. For Peru, the most practical and easy-to-use asphalt additives are portland cement and hydrated lime. These additives are usually used when the quantity of mineral filler is insufficient or when the fine material or AC does not meet standard specifications. Usually 1.0 to 1.5 percent of the mix of hydrated lime, or 2 to 3 percent of portland cement, is sufficient to improve the AC mix and to fulfill Marshall design procedures and immersion compression strength criteria. Using hydrated lime was especially successful and was in accordance with the findings of the National Lime Association (*13*) and Plancher et al. (*14*). The conclusions of the Peruvian experience in using lime in asphalt mixtures are as follows:

- Lime, which reduces stripping of asphalt from aggregates, absorption of water, and swell, makes the pavement more waterproof.

FIGURE 7 AC surface condition—Juliaca Airport at 3,890 MASL.

- Lime increases strength, stability, and resistance to water immersion; improves durability; raises the asphalt viscosity; eliminates tender mixes; and helps to achieve specified densities.
- Lime neutralizes acid aggregates and permits the use of local submarginal aggregates.
- Lime improves surface conditions and reduces oxidation and surface aging.

Lime treatment removes polar viscosity-building components and reduces the susceptibility of the asphalt to laboratory oxidative hardening. The benefits of lime treatment in reducing asphalt oxidative hardening are attributed to two synergistic effects: (a) lime reduces the formation of oxidation products by removing oxidation catalysts or promoters, and (b) lime reduces the sensitivity of the asphalt to these oxidation products by removing polar molecules that would otherwise interact with the oxidation products to cause an increase in viscosity.

The first road section between La Oroya and Cerro de Pasco was constructed without any lime in the AC mix because the local filler was nonplastic with 60 percent of $CaCO_3$ and both the aggregate and the AC mixture fulfill the AASHTO and ASTM standard specifications (*2,3*). When surface thermal cracking developed only 5 to 8 months after construction, authorities studied the use of hydrated lime in the asphalt mix. They decided to use hydrated lime as 2 percent of the total weight of the filler, even though the materials met the specifications. Use of lime in the AC mixture and the other implementations mentioned significantly improved the performance of asphalt pavement at 4,160 MASL. Figure 8 shows a typical improved pavement section 2 years after construction. After this performance period, the width of a typical thermal crack was 1 mm (Figure 8b). A typical road condition 5 years after construction is shown in Figure 9. After this period, the typical crack width is about 2 mm.

A visual survey of the road in the spring of 1986 showed that after 5 years of service the thermal cracking reached stable conditions. In the last year or so, no significant deterioration or new thermal cracking has occurred and the typical crack width is still 2 mm, as shown in Figure 9. Riding quality is good and in the first approximation the existing 1 to 2 mm of thermal cracking does not affect the pavement riding quality along the La Oroya-Cerro de Pasco Road at altitudes of 4,100 to 4,300 MASL.

Other additives that might reduce thermal cracking at high altitudes are amine and latex. Adding about 0.5 percent of amine or 5 percent of latex by weight of asphalt cement reduces the penetration index by slightly increasing the asphalt penetration, reducing the softening point ring-and-ball temperature, and increasing ductility after TFOT. The calculated stiffness changes in residue after the TFOT were 2,500 kg/cm^2 or less, which, according to Table 2, indicates an improvement in reducing thermal cracking. Nevertheless, because of the relatively high cost of amine and latex additives, their use in Peru is still limited.

SUMMARY AND CONCLUSIONS

The following preliminary conclusions were reached after 5 years of asphalt surface performance monitoring of the La

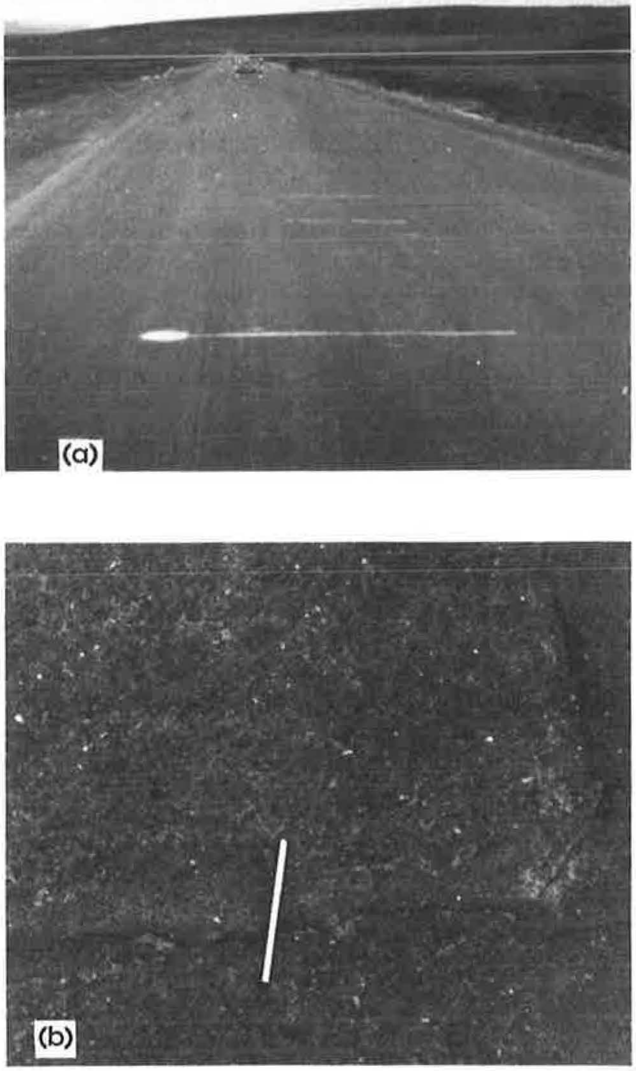

FIGURE 8 a, Road surface 2 years after completion of construction (with 2 percent hydrated lime); b, typical 1-mm thermal crack, 2 years after completion of construction (with 2 percent hydrated lime).

