Hindawi Publishing Corporation
Advances in Civil Engineering
Volume 2010, Article ID 565924, 10 pages
doi:10.1155/2010/565924

Research Article

Investigating In Situ Properties of Recycled Asphalt Pavement with Foamed Asphalt as Base Stabilizer

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Received 9 December 2009; Revised 31 March 2010; Accepted 8 April 2010

Academic Editor: Soheil Nazarian

The objective of the present study was to conduct a comprehensive field experiment for the in situ assessment of in-depth recycled asphalt pavement using foamed asphalt as a stabilization treatment for base works. For this purpose Nondestructive Testing (NDT) data collected using the Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) along a foamed asphalt recycled pavement section was thoroughly analysed. Critical issues including the stabilized material curing and the contribution of the asphalt layers to the structural properties of the in-depth recycled pavement are discussed. In addition, recommendations concerning the improvement of the structural condition of the in-depth recycled pavement are developed based on this practical approach of investigation using NDT.

1. Introduction

In-depth recycling is a method implemented worldwide for the rehabilitation of damaged road pavements. One of the major benefits of the method is that the material of a distressed road pavement is simultaneously recycled in-place and mixed with a stabilizing agent, enabling the road pavement to be strengthened without the need to import expensive aggregate. Other benefits include a short construction period, significantly reduced road closures, and improvements relating to safety. These advantages contribute to significantly lower unit costs for road rehabilitation, in comparison with other rehabilitation methods [1]. In addition, environmental issues related to the reuse of road materials increase the advantages of this technology.

For the in-depth recycling method, which is often referred to in international literature as cold in-place recycling [2], several types of stabilizers are used for the treatment of the in-place recycled material. The present investigation focuses on the use of foamed asphalt for such stabilization purposes. It is worthwhile to note that this technique has gained popularity in recent years. However, the in-depth asphalt pavement recycling using foamed asphalt as a stabilization treatment for base works requires a certain time period necessary to allow the newly produced foamed asphalt mixture to cure, as is the case for most stabilizing agents, and to build up enough internal cohesion before being covered by a wearing course. Studies have shown that such recycled mixes do not develop their full strength after compaction until a large percentage of the mixing moisture is lost. This process termed “curing” is a process whereby the in-depth recycled and stabilized mix gradually gains strength over time accompanied by a reduction in the moisture content [3].

Due to different in situ conditions for mixing and compacting of the recycled material, it is difficult to predict the progress of curing from tests on specimens obtained in the laboratory. In addition, laboratory curing procedures do not always represent the curing conditions in the field, which is further complicated by daily and seasonal fluctuations in environmental conditions. The evaporation of water and the build up of cohesion of the recycled mixture are strongly influenced by the ambient temperature and atmospheric relative humidity. Warm and dry weather shorten the first phase of curing, while damp and cold weather has the opposite effect.

Recycled mixture design procedure is a process by which field conditions are simulated in the laboratory to evaluate the long-term performance of the stabilized mixture. This procedure, however, cannot simulate conditions in the field after short-term curing periods. The strength developed after an early or intermediate cure represents the most critical time period [4].

The majority of researches related to the specific technique have focused on material characterization and mix designs performed in the laboratory, including the curing progress and concern mainly case studies on low volume roads [5]. Limited information is available in international literature about the in situ performance of the in-depth recycled pavements as defined in the present work and more specifically about pavement performance when such a technique is implemented for the rehabilitation of heavy duty roads. The present study aims to investigate aspects concerning assessment of in situ properties of asphalt pavement for in-depth asphalt pavement recycling using foamed asphalt as a stabilization treatment for base work. For this purpose the Laboratory of Highway Engineering of the National Technical University of Athens (NTUA) undertook a field experiment to assess the early life performance of a rehabilitated heavy duty pavement. A systematic Nondestructive Testing (NDT) program was conducted along a trial highway pavement section (2.5 kilometres in length) that has been rehabilitated in the mentioned manner, in order to obtain Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) data during early pavement life (<26 months). The collected data was processed and further analysed focusing on the pavement bearing capacity in terms of layer moduli, composite modulus, and strains. Estimated values of the aforementioned in situ mechanical properties are compared to the related design values incorporating critical issues, such as the recycled material curing and the contribution of the asphalt layers to the structural properties of the in-depth recycled asphalt pavement. The paper outlines the related considerations and results, highlighting the value of NDT data for such pavement assessment.

2. Materials, Design and Construction

The usage of in-depth asphalt pavement recycling using foamed asphalt as a stabilization treatment for base works has seen a remarkable increase worldwide in recent years. Asphalt is foamed in a specially designed expansion chamber (Figure 1). A carefully metered quantity of water is mixed with air and hot asphalt, forming foam of a much higher volume and lower viscosity than the asphalt component. This allows the asphalt to disperse through the recycled material. Additional water is sprayed into the mixing chamber to achieve the optimal moisture content for compaction [6].

The objective of a foamed asphalt mix design is to select the mix proportions, for example, the asphalt content, in order to achieve optimum values for laboratory-measured properties, as well the structural and functional requirements of the in-service mix. Retention of the relevant engineering properties at in-service temperature, moisture, and loading

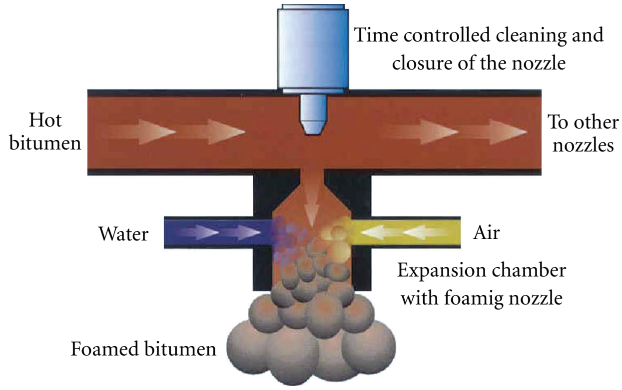

Figure 1: Foamed asphalt production [2].

conditions is also an important issue under consideration. Laboratory tests conducted on foamed asphalt should evaluate resistance to deformation, as well as variations in cohesion and strength with moisture and temperature. As the strength of foamed asphalt mixes is extremely sensitive to moisture conditions, these should be taken into account in the test methods.

