Mechanistic Design and Structural Evaluation of
Time Sensitive Urban Full Depth Strengthening Projects

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ABSTRACT
Cold in-place recycling and full depth reclamation are growing technologies for rehabilitating and strengthening in-service roads. Relative to conventional remove and replace road rehabilitation systems, the potential benefits of full depth strengthening include optimal reuse of *in situ* road materials (particularly high quality aggregate materials), more time efficient construction execution resulting in reduced interruptions to residents and business owners, as well as minimal weather exposure risk for contractors during construction. This paper summarizes the findings of two pilot urban road rehabilitation projects that employed cold in-place recycling and full depth reclamation. Findings include the results of a full depth strengthening mechanistic design approach, non-destructive structural asset management surveys to validate structural end value capital, and construction time comparisons.

This research found that cationic asphalt emulsion and Portland cement stabilization significantly improved the laboratory mechanistic-climatic performance of *in situ* recycled materials. It was also found during the design phase that the addition of Portland cement to the asphalt emulsion stabilization system significantly improved its mechanistic-climatic durability. Based on the post construction structural asset management surveys, it was found that cold in-place recycling and full depth reclamation significantly improved the asset value of rehabilitated urban streets and provided a road structure equivalent to a conventional system. Cold in-place recycling and full depth reclamation is well suited for strengthening urban roads with respect to capital cost savings and where road closure time may have a significant impact on adjacent homeowners and commercial businesses. These two projects showed a reduction in project execution time with cold in-place recycling and full depth strengthening relative to conventional road strengthening systems.

INTRODUCTION

Road usage in urban areas is increasing and many urban roads have been in service for several decades. As well, urban roads with high load spectra user demands, particularly commercial haul corridors and/or public transit bus routes, experience significant load spectra relative to many other roads. Consequently, many urban roads are showing severe structural deterioration and are in need of structural strengthening.

Conventional full depth remove and replace road reconstruction is labour intensive and quality aggregate sources are becoming more expensive due to increased haul distances in many regions (1, 2, 3). In addition, the overall construction costs of conventional full depth remove and replace reconstruction systems have increased significantly over recent years (1, 2, 3). This is primarily due to increasing energy, materials, labour, and time input costs. Moreover, quality aggregate resources are becoming increasingly scarce in many regions of the province, particularly urban areas with high demands for aggregates. To compound matters, urban field state conditions can be highly variable and the aged state of many in-service roads has resulted in highly variable structural performance. For example, significant portions of the Cities of Regina and Saskatoon are constructed on marginal subgrade materials and many areas have been subjected to a high water table in recent years (1).

With the rising costs of energy and depletion of quality aggregates, many urban road agencies have identified the need to investigate alternative systems for structural road rehabilitation (1, 2, 3, 4). Cold in-place recycling and full depth strengthening is typically performed in-place, although reclaimed material may be moved off-site for further processing and refinement. Cold milling the bituminous surface coarse with or without the granular base layer, adding various stabilizers, and laying the recycled coarse as a strengthening system in a continuous operation has evolved as a popular technological solution (4).

Full depth reclamation involves the process of pulverizing the bituminous surface coarse to its full depth and blending in a portion of the substructure materials. Once the recycled *in situ* quality granular materials are blended uniformly, the material is placed and compacted to form a new sub-structural material. This new material is often stabilized with an emulsion, cement, or foamed asphalt depending on specific soil conditions.

The benefits of cold in-place recycling and full depth reclamation for rehabilitating urban streets include (1, 2, 3, 4, 5):

- Reuse of existing road materials, particularly high quality aggregate materials (for many regions, the highest quality aggregate materials are *in situ*).
- Elimination of structural cracks present in the upper portion of the pavement structure during the pulverization process.
- Reduction in construction related damage to surrounding streets due to reduced material haul in and out of the project site.
- Time efficient road rehabilitation with minimal interruptions to road users, residents, and business owners during construction.
- Reduction in total construction energy consumption and carbon footprint including aggregate haul related emissions.
- Minimal weather exposure risk during construction.
- Modern reclaimer/stabilizers have the ability to homogeneously reclaim high quality granular materials.
- Reduced consumption of new source virgin aggregates near urban areas therefore optimizing the allocation of quality aggregates across various urban commercial uses.

