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Re-Cementation of Crushed Material in Pavement Bases

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Perform periodic pavement evaluations through 2008 and prepare final summary report containing summaries of laboratory and field test data obtained during the period 1999–2008 and analyses associated with the design, construction, and performance of the pavement sections.

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Davis and Berkeley

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Abstract: When recycled crushed concrete and crushed cement-treated materials have been used in pavement bases and subbases, increases in stiffness have been observed. This stiffness increase has been attributed to re-cementation of these materials. To evaluate this phenomenon, four projects that used these recycled materials and for which data are available have been studied. Two of the projects are pavements that had been subjected to Heavy Vehicle Simulator (HVS) testing at University of California Pavement Research Center (UCPRC) test sites at the Richmond Field Station, the third is an HVS study conducted by Council for Scientific and Industrial Research (CSIR) on an in-service pavement in South Africa (2004), and the fourth is the periodic evaluation of the Phase One rehabilitation of the I-710 Freeway in Long Beach, California, which has been subjected to traffic over a five-year period (2003–2008). This technical memorandum presents the results of these studies with recommendations for design parameters to use with these materials in pavement design methodologies.

Keywords: recycled crushed concrete**,** recycled crushed cement-treated material, re-cementation, stiffness modulus, base and subbase courses

Proposals for implementation: Three gravel factors for recycled crushed concrete and recycled cement-treated material are suggested for use (depending on the proportion of recycled materials) when these materials are substituted for Class 2 aggregate base in the Caltrans method of flexible pavement design. For the newly developed *CalME* design methodology, a range of stiffness moduli for these materials are also suggested.

Related documents:

- Jones, D., Steven, B., and Harvey, J. 2007. *Reflective Cracking Study: HVS Test Section Forensic Investigation.* Report prepared for the Caltrans Division of Research and Innovation by the University of California Pavement Research Center, Davis and Berkeley. UCPRC-RR-2007-05.
- Monismith, C. L., Harvey, J. T., Tsai, B.-W., Long, F., and Signore, J. 2009. *Summary Report: The Phase One I-710 Freeway Rehabilitation Project: Initial Design (1999) to Performance after Five-Plus Years of Traffic (2009).* UCPRC-SR-2008-04.
- Steyn, W., and Jones, D. 2005. *HVS Testing of N12-19 East Section 2.* Technical memorandum prepared for Gauteng Provincial Government, CSIR Built Environment Department of Public Transport, Roads and Works by CSIR. 156 pp.
- Harvey, J. T., M. Bejarano, A. Fantoni, A. Heath, and H. C. Shin. 2000. *Performance of Caltrans Asphalt Concrete and Asphalt-Rubber Hot Mix Overlays at Moderate Temperatures--Accelerated Pavement Testing Evaluation.* Draft report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley. UCPRC-RR-2000-09, 258 pp.

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PROJECT OBJECTIVES

1. Evaluate the stiffness changes with time and traffic loading of aggregate bases constructed using recycled crushed concrete and crushed cement-treated materials.
2. Determine a range in gravel equivalent factors for use in the current Caltrans method of flexible pavement design and stiffness moduli for the *CalME* design method when these recycled materials are used in base or subbase courses.

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1 INTRODUCTION

Use of recycled materials as a source of aggregate for pavement construction has become a more common practice in recent years as resource conservation and environmental preservation have become greater priorities in both new and reconstructed pavement projects. Among the recycled materials used in pavement, crushed concrete and crushed cement-treated materials from both recycled pavement and recycled building waste are frequently used as compacted base and subbase layers. Studies reporting valuations of pavements containing these recycled materials report increased layer stiffness after their use in construction *(1, 2)*. A limited amount of research has been conducted to evaluate the reasons for and the mechanisms responsible for this stiffness increase *(3, 4)*.

This technical memorandum provides a brief discussion of the reasons for this increase in stiffness together with summaries of the results of forensic studies from four different pavement investigations in California and South Africa *(5, 6, 7, 8, 9, 10, 11)* documenting the occurrence of this phenomenon in crushed concrete and cement-treated aggregate used as base materials.

2 RE-CEMENTATION BEHAVIOR

Re-cementation is a process that occurs when materials such as crushed concrete and cement-treated soils are mixed with water and other granular materials to improve compactability, and compacted as base and subbase layers in pavement structures. Previously unhydrated cement particles will be exposed to water allowing additional hydration to continue in the compacted material over a long period of time. Figure 2.1 shows an example of new crystals of cement reaction products formed from the re-cementation process. That material shown is from an asphalt emulsion–stabilized base made with in-place recycled cement-treated base with 4 percent cement that was originally built in the late 1960s and later recycled with the emulsion in 1974 because it had failed by block cracking from shrinkage of the cemented base. The sample shown was freshly taken from the pavement 30 years later in 2005, but it shows evidence of ongoing formation of new cementitious material, in addition to evidence of older cementitious material apparently dating back to the original construction. Evidence was also found in the base of unhydrated cement even 35-plus years after the original mixing of the cement and 30 years after its being recycled with emulsion. The evidence that this is a new re-cementation product is its shape and the presence of unhydrated cement in the face of the base layer when the pit was opened in 2005.

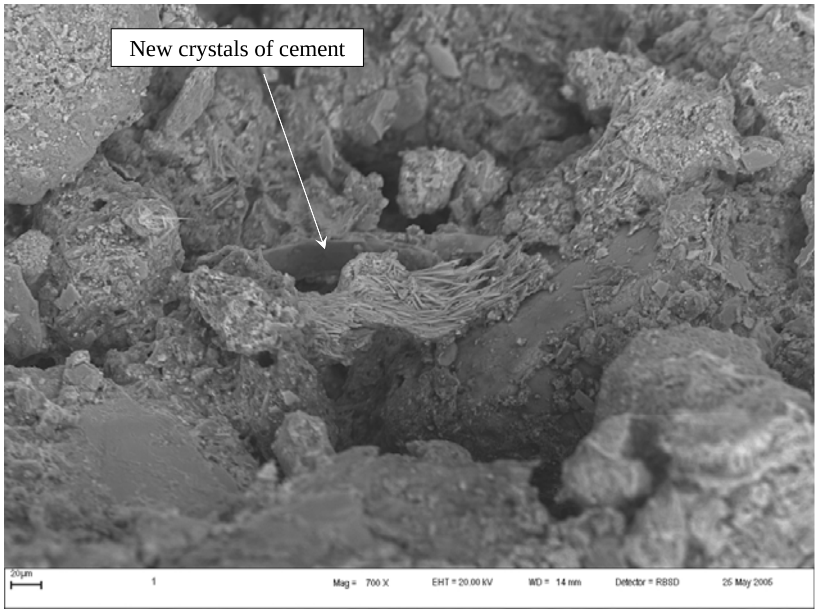

Figure 2.1: New crystals of cement reaction products *(10).*

There have been a limited number of studies to document the re-cementation process. Stiffness increases were evaluated by Arm *(4)* using both triaxial compression tests in the laboratory and loading tests on field sections that contained crushed concrete and added bottom ash. Her investigations indicated that the stiffness of reworked base with this material increased with time. Proportions of bottom ash which produced the best results were 16 percent (by weight) in the field sections and 4 percent in the laboratory tests.

Poon et al. *(3)* analyzed both the cause and influence of the re-cementing process. Based on this study, it was concluded that a minimum amount of fine concrete (particle size <5 mm) is essential to insure the bonding that results from re-cementation.