Because foamed asphalt mixes can take on characteristics ranging from granular materials to those of high-quality asphalt materials, the test method selected should be able to handle a wide range of material types. It is advisable to correlate field performance with laboratory test results in order to develop suitable target values (criteria) for the laboratory measured properties. Additionally, it would be ideal to simulate pavement conditions in the field after a short curing period of the stabilized material or to develop evaluation criteria related to recycling procedures and construction aspects.

All of the above considerations have been taken into account for the purpose of the present study. The selected pavement section under investigation belongs to a heavily trafficked Greek Highway that had suffered severe structural distresses with defects mainly consisting of severe localized distress cracking (Figure 2). In response to these failures, limited corrective work was undertaken, mainly in the form of patching, which was implemented soon after the presence of the cracking was first noticed. However, distresses were soon detected within the patches. It was decided to address these issues by rehabilitating the asphalt pavement using in-depth cold in-place recycling using foamed asphalt as a stabilization treatment for base works (Figure 3).

For the particular pavement design and construction, foamed asphalt mix design was undertaken to establish the application rates for foamed asphalt and active filler (cement) to achieve optimal strength. The indirect tensile strength (ITS), tensile strength retained (TSR), and unconfined compressive strength (UCS) of the treated material were determined, according to methodology described in [2]. A range of foamed bitumen contents were tested to identify the optimum application rate, indicated by the highest ITS for each blend, using 100 mm Marshall-compacted briquettes (dry, wet). The application rate was then utilized

Figure 2: Distressed pavement of the heavy duty highway under investigation.

Figure 3: Cold in-place recycling using foamed asphalt.

for further testing and for ITS, TSR, and UCS determination using 150 mm diameter (120 mm high) briquettes (wet and equilibrium moisture content). A summary of the above-mentioned results (average values) are presented in Table 1. According to the mix design, 2.25% foamed asphalt and 1% cement was used in the stabilized material. The decision to introduce 1% cement was based on the improvement in the achieved soaked (wet) strengths.

An analytical design approach was used in order to estimate the structural capacity of the pavement, taking into account traffic loading in excess of 10×10^6 equivalent 13 ton axles. The stiffness modulus of the asphalt layers was considered to be 3500 MPa. From the dynamic tri-axial tests, an average resilient modulus value of 2020 MPa was determined. However, for a conservative analytical design approach, a modulus value of 1500 MPa was considered for the foamed asphalt in-depth recycled and stabilized material.

According to the analytical design, a pavement structure consisting of a 90 mm asphalt concrete (AC) layer overlaying the foamed asphalt stabilized recycled material was assumed. An iterative process was applied to adjust the thickness of the stabilized layer (base layer) until structural capacity requirements were met. A uniform thickness of 280 mm was adopted over which two AC layers were laid. First,

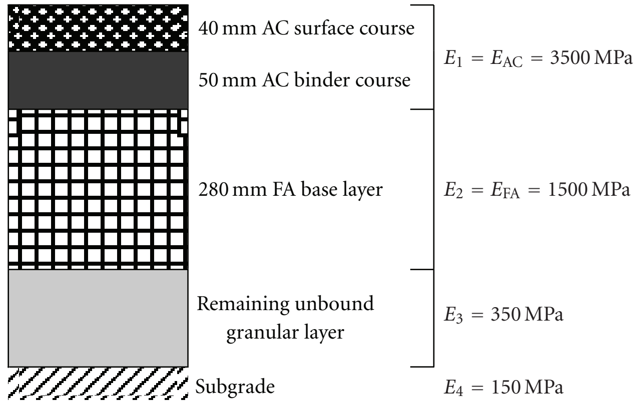

Figure 4: Pavement design cross-section of the in-depth recycled pavement.

a dense binder leveling course with a nominal thickness of 50 mm was laid and this was followed by a 40 mm semiopen graded polymer modified asphalt mix surface course. The final pavement design is presented in Figure 4. Rehabilitation work was undertaken in four construction stages, as illustrated in Figure 5.

No premilling was performed before the pavement was pulverised, primarily to include as much recycled asphalt pavement (RAP) as possible in the base material. The entire process performed in situ.

3. Nondestructive Testing (NDT)

3.1. FWD Measurements. FWD NDT testing was conducted in the present research work in order to estimate the pavement materials moduli. The FWD generates a load pulse by dropping a weight on a damped spring system mounted on a loading plate as shown in Figure 6. The falling mass, the spring system (rubber buffers), and drop height can each be adjusted to achieve the desired impact loading on the pavement. Vertical deflection peaks are measured at the centre of the loading plate and at multiple radial positions by a series of deflection sensors. The impulse load acting on the pavement causes a “wave front” of recoverable deformations, or deflections, that spread out from the centre of the load. Both the peak impulse load (force) and maximum vertical deflections of the “wave front” are measured at multiple radial distances from the load centre. These deflections, considered as a function of the applied impulse load, provide an indication of the structural strength of the pavement.

The NTUA’s FWD system, which was used for the purpose of the present investigation, is vehicle-mounted (Figure 7) and is equipped with a weight and nine velocity transducer sensors. In order to perform a test, the vehicle is brought to a stop and the loading plate (weight) is positioned over the desired location. The sensors are then lowered to the pavement surface and the weight is dropped. Frequently, multiple tests are performed on the same location using different drop weight heights. All deflections recorded by the nine sensors were utilized for analysis purposes.