OBJECTIVE

The primary objective of this research was to characterize the mechanistic material properties and end product structural asset management survey results of two urban full depth strengthened systems constructed in Saskatchewan under typical in-service urban field state conditions. A secondary objective of this research was to evaluate the capital costs as well as construction time required to rehabilitate two urban roads and compare these results to conventional road rehabilitation solutions.

RECLAIMED GRANULAR MATERIAL STRENGTHENING DESIGN PROPERTIES

The case studies considered herein include the Idylwyld Service Road in the City of Saskatoon and Shannon Road in the City of Regina. Conventional methods used in Saskatchewan to characterize road materials are primarily based on physical properties such as grain size distribution, soil classification, California bearing ratio, and the empirical correlation of these properties to empirical field performance observations. Due to inherent empiricism of conventional granular base characterization and road design methods, relying on these traditional conventional road design methods to predict performance of recycled materials under worsening field state conditions on aged road structures typically induces significant inaccuracy in road performance predictions (1, 2, 3, 6).

This research employed a mechanistic based design approach involving triaxial frequency sweep characterization performed across load frequencies ranging from 10 Hz to 0.5 Hz, as well as across stress states typical of those experienced under modern Saskatchewan urban road field state conditions, as listed in Table 1 (1, 2, 3, 5). It is believed that if the triaxial mechanical behaviour of road materials can be accurately characterized under realistic critical field state conditions, improved optimization of reclaiming road materials within specific strengthening systems to structurally upgrade thin granular roads may be determined in a more reliable and scientific manner (1, 2).

Triaxial frequency sweep characterization was used to determine dynamic modulus and Poisson's ratio of gyratory continuum laboratory prepared samples of the *in situ* Idylwyld Service Road and Shannon Road materials used in the design. The critical stress state is found at low frequency loading to represent slow moving heavy industry traffic and was therefore chosen as the critical field state condition.

Dynamic modulus is a primary mechanical material property used to characterize material stiffness under dynamic loading and triaxial stress states representative of typical field state conditions (7, 8). Figure 1 shows the selected cement-emulsion strengthening system increased the mean dynamic modulus of both the Idylwyld Service Road and Shannon Road *in situ* granular material.

As seen in Figure 1, the mean dynamic modulus of the *in situ* granular material of Idylwyld Service Road increased from 345 MPa to 864 MPa when strengthened with the specified cement-emulsion system. The dynamic modulus of Shannon Road *in situ* was assumed to be zero as the samples failed during frequency sweep testing. When strengthened with a cement-emulsion system, the *in situ* material of Shannon Road was observed to increase significantly to a stiffness of 1897 MPa.

Poisson's ratio is a material constitutive relation used in road structural modeling to help formulate multi-axial strain behaviour within road structures (7, 8). As seen in Figure 2, the cement-emulsion strengthening systems selected for Idylwyld Road and Shannon Road significantly decreased the

Poisson's ratio of the *in situ* materials. Therefore, structural road modeling showed the lateral strain states in the field to be significantly reduced with the addition of the cement-emulsion stabilization system.

NON DESTRUCTIVE STRUCTURAL ASSET MANAGEMENT SURVEY RESULTS

Non-destructive road structural asset management diagnostic technologies have been used for several years to accurately quantify structural performance and *in situ* structural composition to design pavement strengthening systems (1,3). Ground penetrating radar (GPR) was used to determine the thickness profiles of the pavement structure. Heavy weight deflectometer (HWD) measurements were used to provide direct measures of structural primary response of the road structure under the spectra of typical commercial truck loadings experienced in the field (secondary legal load limits to primary legal load limits plus 50 percent).

The GPR survey was performed employing a one GHz central frequency air coupled pulse radar system. GPR profiles were collected in both directions along each wheel path at one meter intervals spatially referenced by electronic distance measurement. Using the GPR profiles collected, the surface layer quality index and surface thickness was tabulated and illustrated as contour profiles.