3 CASE STUDIES

This section briefly summarizes four case studies:

- University of California Pavement Research Center Reflective Cracking Study (2002 to 2007) (Strategic Plan Element 4.10, MB Test Road) conducted at the Richmond Field Station *(5, 6, 7, 8);*
- Phase 1 I-710 Freeway Rehabilitation. Periodic falling weight deflectometer (FWD) measurements over five-plus years (2003 to 2008) following construction *(9);*
- CSIR, Gautung Province, Republic of South Africa. Heavy Vehicle Simulator (HVS) Test 425A5; in-service pavement (2004), Highway N12-19 East,*(10);* and,
- University of California Pavement Research Center Goal 3. Accelerated Pavement Test Project (1995 to 2000) *(11).*

3.1 Reflective Cracking Study, UCPRC Strategic Plan Element (SPE) 4.10 (MB Test Road)

The objective of this research was to evaluate the reflective cracking performance of hot-mix asphalt (HMA) containing different asphalt binders and aggregate gradations used in overlays for rehabilitating cracked HMA pavements in California. The investigation included: (1) accelerated pavement testing using Heavy Vehicle Simulators on a series of pavement sections constructed at the Richmond Field Station (RFS); and (2) a laboratory test program at the RFS that included shear and fatigue tests on the various HMA mixes used in the test sections.

The test track was constructed in September 2001 according to Caltrans practice. Figure 3.1 illustrates the schedule for the test plan followed in the project. Figure 3.1 shows that the program involved (1) construction of a new pavement section, (2) cracking the HMA layer of this pavement using an HVS to produce cracked sections for overlays (Phase One), (3) overlay construction, and, (4) HVS testing of the various overlay sections (Phase Two).

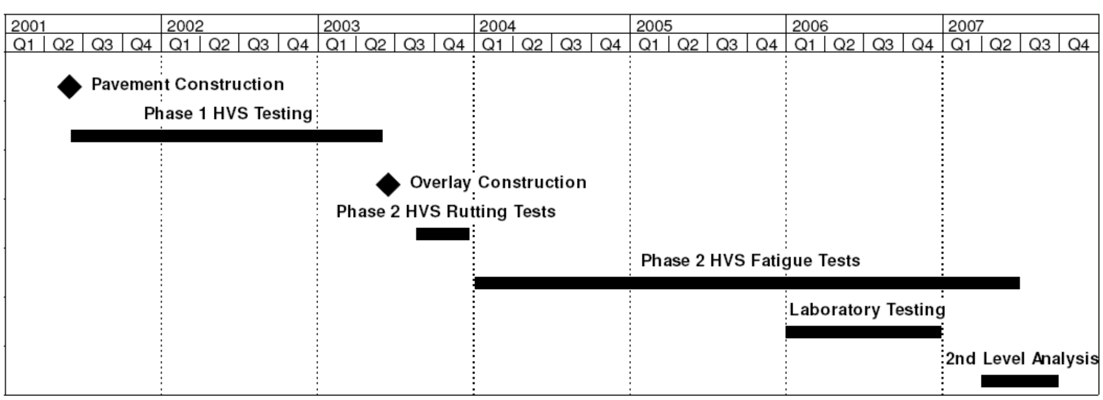

Figure 3.1: Reflective Cracking Study schedule. (*5*)

3.1.1 *Materials*

Prior to construction of the test pavement, the existing HMA and aggregate base were milled to a depth of 250 mm (10 in.); this operation resulted in removal of all material above the subgrade surface.

The new aggregate base contained recycled material which included crushed brick, milled HMA, and crushed portland cement concrete. The aggregate base was constructed from material supplied by the Dutra Materials plant in San Rafael, California. The Caltrans Standard Specification for a Class 2 aggregate base at the time of construction limited the inclusion of recycled material to not more than 50 percent provided that it met all other Class 2 AB requirements, however the recycled material content in the Class 2 AB used in this project was estimated to be 100 percent based on visual inspection. Subsequent laboratory testing indicated that the material met or exceeded the Class 2 AB specification requirements. The age of the recycled material could not be determined and likely contained crushed building waste from a number of sources with different ages.

During the approximately five years of testing, pavement performance of the test sections was monitored on a prescribed basis. Deflection data were obtained using the FWD soon after initial construction, and before and after each HVS test in both the Phase 1 and Phase 2 test programs. HVS testing involved one to two million repetitions of the wheel load, the majority at 22,000 lb (100 kN), or 2.2 times the legal limit on state highways.

Stiffness moduli of the pavement layers were determined by backcalculation using the FWD data. At the completion of the Phase 2 program, forensic investigations were conducted on each of the sections using test pits (total of 18).

3.1.2 *Observations and Results*

Observations indicated that most of the deformations measured in the rutting study occurred in the DGAC layer. The forensic investigation conducted six years after the construction of the base layer indicated that ongoing re-cementation occurred in the crushed concrete material in the base. This observation was substantiated with the following: Dynamic Cone Penetrometer (DCP) tests; close inspection of the test pit profile; use of phenolphthalein to determine the pH of the base material; and examination of specimens under optical and scanning electron microscopes. Reference *(6)* includes similar observations from the other test sections

Backcalculation using the FWD data indicated that stiffness of the base increased significantly with time after initial construction, primarily due to re-cementation of the recycled concrete particles. Correlation between the asphalt concrete modulus and the base modulus was weaker in the untrafficked area and/or in the trafficked area before HVS testing, probably because of re-cementation of particles in the base after construction and subsequent destruction of the bonds during HVS trafficking.

3.1.2.1 Test Pit Observations (Example, Section 580RF)

Re-cementation of the base material was visible. A cement odor was present and strong effervescence was noted when dilute hydrochloric acid was sprayed onto the base material, indicating the presence of old cement (Figure 3.2). When phenolphthalein was sprayed onto the base material, the sprayed area turned red, signifying a pH greater than 10, which is indicative of uncarbonated cemented material (Figure 3.2).

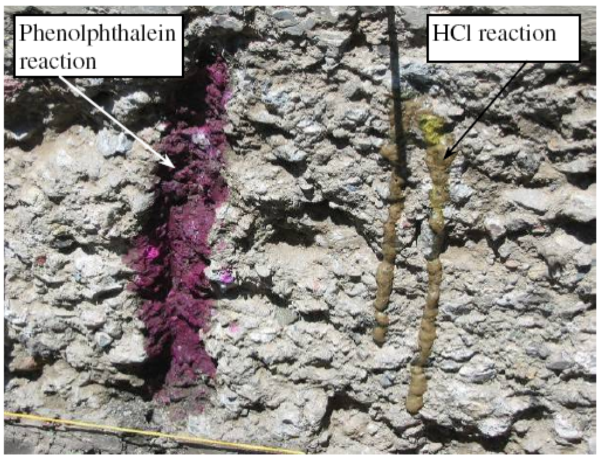

Figure 3.2: 580RF phenolphthalein and hydrochloric acid reaction on base material.

3.1.2.2 Scanning Electron Microscope Observation

To determine whether the cementation of the base material resulted from vestigial cement exposed to water during the crushing and processing of the building waste or was cement that hydrated during the original construction of the source material, samples removed from the test pits in Section 591RF were assessed using optical and scanning electron (SEM) microscopes.

Figure 3.3 (optical microscope at ±100x magnification) and Figure 3.4 (optical microscope at ±200x magnification) show the presence of calcite crystals associated with the cracking in the carbonated sample, none of which were evident in the uncarbonated material. The well-crystallized nature of the material is indicative of recent formation (during the week before examination). There was also a conspicuous absence of calcium hydroxide, indicating severe carbonation.