Table 1: Summary of foamed asphalt mix design results.

Blend	RAP (%)	Granular (%)	ITS Φ 100 mm (kPa) Dry	ITS Φ 100 mm (kPa) Wet	TSR (%)	ITS Φ 150 mm (kPa) Equ.	ITS Φ 150 mm (kPa) Wet	TSR (%)	UCS Φ 150 mm (kPa) Equ.
1	75	25	318	238	75	301	237	79	1900
2	50	50	472	379	80	279	252	90	2400

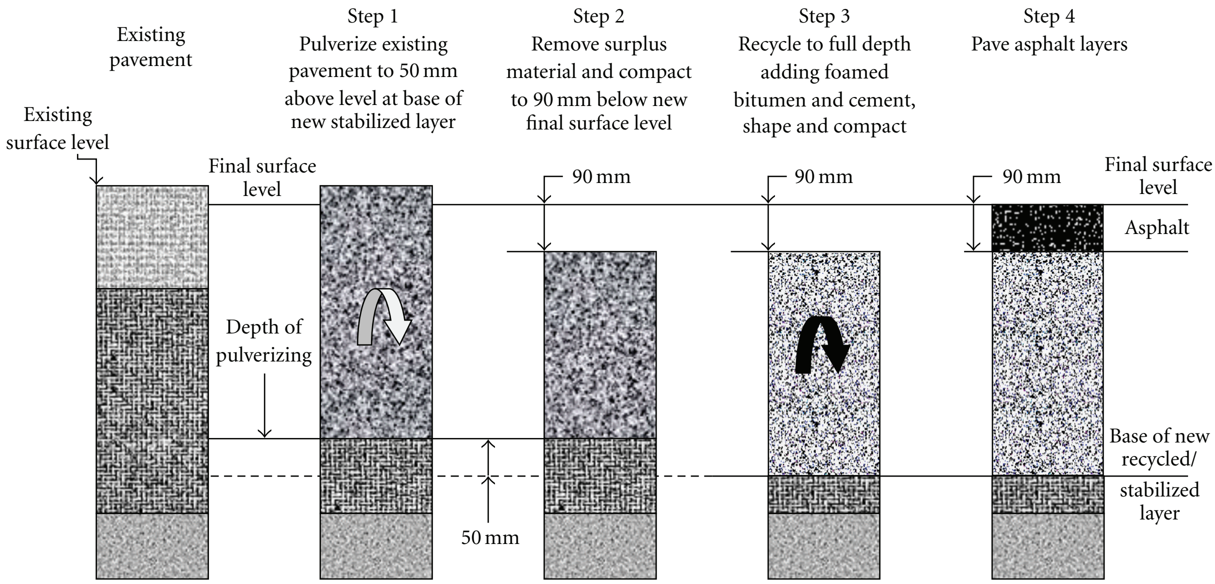

Figure 5: Four-stage construction sequence.

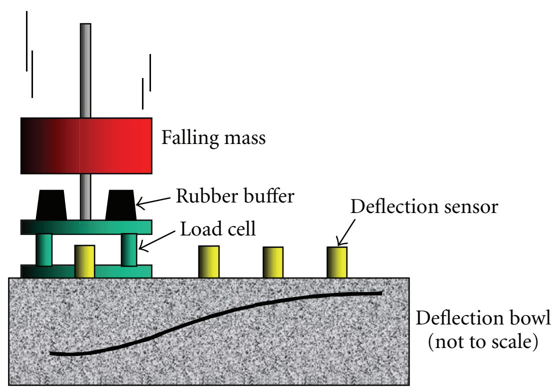

Figure 6: Schematic diagram of an FWD.

Figure 7: NTUA FWD system used for the experiment.

For the purpose of the present study, deflections measurements from the FWD are used in a back-calculation procedure to determine pavement structural stiffness in terms of layers and subgrade modulus, as well as for strain analysis.

3.2. GPR Testing. In order to perform the back-analysis of the measured FWD data, pavement layer thickness data is necessary. Traditionally, pavement layer thickness is determined by digging test-pits and/or by extracting cores from the pavement. These are destructive manners to gather thickness data and are both time-consuming and cost consuming-methods that provide limited localized information for pavement evaluation. For the present investigation, it was difficult and in some cases near impossible to gather thickness data from the coring of foamed asphalt treated material shortly after construction because of the "noncured" nature of the in depth recycled and stabilized material.

GPR surveys seem to be a powerful NDT tool used as an alternative to the coring method for assessing, amongst

Figure 8: NTUA GPR horn antenna system used for the experiment.

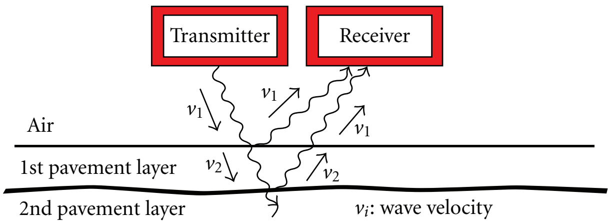

Figure 9: Pulse propagation principle.

others, pavement layers thickness [7]. The NTUA Laboratory of Highway Engineering's GPR system (Figure 8) used for the present investigation has an air-coupled antenna and is consistent with the impulse technique. The impulse radar technique is based on the principle that a short (0.5 to 1.5 ns) electromagnetic pulse (wave) is transmitted into the pavement through its surface.

The wave travels through the pavement layers and reflects off surfaces or objects, which bear discontinuities in electrical properties, for instance, different materials or changes in either moisture content or density. In other words, where there is a contrast in the dielectric constants of the pavement materials the reflected pulses from the internal pavement interfaces are recorded. The recorded reflections depend on the velocity (v_i) of the waves propagation (see Figure 9), which is governed by the dielectric properties of the materials as a function of the dielectric constant of the material mixture. Dielectric properties of asphalt layers also depend slightly on the compaction during construction and thus on the pore/void content of the final layer material, as well on the water content.