Dynamic surface deflection measurements were obtained by HWD testing to provide direct measures of structural performance of the road structure under load spectra of typical commercial truck loadings experienced in the field. Measurements were taken every 50 meters in each lane using the HWD. Peak surface deflection profiles were collected across load spectra of secondary legal load to primary legal load plus 50 percent weight limits.

A summary of the field construction process and end-product structural asset value of the two field case studies are presented independently below.

CASE STUDY 1: IDYLWYLD SERVICE ROAD, CITY OF SASKATOON

In 2007, the City of Saskatoon structurally upgraded the Idylwyld Service Road from km 0.500 (0.5 kilometers north of 51st Street East) to km 1.700 (60th Street East). Full depth reclamation was a time efficient upgrade solution that did not require major upgrading of the gradelines of the road. A non-destructive structural asset management survey was performed on the entire length of the Idylwyld Service Road in spring 2007 as part of the design analysis (prior to upgrading), and in fall 2007 and spring 2008 as part of the post construction survey. As seen in Figure 3 (a), primary distresses observed included severe permanent deformation, surface disintegration, and localized fatigue cracking in the wheelpaths.

The Idylwyld Service Road was rehabilitated using a full depth reclamation strengthened cement-emulsion system as illustrated in Figure 4. Reclaimed asphalt concrete material was surgically added to Idylwyld Road to provide a uniform structural surface of 350 mm for reclamation and cement-emulsion stabilization illustrated in Figure 4. Figure 3 (b) shows the typical post construction surface condition of Idylwyld Service Road.

Figure 5 shows the *a priori* reclaimed composite thickness, as determined by the GPR survey of the Idylwyld Service Road (from km 0.000 to km 3.400). The *a priori* reclaimed composite thickness was found to vary from 30 mm to 130 mm over its entire length. As seen in Figure 5, the granular base dielectric profile was observed to be relatively high throughout km 0.200 to km 1.800. This is most likely an indication of relatively high moisture content and/or fines content in the *in situ* granular base material. As a result, based on the estimation of substructure moisture profiles, full depth rehabilitation was recommended between km 0.200 and km 1.800.

Based on the *a priori* structural asset management survey performed, the Idylwyld Service Road yielded a poor surface layer quality index, as illustrated in Figure 6 and Figure 7. In addition, Idylwyld Service Road was found to be structurally failed across most of the survey limits relative to primary load limit carrying capacity, as illustrated in Figure 8 and Figure 9. Consequently, pre construction, the Idylwyld Service Road structural asset management survey results showed a high degree of variability.

Figure 6 and Figure 7 show the Idylwyld Service Road GPR surface layer quality index contour profiles and summary statistics, respectively. Overall, Idylwyld Service Road showed significant improvement in surface quality after construction. Also, as seen in Figure 6 and Figure 7, the post construction (2007) surface layer quality index increased from an average of 75 percent before construction to 91 percent post construction (2007). Also, as seen in Figure 6 and Figure 7, the post construction (2007) average surface layer quality decreased from an average 91 percent to 86 percent (2008). The surface layer quality index of Idylwyld Service Road maintained its improvement one year after construction.

As seen in Figure 8, the peak surface deflection profiles of Idylwyld Service Road were significantly decreased due to the construction of the structural system. In fact, the primary deflection response of the entire segment of Idylwyld Service Road demonstrated a primary plus 50 percent load carrying capacity. This is an important benefit for the Idylwyld Service Road given the significant volumes of slow moving and turning heavily loaded trucks that utilize the Idylwyld Service Road.

Figure 9 shows the peak surface deflection of Idylwyld Service Road, as determined using HWD under primary weight limits plus 50 percent. The peak surface deflection greatly decreased after construction and consistently exhibited low surface deflections throughout the entire segment. The most noticeable decrease can be seen at primary weight limits plus 50% in Figure 9 (a) and (b) where the maximum post-construction peak surface deflection is less than the minimum pre construction peak surface deflection.

The structural strengthening of the *in situ* Idylwyld Service Road was performed in four days and the HMAC paving was placed in three days. The estimated time required to perform a conventional re-grade and composite flexible structure was estimated to be approximately five weeks, pending good weather. As a result, the full depth reclamation process was performed in approximately 20 percent of the time required for a full depth reconstruction assuming no weather delays.