Oroya-Cerro de Pasco highway located at altitudes of 4,100 to 4,300 MASL in Peru's mountainous region.

1. The preferable topped crude used for asphalt production for high altitudes should contain mainly pure aromatic or Naftanic with the Watson characterization factor K_W value between 10.0 and 10.5.
2. Road sections in which the asphalt cement absolute penetration index (PI) is equal to or less than 0.5 show less cracking than other sections, in which the asphalt cement had a PI value of 0.9. A 120 to 150 penetration (in 0.1 mm) grade asphalt cement with a PI value of less than 0.5 is recommended for use in high altitudes, even for extremely overloaded trucks.
3. The asphalt stiffness changes in residue of the TFOT reflect the resistance of the asphalt mixture to thermal cracking. When the calculated stiffness changes after the TFOT are greater than 4,000 kg/cm^2, severe thermal cracking is expected. Significantly less cracking occurred when the stiffness changes were less than 3,000 kg/cm^2. The stiffness changes were calculated for the representative extreme conditions (a) temperature of -5°C and loading period of 0.01 sec, and (b) temperature of $+20$°C and loading period of 0.1 sec. Another indicator that reflects the resistance of the asphalt mixture to thermal cracking is the ductility of the residue of the TFOT. The use of additives is required when the ductility of the residue is less than 75 percent of the original ductility. The use of 0.5 percent of amine or 5 percent of latex by weight of asphalt cement is effective in increasing ductility and reducing thermal stiffness changes and surface cracking.
4. To reduce thermal cracking in the Peruvian high-altitude region, the following engineering properties and construction procedures of the base course materials were specified:

- Open grading with less than 55 percent passing sieve 200, PI < 2, and generally good drainage conditions.
- Asphalt prime coat laid immediately after the completion of the base course and with penetration into the base course of 20 mm or more.
- Coated base course carefully maintained to limit rainfall penetration.

5. Natural and crushed gravel were adequate for the asphalt mixture when the material passing sieves 40 and 200 was nonplastic.
6. When the asphalt cement and AC mixture produced in the high altitudes of Peru were heated to 140°C, better aggregate coating and less oxidation and thermal cracking occurred in the road. These conclusions were compared to the road sections in which the heating temperature was about 160°C. The 140°C temperature corresponds to the Sabolt Fural viscosity of 100 SSF and is found to be the optimum asphalt heating temperature in road projects at such high altitudes.
7. Compaction of the dense AC mixture was better achieved when breakdown temperatures were 115°C to 130°C and the required degree of compaction was obtained before the mix temperature in the road was reduced to 85°C or 90°C.

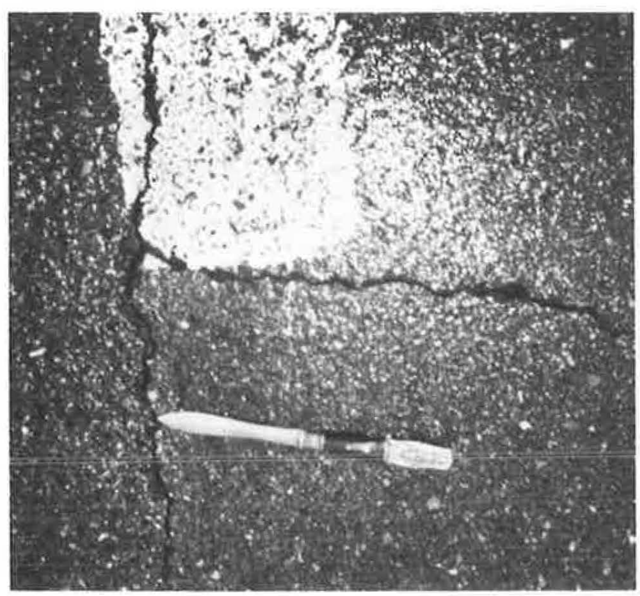

FIGURE 9 Typical 2-mm thermal crack, 5 years after completion of construction (with 2 percent hydrated lime).

8. When the ambient air temperature drops to 15°C, construction should stop. Road sections in which AC was laid at an ambient air temperature of 12°C to 15°C show relatively poor performance, and severe cracking occurred when the ambient temperature had dropped to 12°C or less.

9. Road sections constructed in full width show less longitudinal cracking than when each lane is constructed separately.

10. Road sections with 1 to 2 percent of hydrated lime enriched with CaO or 3 percent of portland cement show less thermal cracking. Also, the hydrated lime improved workability, reduced stripping of asphalt from aggregate, reduced absorption of water, and increased stability and resistance to immersion. In general, use of hydrated lime contributed to performance of the AC in the road.

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