The travel time Δ_t (ns) of the transmitted pulse within a pavement layer, in conjunction with its dielectric constant (ε) and based on the wave propagation velocity V (m/ns) determines the layer thickness (h) in meters according to (1).

$$h = \frac{V \cdot \Delta t}{2} = \frac{c \cdot \Delta t}{2 \cdot \sqrt{\varepsilon}}, \quad (1)$$

where c is the propagation velocity in free space (0.3 m/ns).

Research has been conducted to evaluate the accuracy of thickness estimation through the GPR technique. In most cases, comparison with core data (ground truth data) provided encouraging results. GPR proves to be a proper tool for road surveying since the calculated errors, especially in the case of new pavements, range within acceptable levels for practical estimation of asphalt layer thickness [8–10]. Furthermore an ad hoc research [11] related to the specific in-depth recycling technique proved that the GPR thickness error results for the stabilized with foamed asphalt in-depth recycled base, encourage, also in this case, the use of GPR for continuous pavement monitoring or even in pavement mechanistic analysis models such as ones based on the FWD technique.

Table 2: Measurements stages.

Stage	Contact surface
(a)	Stabilized with foamed asphalt layer (base) (2 days after in-depth recycling)
(b)	AC surface course (20 days after rehabilitation)
(c)	AC surface course (16 months after rehabilitation)
(d)	AC surface course (26 months after rehabilitation)

4. Data Acquisition

FWD tests were conducted along a trial highway pavement section (~2.5 kilometres in length) that has been rehabilitated by in-depth recycling using foamed asphalt as a stabilization treatment for base works. Testing was conducted approximately every 50 meters in the outer wheel path (OWP) (Figure 7) of the heavy-duty traffic lane of the trial section at four stages (a)–(d). The stages are referred to in Table 2. Temperature was measured in the pavement layers throughout the FWD testing.

It is worth mentioning that no premature failures or distresses were observed on the pavement surface at stages (c) and (d) (up to 26 months after rehabilitation).

GPR surveys were conducted at the same positions in two stages: (a) and (b). These stages were considered as optimum for the estimation of layer thickness. According to [11] the GPR thickness errors compared to cores thickness range approximately between 6% and 7.5%. Numerous researchers have proved that the GPR error for the asphalt layers thickness estimations is in the range of approximately 5% [8–10]. These results encourage the use of GPR thickness not only for quality control purposes (i.e., layer thickness evaluation) but also as input for the purpose of pavement mechanical analysis, as is the case of the present investigation. GPR thicknesses can be used for the estimation of the layer moduli for the back-analysis of the measured deflection data. This is verified through results obtained from research on a similar in-depth recycled pavement implementation using foamed asphalt treatment proving that the moduli estimated based on core thickness are similar to those based on GPR thickness [12]. This finding supports the use of GPR thicknesses for the purpose of the present investigation.

Taking into account the findings of [11], the thickness values of foamed asphalt treated layer were estimated based

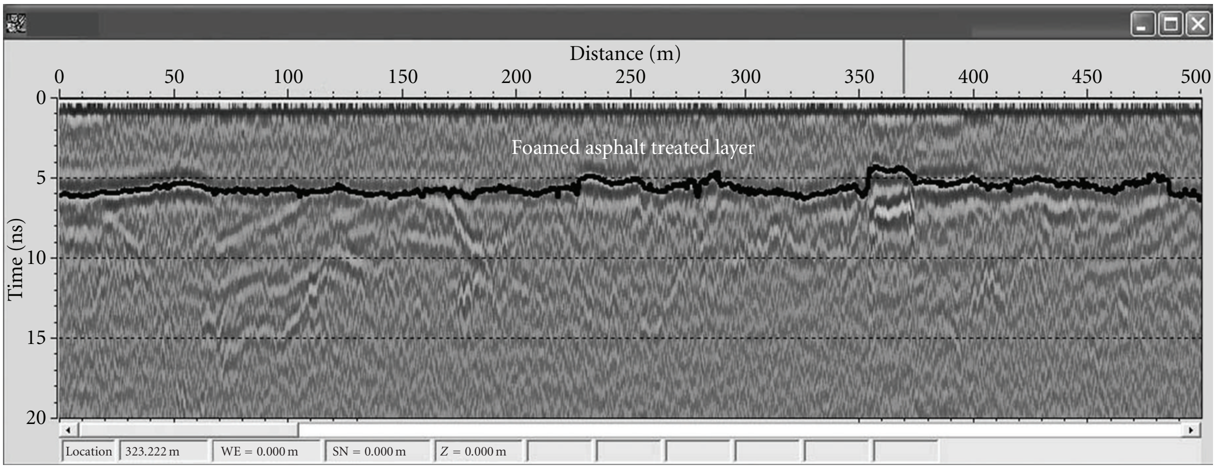

Figure 10: GPR data interpretation for the thickness estimation of stabilized with foamed asphalt layer.