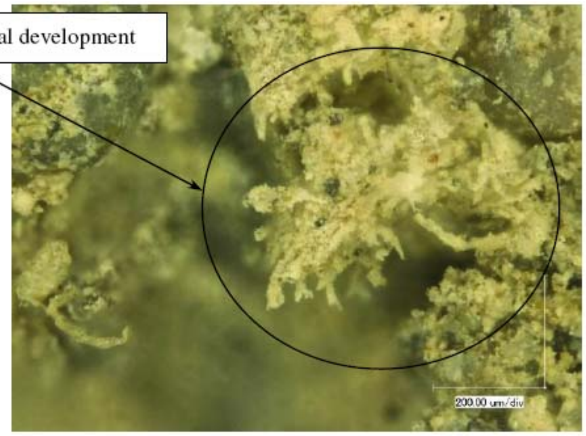

Figure 3.3: Optical microscope view (±100x) of calcite crystal development associated with cracks.

Figure 3.4: Optical microscope view (±200x) of calcite crystal development associated with cracks.

3.1.2.3 Backcalculation Results (Sections 567RF/586RF and 572RF/590RF)

Very little time passed between the initial construction and the initial HVS testing on Section 567/586RF, and during that period no FWD tests were conducted. Backcalculations show that the moduli of the base changed between 1,000 and 4,000 MPa (145,000 and 580,000 psi) during the approximately five years that passed between the initial and the second HVS trafficking; Figure 3.5 and Figure 3.6 show that changes especially occurred during the first two years. During this time there was almost no truck traffic and only light car traffic. This would indicate that while some of the stiffness increase is likely due to curing (drying out causing suction) of the base, much of the stiffness gain should attributed to re-cementation of the recycled concrete aggregate particles used in the base material *(12)*. Most virgin Class 2 bases have stiffnesses that generally do not exceed 500 MPa (73,000 psi), while this base material had stiffnesses that were 2 to 8 times higher than most virgin Class 2 AB materials.

A similar trend can be seen for Section 572/590RF which was constructed at the same time with materials from the same source (Figure 3.7 and Figure 3.8). Section 572/590RF had approximately 18 months of light traffic between initial construction and initial HVS trafficking, another year between the two HVS tests, and another two years between measurements after the second HVS trafficking. It can be seen in Figure 3.8 that in the 18 months after initial construction the stiffness increased to approximately 1,000 MPa (145,000 psi). The very heavy loading of HVS trafficking then reduced the stiffness to approximately 150 MPa (22,000 psi), after which it increased over the next year to approximately 750 MPa (108,000 psi). The second round of heavy loading from the HVS brought the stiffness down to about to 250 MPa (36,000 psi), which then increased over the next two years to about 500 MPa (73,000 psi).

Some of the increases can be attributed to thixotropic recovery and aging of the asphalt which provided some more confining stress to the aggregate base, but it is highly unlikely that stiffnesses as high as those measured would have occurred without a significant contribution from ongoing re-cementation after construction and each round of HVS testing. The HVS testing was heavy enough that it appears to have broken nearly all of the re-cementation that occurred up to that time, with the moduli of the aggregate base after HVS loading typical of virgin aggregate base. The increased stiffnesses are not as high as on 567/586RF probably because 572/590RF did not have as long before the HVS was put on it. It appears that the re-cementation occurred at a decreasing rate over time, with the improvement after the first HVS testing being less than after construction, and the improvement after the second HVS less again. This makes sense based on the assumption that a finite amount of previously unhydrated cement was exposed during manufacture of the base material, which was being continuously consumed by hydration.

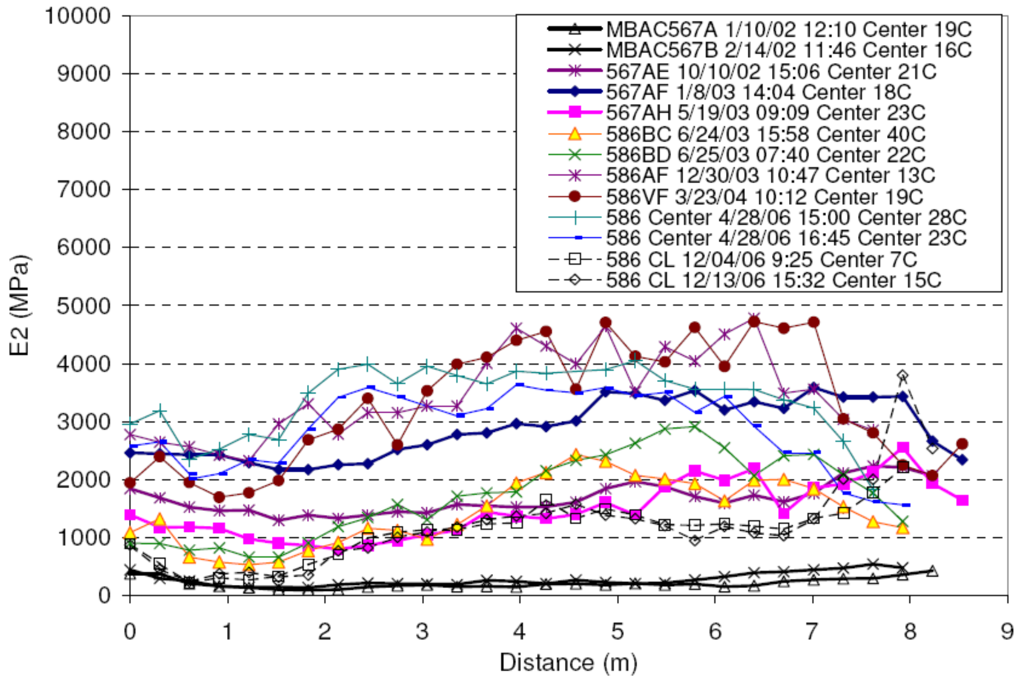

Figure 3.5: Moduli of aggregate base from FWD measurements over a period of about five years; Sections 567RF/586RF (center of wheelpath).