CASE STUDY 2: SHANNON ROAD, CITY OF REGINA

In 2006, the City of Regina undertook a cold in-place recycling and full depth reclamation of Shannon Road from Grant Road at km 0.000 to Grant Road at km 2.270. Shannon Road is located in the south end of Regina known for high water table as well as a highly plastic *in situ* lacustrine clay subgrade. Shannon Road is also a bus route for the City of Regina transit system. As part of the engineering design process, a non-destructive structural asset management survey was performed on Shannon Road. The purpose of the *a priori* survey was to quantify the *in situ* structural thickness and the structural primary response of the road prior to strengthening. The *a priori* pavement distresses on Shannon Road included several localized fatigued areas as pictured in Figure 10 (a), and a depressed centerline most likely associated with settled utilities and/or differential heaving expansive clay subgrade.

Based on the structural assessment performed, Shannon Road was rehabilitated using a full depth strengthening system as seen in Figure 11. The reclaimed asphalt concrete materials were cement-emulsion stabilized to a uniform structure. Figure 10 (b) shows the typical post construction surface conditions of Shannon Road.

Figure 12 shows the *a priori* composite thickness profile of Shannon Road pre construction (2006). As seen in Figure 12, the pre construction *in situ* structural composition of Shannon Road was comprised of an asphalt mat with an average thickness of 110 mm with a range in HMAC thickness from 56 mm to 166 mm. The granular base layer had an average thickness of 187 mm, ranging from 136 mm to 227 mm. As illustrated in Figure 12, Shannon Road showed a significant increase in subgrade dielectric permittivity from km 0.100 to km 0.400 and from km 0.700 to km 0.900. This indicated severe localized wetting up of the road substructure in the vicinity of the increased dielectric permittivity profile. Combined with the highly plastic nature of the *in situ* subgrade, it was determined that Shannon Road was experiencing full depth structural failures compromised by the deep subgrade with moisture.

Figure 13 through Figure 15 show the pre and post construction results of the GPR and HWD surveys. Figure 13 shows the GPR surface layer quality index pre construction (2006), immediately post construction (2006), and one and two years post construction in 2007 and 2008, respectively. Figure 14 presents the GPR surface layer quality index summary statistics. As seen in Figure 13, Shannon Road is showing a relatively poor surface layer quality index according to the GPR measurements both pre and post construction. This is believed to be the result of slag aggregate used in the HMAC surfacing mix which interferes with the GPR measures. Nevertheless, there is an improving trend in the GPR surface layer quality index with time. As a result, the surface layer quality index may have to be modified to better characterize hot mix asphalt concrete that employs slag aggregate.

Figure 16 shows the peak surface deflection of Shannon Road, as determined using the HWD, under the target design of primary weight limits plus 25 percent to accommodate bus traffic. The *a priori* peak surface structural deflection response of Shannon Road was poor given its condition prior to structural rehabilitation. The post construction structural primary deflection response measures show a significant improvement in the structural integrity of Shannon Road that has been maintained since construction. Figure 15 presents the summary statistics of peak surface deflection of Shannon Road under primary weight plus 25 percent.

The full depth reclamation and structural strengthening of Shannon Road was performed in 24 days. The estimated time required to perform a conventional rehabilitation and re-grade is estimated to be approximately 90 days. As a result, the full depth reclamation process was performed in approximately 25 percent of the time required for a full depth reconstruction assuming no weather delays. In addition, the full depth strengthening system deployed on Shannon Road significantly reduced the amount of road materials haul in and out of the project site, thus reducing the potential for adjacent road damage.

ADVANTAGES OF FULL DEPTH RECLAMATION STRENGTHENED SYSTEMS

Based on the *in situ* structural characterization of the Shannon Road subgrade and granular base materials, a conventional and full depth reclamation structural rehabilitation option for each road were compared as seen in Figure 4 and Figure 11. Table 2 summarizes the construction cost associated with each option. As seen in Table 2, there was a construction savings for full depth reclamation strengthened system as compared to a conventional urban structure system for both Idywyld Service Road and Shannon Road. A construction savings associated with full depth reclamation and strengthening was $14.50 for Idylwyld Service Road and $19.74 for Shannon Road full depth reclamation relative to a conventional rehabilitation system. This demonstrates the cost savings of a full depth strengthened system in lieu of a conventional system. The cost of the final paved surface was assumed the same for both systems.