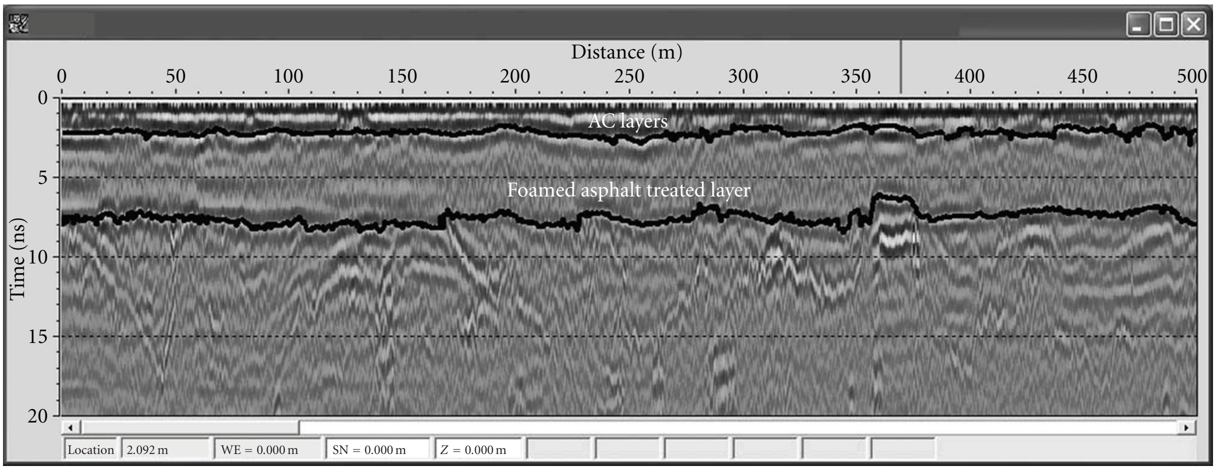

Figure 11: GPR data interpretation for the thickness estimation of the AC layers.

on GPR measurements of stage (a), while those of the AC layers were estimated based on GPR measurements of stage (b). This was done in order to estimate more accurately the layers' thickness values along the pavement section under investigation.

5. Data Analysis

For the purpose of the present study, the collected GPR data was analyzed using the Road Doctor software [13] in order to identify the interfaces of the pavement layers. Raw data passed through a filtering process to amplify the GPR signal and to remove any possible interference. Specifically, vertical and horizontal filtering was applied on the collected data. The vertical filtering operation created a band pass filter in the time domain for local noise and interference removal. This operation is also used to remove high-frequency noise and signal wowing. Horizontal filtering was used in order for the rapid changes from scan to scan to be smoothened. GPR data was interpreted for the thickness estimation of stabilized with foamed asphalt-treated layer (base) in Figure 10 and for the thickness estimation of the AC layer in Figure 11.

Based on the measured deflections a back-analysis was performed in order to estimate the pavement layers modulus. The model used for the back-calculation is presented in Figure 12. The back-analysis was undertaken according to [14]. In addition the composite modulus (i.e., the modulus of the combined AC and foamed asphalt-treated layers) was calculated. All calculations were made at each stage.

For the back-analysis, the measured temperature values were adjusted to the 20°C reference temperature in order to be used in the back-analysis. For the AC layers the temperature was corrected according to [15] (2), while for the foamed asphalt treated layer the laboratory estimated (3) as documented in reference [16] was utilized

$$E_{\mathrm{AC}}(T_{\mathrm{ref}}) = \frac{E_{\mathrm{AC}}(T)}{1 - 2.2 * \log(T/T_{\mathrm{ref}})}, \tag{2}$$

where $E_{\mathrm{AC}}(T_{\mathrm{ref}})$ is the estimated AC modulus at the reference temperature (T_{ref}) and $E_{\mathrm{AC}}(T)$ is the estimated AC modulus

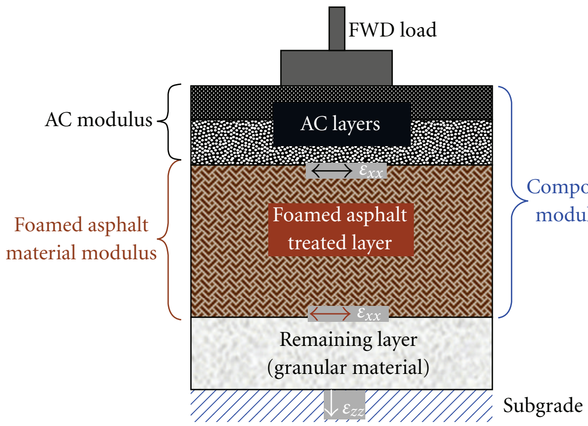

FIGURE 12: Pavement model for back-analysis.

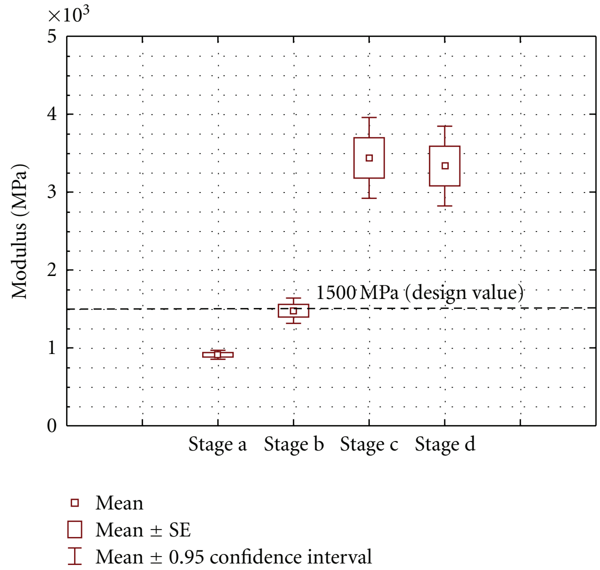

FIGURE 13: Moduli of foamed asphalt-treated layer at each stage.