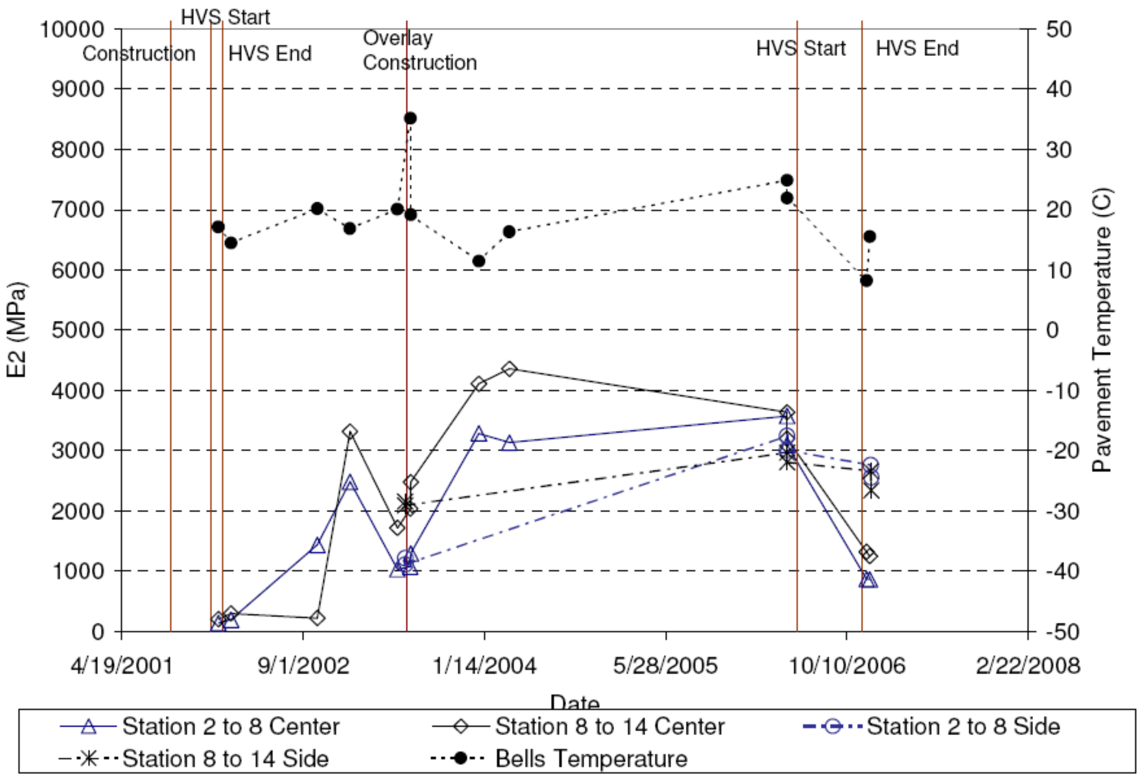

Figure 3.6: Moduli of aggregate base from FWD measurements versus time for Sections 567RF/586RF.

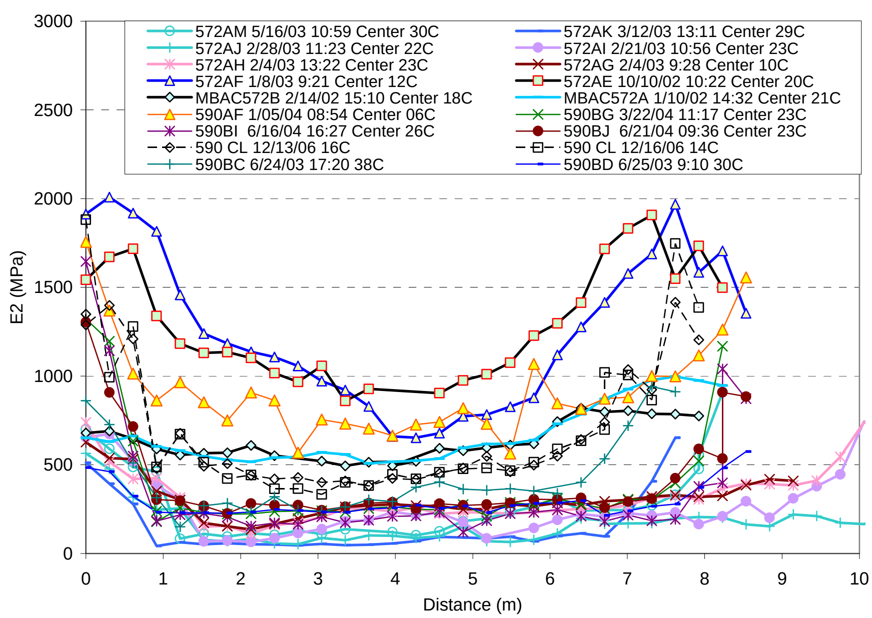

Figure 3.7: Modulus of aggregate base from FWD on Sections 572RF/590RF (center of wheelpath).

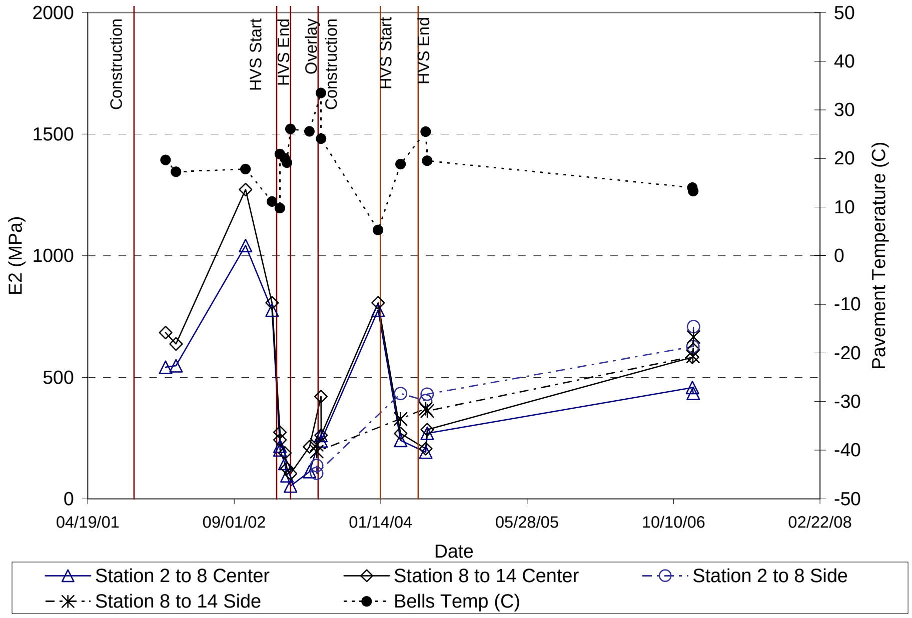

Figure 3.8: Modulus of aggregate base from FWD versus time on Section 572RF/590RF.

3.2 Phase 1 I-710 Freeway Rehabilitation Project, UCPRC Studies

Aggregate bases with recycled concrete have also been built on the state highway system. A major difference between pavements built on the state highway network and HVS test sections is the loading: most wheel loads on the state network are below the legal limit, while heavy overloads are typically used on HVS sections to accelerate damage.

The Interstate 710 freeway is a heavily trafficked route in Southern California which carries traffic into and out of the ports of Long Beach and Los Angeles. The original jointed plain concrete pavement structure was built in 1955, and consisted of 200 mm (8 in.) of portland cement concrete, 100 mm (4 in.) of cement-treated base, 100 mm (4 in.) of aggregate base, and, 200 mm (8 in.) of imported subbase material *(9)*. Due to vertical clearance limitations, two different types of pavement cross section were selected for the rehabilitation in 2002: full-depth asphalt concrete on aggregate base under the overcrossings; and crack, seat, and asphalt concrete overlay (CSOL) on the sections where vertical clearance was not a problem. Figure 3.9 illustrates the rehabilitation methods used. The new aggregate base shown under the full-depth sections was manufactured by the contractor from various sources of concrete pavement slabs from the Port of Long Beach. These slabs were crushed to meet Caltrans Class 2 AB specifications, and then placed as Class 2 AB before paving asphalt over the top. As part of the post-construction monitoring of this initial project using this type of design, the pavement was evaluated for five years.