Additional advantages to full depth reclamation strengthened systems include improved climatic and mechanistic performance of *in situ* reused materials, improved long term performance of the structural system, reduced weather exposure, and minimized risks due to increasing construction costs related to construction capacity and energy prices. Full depth reclamation systems provide the ability to optimize the use of select materials already in place and typically require reduced overall construction time relative to conventional methods, therefore significantly reducing risk and exposure to weather. When these issues are considered in whole, the benefits of strengthening roads with full depth reclamation are significant relative to conventional remove and replace reconstruction.

SUMMARY AND CONCLUSIONS

Cold in-place recycling and full depth reclamation are growing technologies for rehabilitating and strengthening in-service urban roads. This study demonstrated the ability to characterize full depth reclamation material properties using mechanistic material constitutive relations and relate them to the end-product using mechanistic design, mechanistic testing parameters, and non-destructive testing for urban pavement structures. Based on the triaxial frequency sweep characterization, it was found that stabilization with cement and cationic emulsion significantly improved the climatic durability of the Idylwyld Service Road and Shannon Road *in situ* granular materials. Asphalt emulsion and Portland cement stabilization significantly improved the laboratory mechanistic-climatic performance of *in-situ* recycled material and emulsion stabilized material. Based on structural asset management measurements, cold in-place recycling and full depth reclamation significantly improved the asset value of the urban streets rehabilitated.

This research also found cold in-place recycling and full depth reclamation are well suited for strengthening urban haul roads where closure time may have a significant impact on adjacent homeowners and businesses. In addition, advantages to the full depth reclamation strengthened system include improved climatic and mechanistic performance of the materials, improved long term performance of the structural system, and a minimized risk due to increasing construction costs. It was also found that full depth reclamation typically requires approximately 25 percent of the overall construction time relative to conventional full depth remove and replace methods, therefore significantly reducing exposure to weather. When these issues are considered in whole, the benefits of strengthening urban roads with full depth strengthening are significant relative to conventional full depth remove and reconstruction.

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Table 1 Triaxial Frequency Sweep Testing Parameters

Testing Parameters	Low Deviatoric Stress State	High Deviatoric Stress State
Vertical Traction (kPa)	400	400
Confinement Traction (kPa)	250	50
Deviatoric Stress, σ_d (kPa)	150	350
First Stress Invariant, I_1 (kPa)	900	500
Second Deviatoric Invariant, J_2 (kPa)	7,500	40,833

Table 2 Estimated Construction Costs Per Square Meter

Construction Item	Construction Costs ($/m^2)			
	Idylwyld Service Road		Shannon Road	
	Conventional	FDR	Conventional	FDR
Regrading	$ 20.83	N/A	N/A	N/A
Granular Material	$ 10.42	$ 8.75	$ 35.44	N/A
Excavation to Waste	$5.00	N/A	$5.00	N/A
Full Depth Strengthening	N/A	$ 13.00	N/A	$24.25
Drainage	$ 5.00	$ 5.00	$ 8.06	$ 4.51
Total	$ 41.25	$ 26.75	$ 48.50	$ 28.76
Cost Difference		$ 14.50		$ 19.74