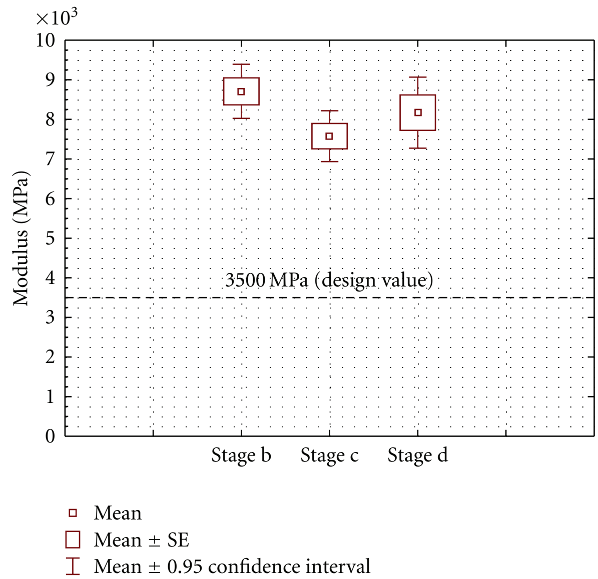

FIGURE 14: Moduli of AC layer at each stage.

at the measured temperature (T)

$$E_{FA}(20^\circ C) = E_{FA}(T) \cdot 1.037^{(T-20)}, \tag{3}$$

where $E_{FA}(20^\circ C)$ is the estimated FA modulus at the reference temperature ($20^\circ C$) and $E_{FA}(T)$ is the estimated FA modulus at the measured temperature (T).

In addition a strain analysis was applied in stages (b), (c), and (d). The statistical analysis of the considered moduli and strain data which is applied in the following chapter aims to quantify the in situ properties of the rehabilitated pavement under investigation with the passage of time.

6. Statistical Analysis Results

6.1. Pavement Layer Moduli Analysis. The pavement layer modulus is a major parameter to study the structural condition of the in-depth recycled asphalt pavement and therefore is used as a field curing criterion of the stabilized material. The back-calculated modulus values when compared with the design modulus, of the cured material, can give useful information about the curing progress of the recycled material. If the in situ values are equal or higher than the design value, the recycled material can be considered as cured. Otherwise, the recycled material may not be fully cured, or is cured with mechanical properties lower than expected. In this case, the authors suggest to incorporate in the analysis process the asphalt overlay as well, for an alternative in situ structural evaluation. The design values of the modulus for the foamed asphalt stabilized layer and AC layer are 1500 MPa and 3500 Mpa, respectively.

Figure 13 illustrates the moduli of foamed asphalt treated layer in box plot graphs, with the mean value, confidence (95%) and standard deviation. At stage (a) the modulus values (mean = 912 MPa) is lower than the design value. Twenty (20) days after construction stage (b), when the rehabilitated pavement is in use, the in-depth recycled base layer moduli reaches the design value level.

During the next stages (c) and (d) the moduli of the base are in the range of 2800 to 4000 MPa, which are higher than the laboratory estimated values, indicating the fully cured in-depth recycled material condition. This result produces evidence in support of the statement that the appropriate time to assess the in situ properties of the stabilized material is approximately one year after construction. According to the above mentioned results, a more realistic value of foamed asphalt modulus for pavement analysis purposes could be 2500 MPa.

Following the same procedure, Figure 14 illustrates the moduli of AC layers at stages (b), (c), and (d). Since the AC layer has not been constructed at stage (a), there are no AC modulus results. As was expected, the AC layers gain strength from the beginning (stage (b)), as the average

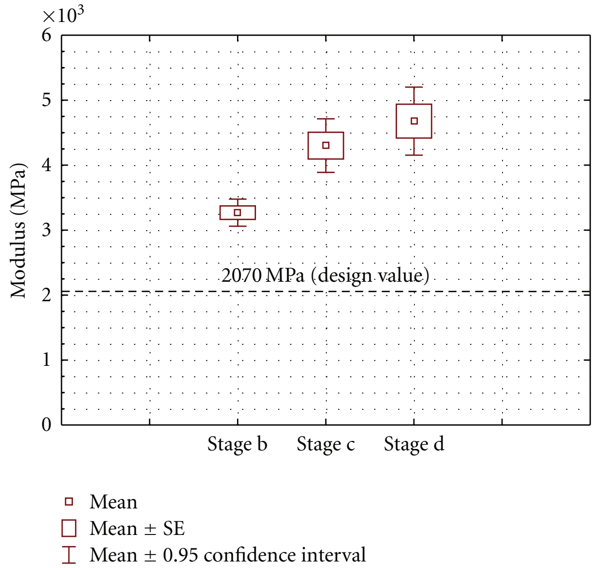

Figure 15: Composite moduli of pavement at each stage.

modulus is 8700 MPa (far more than the design value, i.e., 3500 MPa). It is assumed that the variation of the AC modulus values from stages (b) to (d) (see Figure 14) arise from the uncertainties of the temperature adjusted models that were used. In any case the high modulus values of AC layers contribute to the structural performance of the in-depth recycled pavement. It is thought that the extent of this benefit, could be evaluated based on the assessment of the composite moduli as described below.

As stated in the previous chapter, if the stabilized material is not fully cured, or is almost cured with mechanical properties less than the fully cured condition, it is suggested to incorporate in the mechanical analysis process the contribution of the asphalt overlays. The contribution of the asphalt layers to the structural condition of the in-depth recycled asphalt pavement is important, especially during the first days of the pavement's life, where no complete curing of the stabilized with foamed asphalt material has occurred. A simplified approach, which takes into account both the influence of the AC layer and the in-depth recycled base, is the estimation of the composite modulus, that is, the combined AC layer and base modulus [17]. It can be used as an alternative characteristic in order to evaluate the structural condition of the rehabilitated pavement.

Composite moduli were back-calculated based on GPR thickness values at stages (b), (c), and (d). The moduli were corrected to 20°C according to (2). The composite modulus value based on the analytical design was estimated to be 2070 MPa using the SHRP algorithm [18]. Figure 15 illustrates the composite moduli of pavement layers in the form of box plots.

According to the results illustrated in Figure 15, from the beginning (stage (b)) the composite modulus values are higher than the design value. The further improvement of the composite moduli seems to arise from the curing and the improved properties of the in-depth recycled base material.