3.2.1 *Pavement Evaluations*

To assess pavement structural response, an FWD was used to conduct deflection testing along the northbound and southbound lanes. Testing was conducted typically between the hours of 9 p.m. and 7 a.m. during the five years of testing (2003 to 2008). Lanes were designated 1, 2, and 3 for the inner, center, and outer (truck) lanes, respectively. Stiffness moduli of the pavement layers were obtained by backcalculation using the FWD data**.**

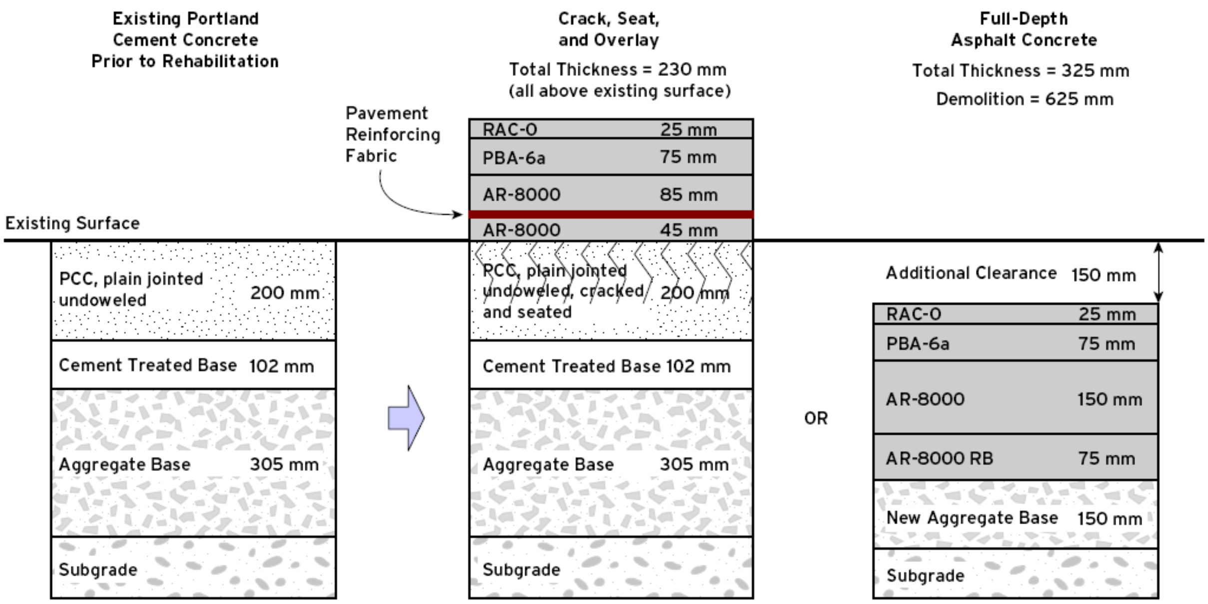

Figure 3.9: Illustration of I-710 rehabilitation strategies.

3.2.2 *Results*

Figure 3.10 through Figure 3.12 show the backcalculated base moduli for the three full-depth sections. Average moduli values for the crushed concrete base section in the full-depth sections were of the order of 4,000 MPa (580,000 psi) with a range of about 1,200 MPa to 7,000 MPa (174,000 to 1,016,000 psi). These values are higher than observed values for conventional crushed aggregate base material. It is suspected that significant cementing must have taken place in the base layer to account for the high levels determined through backcalculation even though no cores were obtained that could be used for strength measurement or to provide evidence of cementation in a laboratory study. Nevertheless, although the computed values might not precisely represent the in-situ characteristics of the material, increased stiffness was evident.

It is apparent from these results that over the five-year period of evaluation after construction the stiffness of the base did not decrease significantly, while it did decrease to values typical of aggregate base with no cementation under the HVS loading. The wheel loads on the I-710 pavement do not include many loads over the legal limit, while the HVS sections were subjected to at least a million repetitions with double the legal limit. The asphalt layers over the I-710 base material are also much thicker than those on the HVS test sections. This indicates that the stresses on the I-710 pavement were not high enough to break down the cementation that apparently occurred.

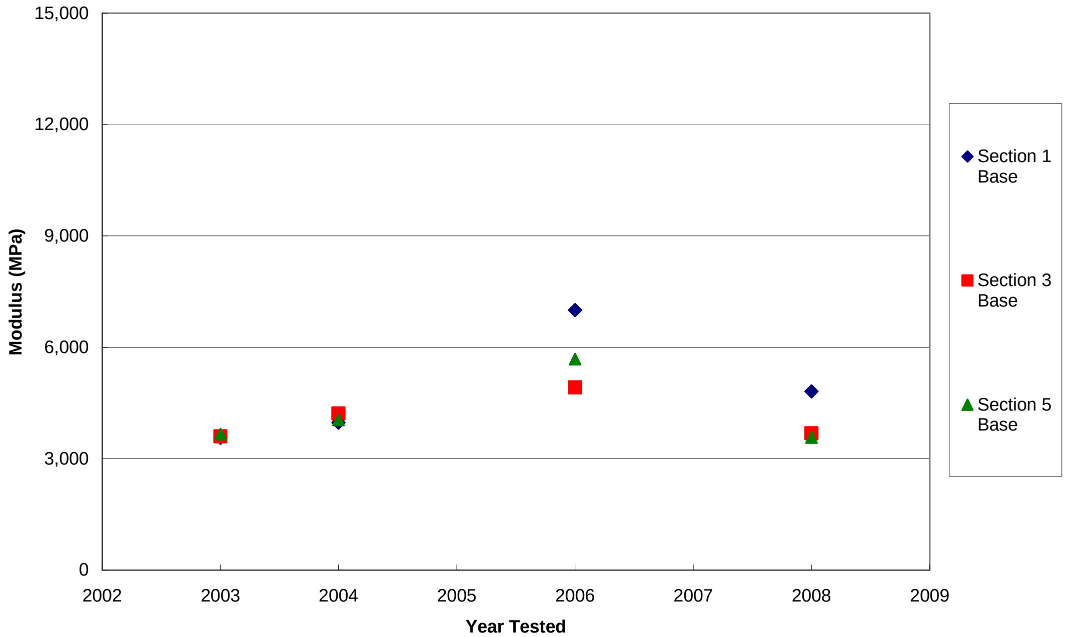

Figure 3.10: I-710 Northbound Lane 1 full-depth sections—layer moduli with time.

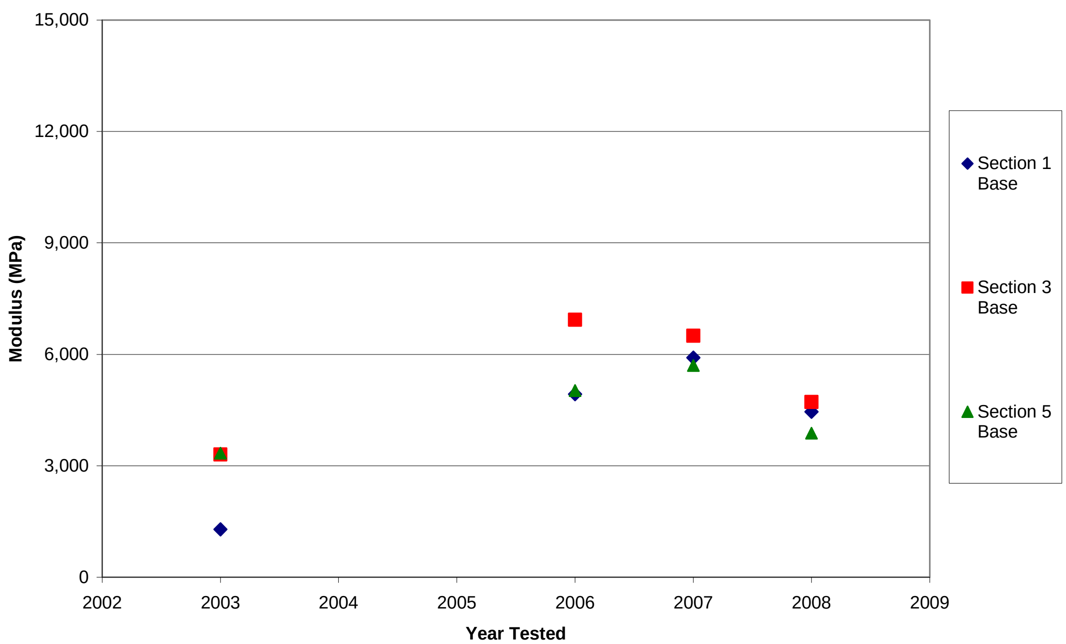

Figure 3.11: I-710 Northbound Lane 2 full-depth sections—layer moduli with time.