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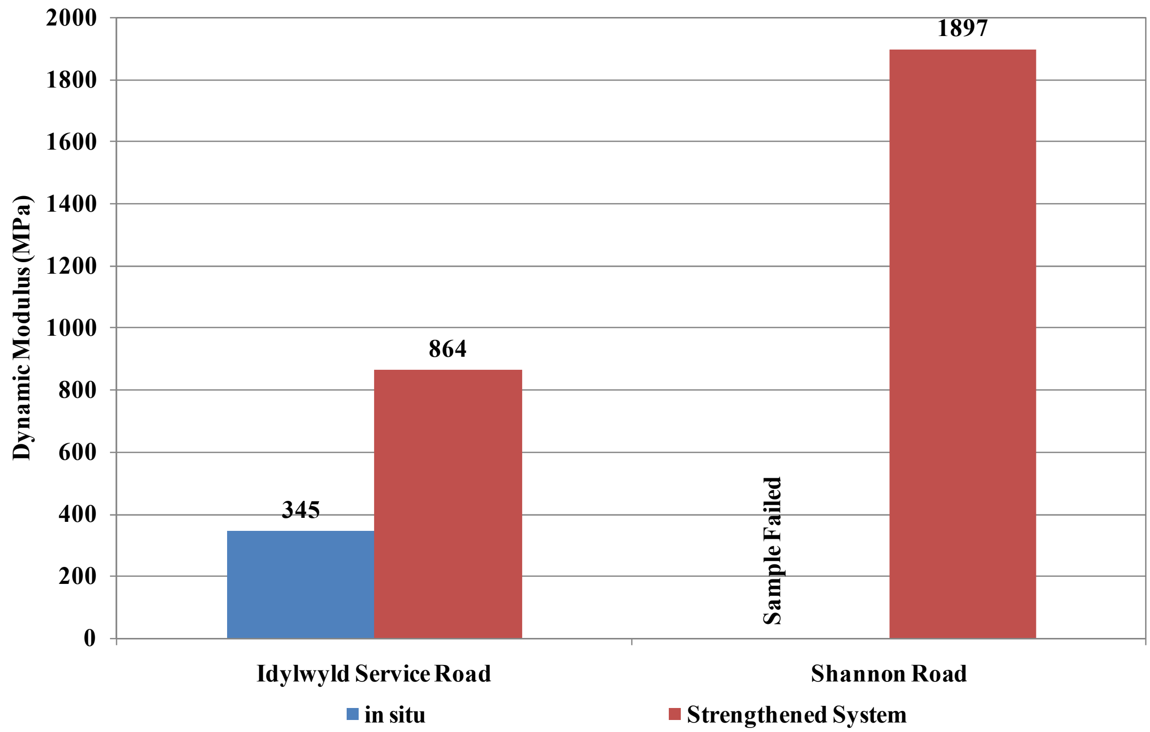


Figure 1 Dynamic Modulus