Table 3: Strain design values.

Layer	Strain value
AC	54.7
Stabilized with foamed asphalt	86.0
Subgrade	75.3

7. Strain Response Analysis

The in situ average tensile strain in the body of the base layer is an important factor for the curing evaluation during the early life of the pavement, as it reflects the distress and consequently the rate of damage in the body of the in-depth recycled material. Although the calculation procedure is rather complicated, the in situ average strains can be used for comparison with the relative one using the design data. If it is equal or lower than the relative strain based on the design data, the distress in the body of the base is equal or lower than expected and consequently the structural condition of the in-depth recycled pavement is adequate.

For the purpose of the present research investigation, the in situ average tensile strains at the bottom of the AC layers and the foamed asphalt treated base, as well the average vertical strain on the surface of the subgrade were calculated according to [14] using the pavement layer system modeled in Figure 12. However, it should be mentioned that pavement systems often exhibit stress-dependent behavior. Advanced models may help to explain the discrepancies between the theoretical analysis and the observed pavement behavior and pavement responses, an issue that merits further investigation beyond the limits of the present research study.

The load used for the calculations was a 40 kN single wheel with 15 cm radius. For the in situ evaluation of the curing progress, the back-calculated moduli of (b), (c) and (d) stages were used. The calculated based-on-design data strain values are included in the Table 3.

Figure 16 shows the average horizontal tensile strain (ε_{xx}) at the bottom of the in-depth recycled material at stages (b), (c), and (d). In every case, especially at the beginning (stage (b)), it can be seen that the average ε_{xx} values are much lower than the design value (86 microns). It is clear that the foamed asphalt-treated layer has adequate structural condition, during the stages under consideration.

Figure 17 shows the average tensile strain (ε_{xx}) at the bottom of the AC layers at stages (b), (c), and (d). It can be seen that the max ε_{xx} values are much higher than the design value (54.7 microns) at the beginning of traffic (stage (b)); this results in an increase of the damage to the AC overlays. It seems that the curing of the stabilized base material benefits the structural condition of the AC layers as the damage is less at stages (c) and (d). However, although the average strains values are lower, they are near to the design strain value level. This is circumstantial evidence that the AC layer should be reinforced for instance by increasing its thickness.

Figure 18 shows the average vertical strain (ε_{zz}) on the subgrade at stages (b), (c), and (d).

It can be seen that the average ε_{zz} are higher than the design value (75.3 microns) at the beginning of traffic (stage

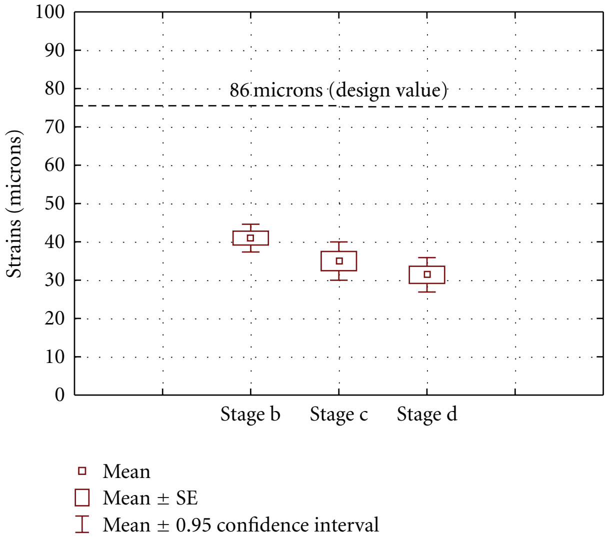

FIGURE 16: Average strains at the bottom of the base.

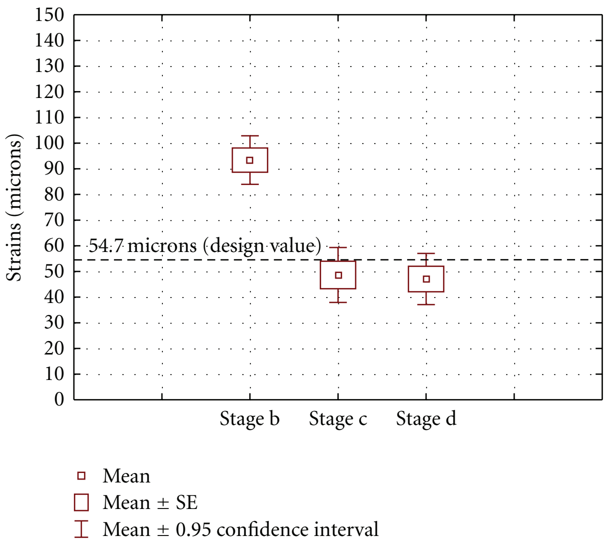

FIGURE 17: Average strains at the bottom of the AC layers.

(b)); this results in damage to the subgrade. However, it seems that the curing of the base material benefits the structural condition of the subgrade as the damage is less at stages (c) and (d); but the subgrade average strain values are equal to or more than the design value. This produces evidence in support of the statement that the AC layer thickness should be increased. In this way not only the structural adequacy of the in-depth recycled asphalt pavement will be further supported but also, the AC layer thickness increase could benefit the roughness level of the pavement surface and consequently the ride quality of the rehabilitated asphalt pavement. This could happen as the increase of the AC layer thickness helps to decrease the amplitudes of the surface waves that are responsible for roughness problems.