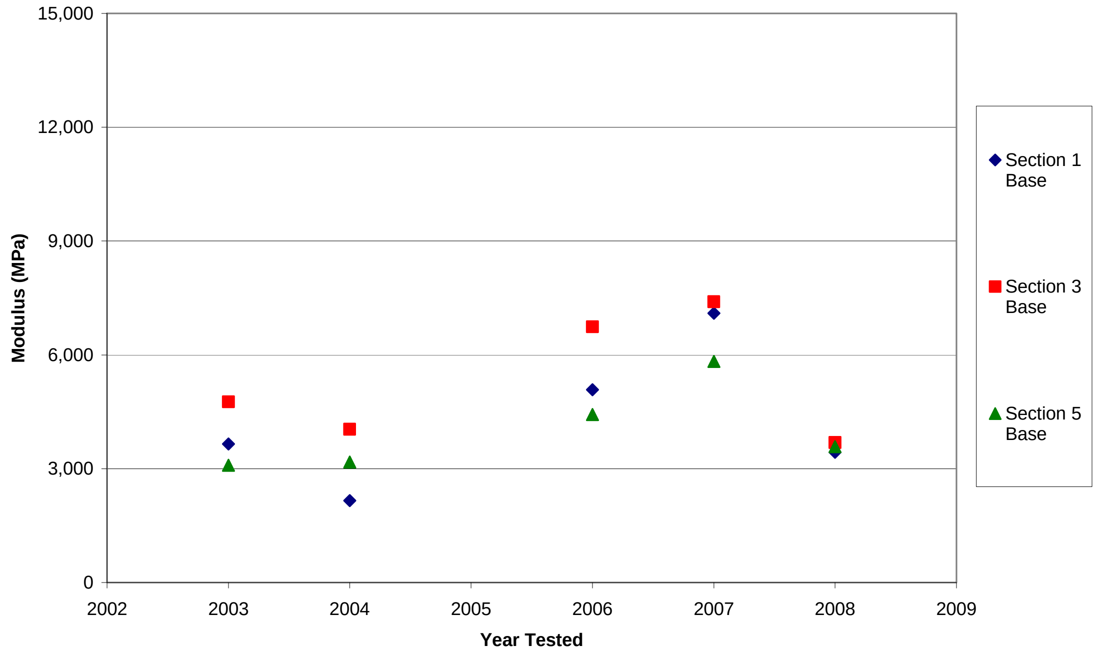

Figure 3.12: I-710 Northbound Lane 3 full-depth sections—layer moduli with time.

3.3 CSIR, Gautung Province Republic of South Africa, Highway N12-19 East Project, HVS Test 425

In 2005, CSIR staff in South Africa conducted an investigation on an HVS test section located in a part of an earlier experiment (S12-Section 2) carried out in the late 1960s on Highway N12-19 East (km 27.210) *(9)*. The object of the study was to determine the reasons for the relatively good performance of the section under traffic. This pavement structure had been rebuilt in 1974 after the original cement-treated base failed within three years of its construction after exhibiting severe block cracking. In the rebuilding, the base was ripped and reworked with the addition of asphalt emulsion (1 percent net asphalt cement) to construct an emulsion-treated base (ETB). No additional cement was included during the recycling. The pavement surfacing consisted of two layers of asphalt mix and an asphalt rubber chip seal. The only recorded maintenance between the end of the reconstruction and the 2005 HVS testing was the application of a fog seal in 1991. By the time the latest HVS testing commenced the pavement had been subjected to approximately 11.5 million equivalent single axle loads (ESALs).

In addition to the HVS test with collection and analyses of the various associated data, a detailed forensic study was conducted. This study included a detailed materials evaluation consisting of: excavation and profiling of five test pits; removal of asphalt slabs; sampling and testing of material from each layer in the test pit; and collection of additional small samples from the base and subbase layers for cement content tests and microscopic scanning.

3.3.1 Observations from Test Pit and Scanning Electron Microscope

3.3.1.1 Test Pit Observations

In Figure 3.13, lumps of cemented base from the original road were noted. Freshly exposed faces reacted to phenolphthalein turning a dark red color, indicating the presence of cement (Figure 3.14). A reaction was also obtained when hydrochloric acid was sprayed onto the material, indicating the presence of carbonate.

Figure 3.13: Base course material from test pit. (Note large cemented lumps.)

Figure 3.14: Phenolphthalien reaction on base.

3.3.1.2 Scanning Electron Microscope Observation

Samples removed from the test pit were assessed using a scanning electron microscope (SEM) to determine whether the excellent performance of the pavement noted during HVS testing was due to cementation that resulted from residual cement that was generated during breaking up and processing of the existing base. Prior inquiry had confirmed that no additional cement was added with the bitumen emulsion.

Figure 3.15 and Figure 3.16 show a typical result of carbonation where the development of calcite (calcium carbonate, $CaCO_3$) from lime (calcium hydroxide, $Ca(OH)_2$) in the material results in expansion and cracking. This cracking was seen previously in a range of different carbonated materials. The highly crystallized nature of the material is indicative of recent formation. There is also a conspicuous absence of calcium hydroxide, indicating severe carbonation.

Well-formed fibrous ettringite is also clearly visible in Figure 3.16 (strawlike [wispy] crystals in the bottom right corner), which indicates that cement was present in the matrix after construction, the former apparently generated during breakdown of the highly cemented pre-existing base.

Figure 3.15: Example of carbonated specimen cracking (shown in the lower part of the photograph).

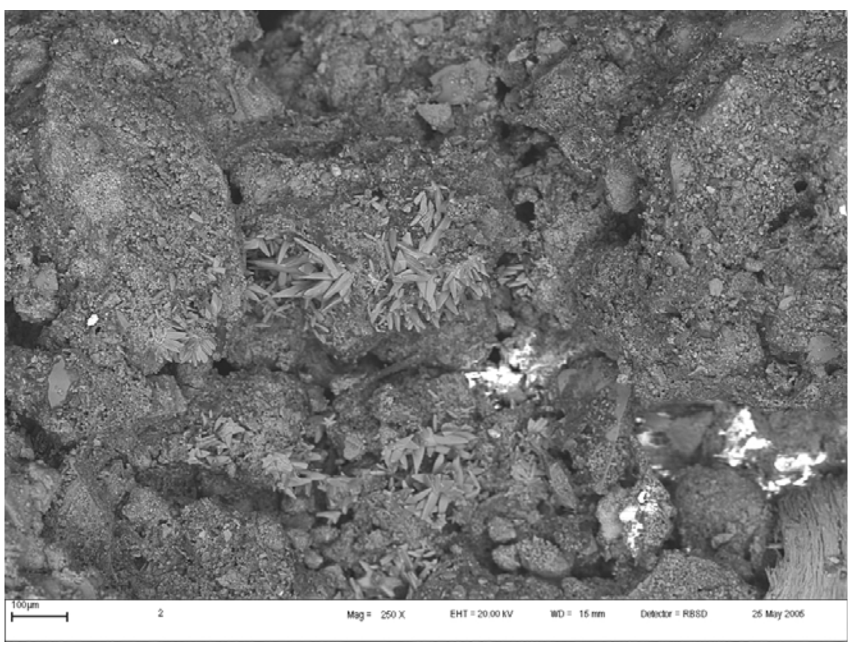

Figure 3.16: Development of young calcite crystals associated with cracks.
(Note ettringite crystals in the bottom right corner).