Averaged Across Stress State and Frequency

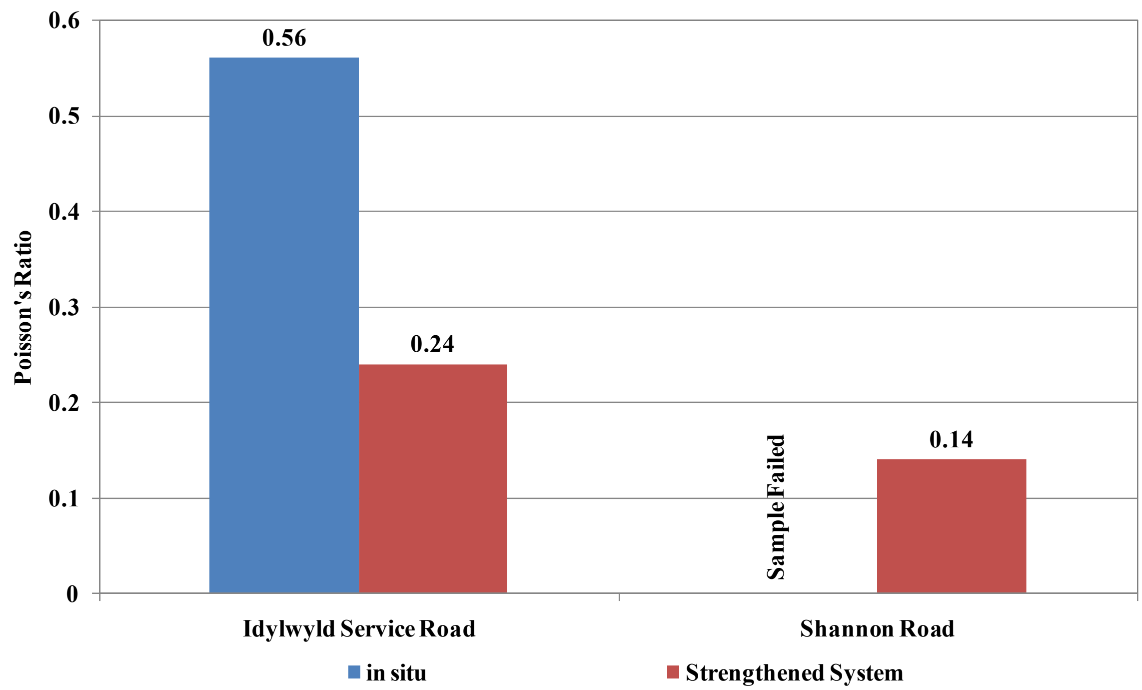
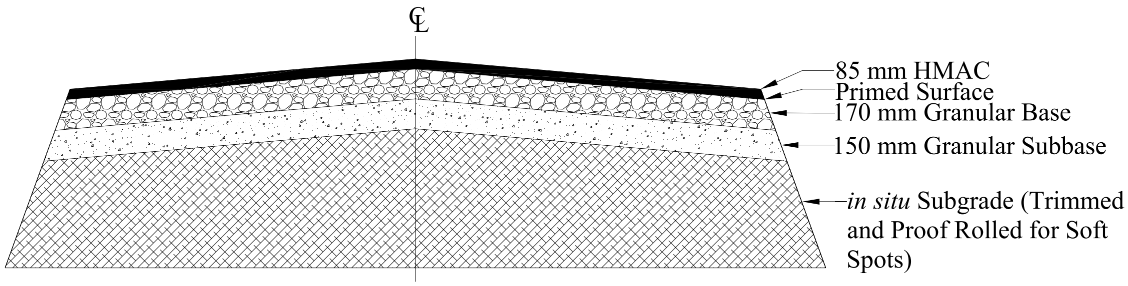