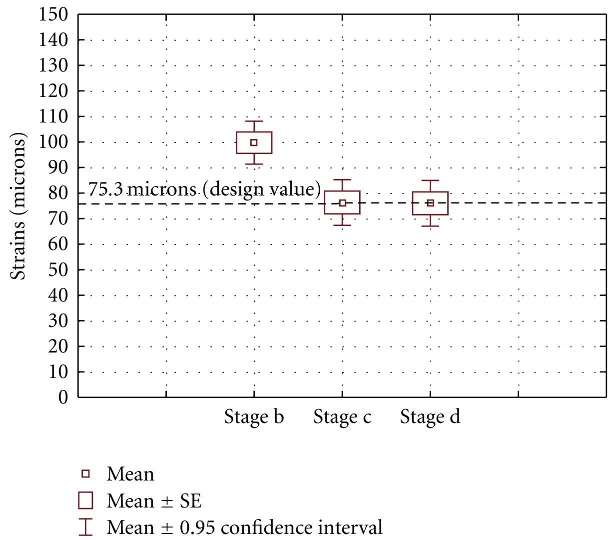

FIGURE 18: Average strains on the subgrade.

8. Conclusions

The present research study focuses on the early life performance of recycled asphalt pavement with foamed asphalt as a base stabilizer in terms of in situ pavement properties. The field investigation is based on NDT data collected using FWD and GPR along a trial heavy duty pavement section. The collected data was analyzed and the related results concluded with the followings main findings.

During the early life of the recycled pavement and before the curing of the foamed asphalt-treated recycled layer, the contribution of the AC overlays to the structural performance benefits the properties of the stabilized material. Since the contribution of the AC overlays is of importance for the early life performance of the in-depth recycled asphalt pavement, the related AC mixes should be designed having a high mechanical bearing strength. Additionally it is believed that an increase of AC layer thickness taken into consideration the analytical pavement rehabilitation design would reduce the strain level at the bottom of the AC overlay. This increase would also contribute towards a better roughness level at the pavement surface, since by experience the achieved roughness level of the stabilized layer is in general high. However, this issue needs further investigation.

It is suggested that the appropriate time to assess the in situ properties of the stabilized material is approximately one year after construction. Curing of the stabilized material benefits the structural condition of both, AC layer and subgrade.

Acknowledgment

The authors would like to thank the Greek Ministry of Public Work, the Responsible Road Authority, and the related bodies for supporting the research work of this study.

References

[1] A. J. N. Lewis and D. C. Collins, "Cold in place recycling: a relevant process for road rehabilitation and upgrading," in *Proceedings of the 7th Conference on Asphalt Pavements of Southern Africa (CAPSA '99)*, Cape Town, South Africa, 1999.

[2] Wirtgen GmbH, *Wirtgen Cold Recycling Manual*, Windhagen, Germany, 2nd edition, 2004.

[3] K. M. Muthen, "Foamed asphalt mixes—mix design procedure. External," Contract Report CR-98/077, SABITA Ltd & CSIR Transportek, Pretoria, South Africa, 1999.

[4] P. J. Ruckel, S. M. Acott, and R. H. Bowering, "Foamed-asphalt paving mixtures: preparation of design mixes and treatment of test specimens," *Transportation Research Record*, no. 911, pp. 88–95, 1983.

[5] K. W. Lee, T. Brayton, and M. Huston, "Development of performance based mix design for cold In-place recycling (CIR) of bituminous pavements based on fundamental properties," FHWA-IF-05-014, FHWA, Washington, DC, USA, 2002.

[6] D.-H. Chen, J. Bilyeu, T. Scullion, S. Nazarian, and C.-T. Chiu, "Failure investigation of a foamed-asphalt highway project," *Journal of Infrastructure Systems*, vol. 12, no. 1, pp. 33–40, 2006.

[7] T. Saarenketo and T. Scullion, "Road evaluation with ground penetrating radar," *Journal of Applied Geophysics*, vol. 43, no. 2-4, pp. 119–138, 2000.

[8] K. R. Maser, "Ground penetrating radar surveys to characterize pavement layer thickness variations at GPS sites," Strategic Highway Research Program, National Research Council SHRP-P-397, National Academy of Science, Washington, DC, USA, 1994.

[9] A. Loulizi, I. L. Al-Qadi, and S. Lahouar, "Optimization of ground-penetrating radar data to predict layer thicknesses in flexible pavements," *Journal of Transportation Engineering*, vol. 129, no. 1, pp. 93–99, 2003.

[10] A. Loizos and C. Plati, "Accuracy of pavement thicknesses estimation using different ground penetrating radar analysis approaches," *NDT and E International*, vol. 40, no. 2, pp. 147–157, 2007.

[11] A. Loizos and C. Plati, "Ground penetrating radar as an engineering diagnostic tool for foamed asphalt treated pavement layers," *International Journal of Pavement Engineering*, vol. 8, no. 2, pp. 147–155, 2007.

[12] A. Loizos, V. Papavasiliou, and C. Plati, "Aspects concerning field curing criteria for cold-in place asphalt pavement recycling," in *Proceedings of TRB 87th Annual Meeting*, Washington, DC, USA, January 2008, CD-ROM.

[13] Roadscanners, "Road Doctor: User's Guide," Roadscanners Oy, 2001.

[14] Dynatest, "Elmod User Manual," 2002.

[15] S. Baltzer and J. M. Jansen, "Temperature correction of asphalt-moduli for FWD measurements," in *Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields (BCRA '94)*, pp. 7–25, University of Minneapolis, Minneapolis, MN, USA, July 1994.

[16] A. Loizos and V. Papavasiliou, "In situ characterization of pavement materials stabilized with foamed asphalt and cement," in *Proceedings of International Conference on Advanced Characterization of Pavement and Soil Engineering Materials*, pp. 875–882, Athens, Greece, June 2007.

[17] L. J. Milton and M. G. Earland, "Design guide and specification for structural maintenance of highway pavements by cold in-situ recycling," Report 386, Transportation Research Laboratory (TRL), 1999.

[18] SHRP, "SHRP's layer moduli backcalculation procedure," Tech. Rep., Strategic Highway Research Program (SHRP), National Research Council, Washington, DC, USA, 1993.