3.3.2 Structural Evaluations from HVS Test Data

Performance measurements corroborated the results from the electron microscope observations that re-cementation had occurred. Stiffness moduli were estimated from multi-depth deflectometer (MDD) and dynamic cone penetrometer (DCP) test data. The calculated stiffness moduli ranged from 500 to 2,000 MPa with a gradual reduction in the moduli under much heavier traffic than experienced during the life of a normal pavement. (While some FWD measurements were made, the data obtained from these measurements were not used to determine modulus values).

From the time of reconstruction up to the time that the HVS test started, it was estimated that the rehabilitated structure carried a total of 11.5 million ESALs. The HVS test added about 16.5 million ESALs before failure occurred. This estimate is significantly larger than the planned design life of 3 million ESALs.

3.4 HVS Tests on Goal 1 and Goal 3 HVS Test Sections: UCPRC Program

This section describes results from accelerated pavement tests using the Caltrans HVS on drained and undrained base structures and with two types of overlays *(11, 13).*

The original pavement structures were constructed in spring of 1995, and consisted of 150 mm (0.5 ft) of asphalt placed on 274 mm (0.9 ft) of aggregate base on an existing high-quality aggregate subbase and clay subgrade. Half of the test section had 182 mm (0.6 ft) of aggregate base with 75 mm (0.25 ft) of asphalt-treated permeable base between the asphalt and the aggregate base. These sections were overlaid in spring 1997. The base consisted of a conventional aggregate base material mixed with recycled crushed concrete, the proportion of which was somewhat less than 50 percent of the total. Laboratory testing was performed on the aggregate base sampled during construction. Pavement performance of the test sections was closely monitored after construction. An FWD was used to measure deflections after initial construction and before and after each HVS test. Stiffness moduli of the pavement layers were obtained from the FWD data by backcalculation.

3.4.1 Observations and Results

Results of the initial laboratory resilient modulus testing on the aggregate base are shown in Figure 3.17. It can be seen that the stiffness is between about 300 and 500 MPa (44,000 and 73,000 psi) depending on the confining stress in the as-compacted moisture condition, which is the expected range for high quality uncemented aggregate base. FWD testing performed across the 1,000 ft-long test pavement just after construction in 1995 showed stiffnesses that averaged 285 MPa (41,000 psi) with a standard deviation 73 MPa (11,000 psi), again well within the range of expected values for uncemented aggregate base.

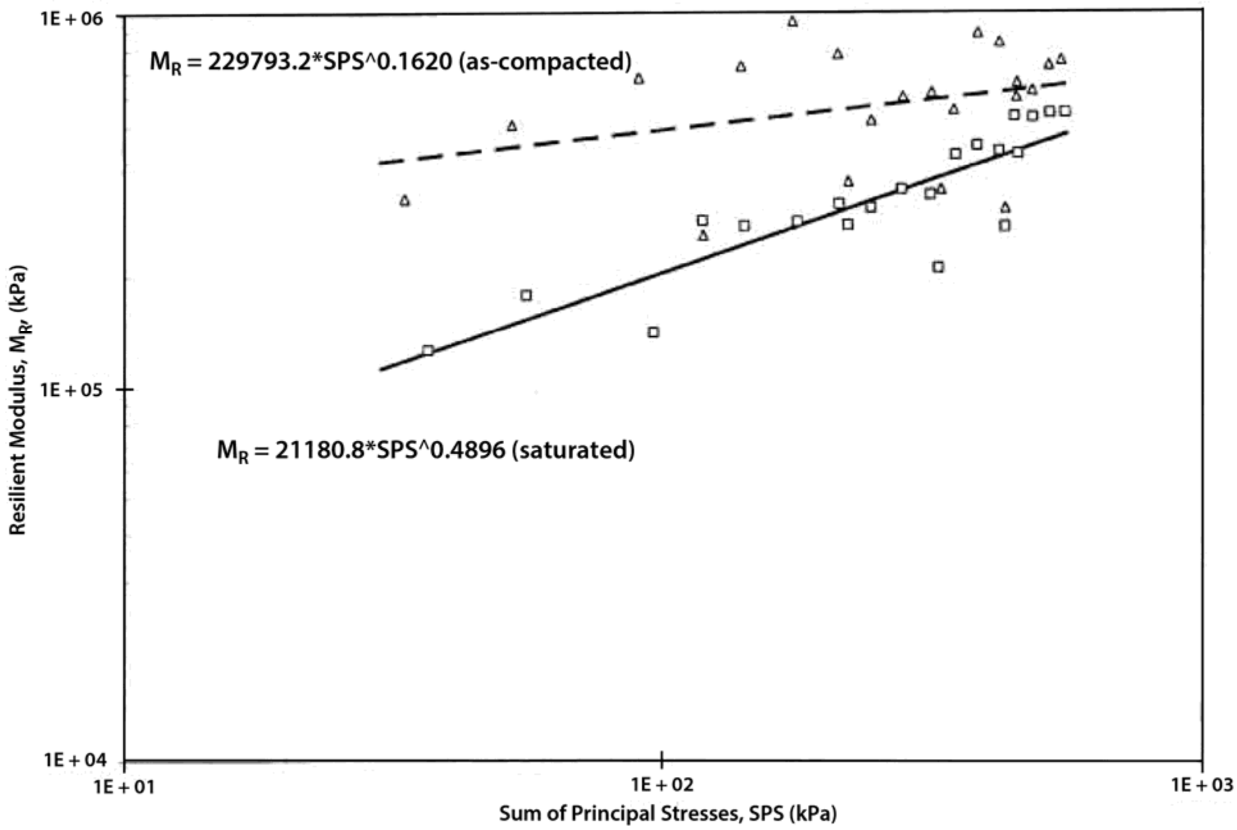

Figure 3.17: Laboratory resilient modulus test results for aggregate base.

FWD testing and backcalculations performed in 1997 and 1998 showed some increase after 1995 on areas that were not subjected to any trafficking from the HVS, as shown in Figure 3.18, with stiffness ranging between 250 and 400 MPa (36,000 and 58,000 psi). For each of three sections examined (RF 515, 517, and 518), the computed stiffness moduli of the granular base layers increased again with time between 1997 and 1998 as seen in Figure 3.18. This increase was about 45 percent for each section over the year.

Observation of the cores of the aggregate base obtained from at least 3 m (10 ft) outside the trafficked areas indicated that some degree of cementation existed, although the results were variable across the entire pavement area. The cementation was sufficient to permit extraction of a complete core from the aggregate base from some locations using a wet coring drill. Cores taken under the HVS-trafficked areas were not cemented, after being subjected to more than a million traffic repetitions with double the legal load.

The results on this pavement indicate much less cementing than on the other three cases, most likely reflective of a lower unhydrated cement content in the material when it was placed on the test sections compared to the other cases.

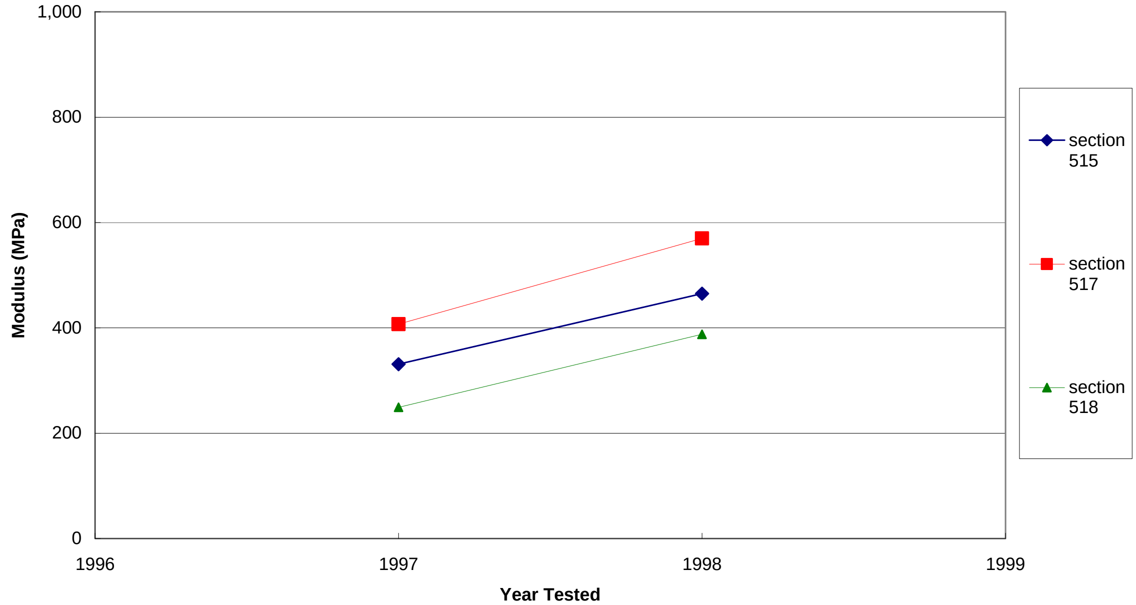

Figure 3.18: Backcalculated moduli from FWD deflections.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion

This study has demonstrated that crushed portland cement concrete (PCC) and cement-treated materials used as a pavement base and/or subbase can exhibit re-cementation. Use of these materials improves the stiffness characteristic of a base or subbase as compared to conventional aggregate base (AB) or aggregate subbase (ASB). Four examples are briefly summarized that illustrate this behavior. The available data suggest that re-cementation leading to stiffness increases of the crushed materials is somewhat time dependent and may be dependent on traffic loading and depth in the pavement structures. None of the structures evaluated in this study have exhibited shrinkage cracking (a commonly associated distress for cemented base and subbase materials).

Table 4.1 summarizes the four studies discussed in Chapter 3. Also included are the ranges of stiffness moduli and the approximate proportions of crushed recycled PCC.

The data also indicate that the percentage of crushed PCC in the AB influences its stiffness modulus. The I-710 Project used 100 percent recycled crushed concrete whereas the MB Test Road base course contained slightly greater than 50 percent and the base course for Goal 3 study less than 50 percent.

Table 4.1: Summary of Stiffness Moduli Determined by Backcalculation for the Four Examples

Project	Base Type	Stiffness Moduli, MPa (psi)	Date of Measurement
UCPRC SPE 4.10 HVS Tests MB Test Road, RFS	Class 2 AB (with >50% crushed PCC, HMA, and brick)	2,800 to 3,700 (4.1 to 5.4x10^5) before HVS tests	April to December, 2006
		1,000 to 2,900 (1.4 to 4.2x10^5) after HVS tests	
I-710 Phase 1 Freeway Rehabilitation Long Beach, CA	100% crushed PCC	3400-8000 (5.0 to 11.6x10^5) After ~5.5 years of traffic, NB and SB lanes	September 2008
CSIR Gautung Province Republic of South Africa, Highway N12-19 East Project, HVS Test 425A5,	Crushed cement treated base mixed with emulsion (1% net asphalt)	500 to 2,000 (0.7 to 2.9x10^5)	January 2005
HVS Tests DGAC and ARHM-GG Overlay Test Sections, RFS UCPRC Goal 3	Class 2 AB (with <50% crushed PCC)	250 to 575 (0.36-0.83x10^5)	June 1995 to May 1999

The stiffness moduli for these four projects reflect the quantitative differences in the proportions of crushed recycled PCC and CTB. Results of this investigation provide preliminary guidelines for the newly developed mechanistic-empirical flexible pavement design program under development termed *CalME*, which requires the use of layer stiffness moduli. Accordingly, for the *CalME* pavement design methodology some preliminary guidelines for stiffness moduli are suggested as follows:

Percentage of Crushed Recycled PCC in AB	**Suggested Stiffness Modulus MPa (psi)**
100	2,500 (3.5×10^5)
50 to 100	1,000 (1.5×10^5)
<50	250 (0.4×10^5)

Two earlier studies of the use of recycled materials used as base courses are reported in References *(12)* and *(14)*. These studies provided recommended gravel factors (G_f,) for pulverized asphalt concrete as an unbound base ($G_f = 1.15$) and provisional gravel factors for pulverized asphalt concrete modified with lime or portland cement for use as a base (with 1% cement, $G_f = 1.2$; and with 3% lime, $G_f = 1.3$). The requirement associated with the use of these values is that stiffness moduli must be comparable to those obtained for the materials evaluated in Reference *(14)*.

The mechanistic empirical (M-E) analyses used to arrive at the gravel factors listed above provide the basis for an estimate of suggested gravel factors for AB containing recycled crushed PCC. In the current Caltrans *Highway Design Manual*, Chapter 630, Table 633.1 (September 2006) *(15)* contains gravel factors for AB ($G_f = 1.1$) and cement-treated base (CTB) ($G_f = 1.7$). Using these values as bounds and considering the gravel factors for the materials described in the previous paragraph and their associated stiffness moduli, the following G_f values are suggested:

Percentage of Crushed Recycled PCC in AB	**Gravel Factor, G_f**
100	1.4
50 to 100	1.2
<50	1.15

These results indicate that the likely stiffnesses for recycled contents between 50 and 100 percent should be investigated further, which may permit a gravel factor of 1.3 for recycled contents of 80 to 100 percent.

4.2 Conclusions

The following conclusions result from the observation and associated analyses:

1. After construction, re-cementation of crushed, recycled PCC occurs when used in aggregate base and subbase pavement layers. Re-cementation likely results from hydration of residual cement in the crushed PCC.
2. Re-cementation results in increased stiffness moduli of the base/subbase layers, which leads to improved pavement performance.
3. The re-cemented materials, based on experience to date, have not exhibited the shrinkage cracking normally associated with conventional CTB.
4. Gravel factors and stiffness moduli for use of these materials in the current Caltrans flexible pavement design methodology and the *CalME* flexible pavement design methodology have been developed based on the results of the four pavement studies evaluated herein and tempered by studies for the use of pulverized asphalt concrete both untreated and with the addition of lime or portland cement as base courses.
5. Some further investigation appears warranted to investigate likely stiffnesses for recycled contents between 50 and 100 percent, which may permit a gravel factor of 1.3 for recycled contents of 80 to 100 percent.

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