Figure 2 Poisson’s Ratio Averaged Across Stress State and Frequency

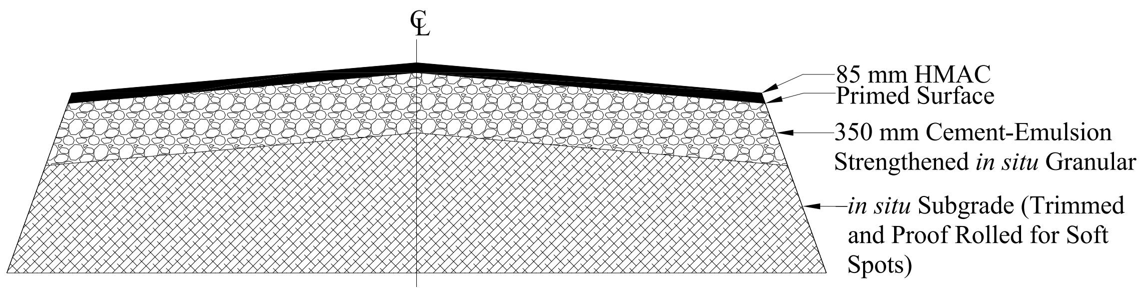
a) Pre Construction 2007

b) Post Construction 2007

Figure 3 Idylwyld Service Road Typical Photos

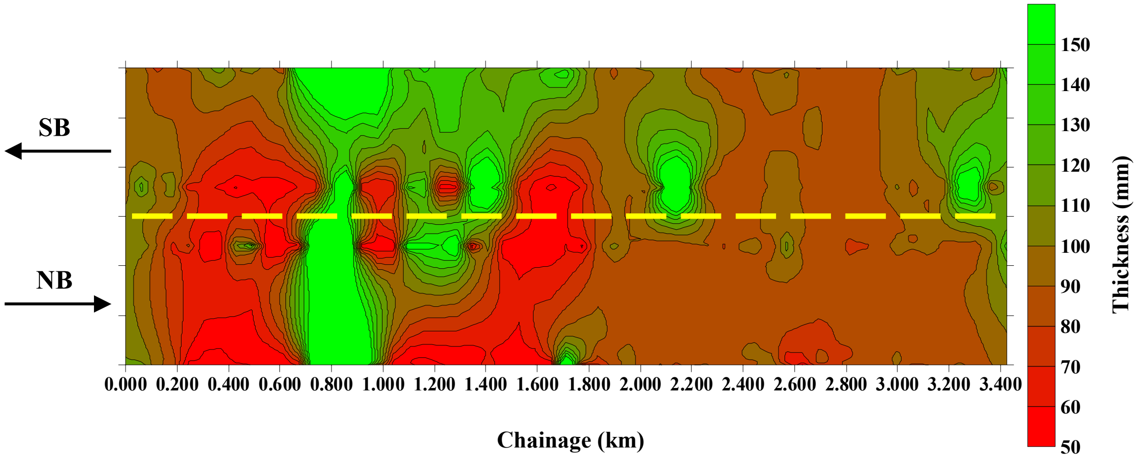


a) Conventional Urban Structural Pavement Cross Section

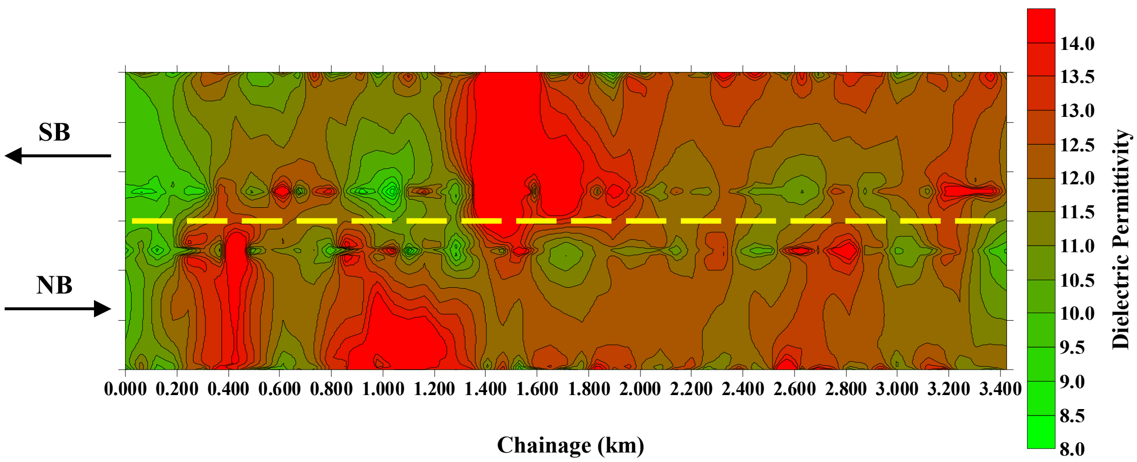


b) Full Depth Reclamation Strengthened Structural Pavement Cross Section

Figure 4 Idylwyld Service Road Proposed Conventional and FDR Strengthened Design Cross Sections

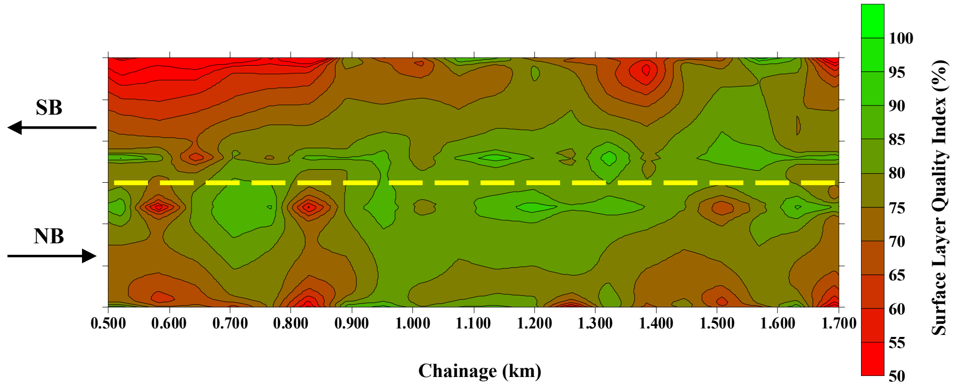


a) Idylwyld Service Road Composite Thickness Contour Profile

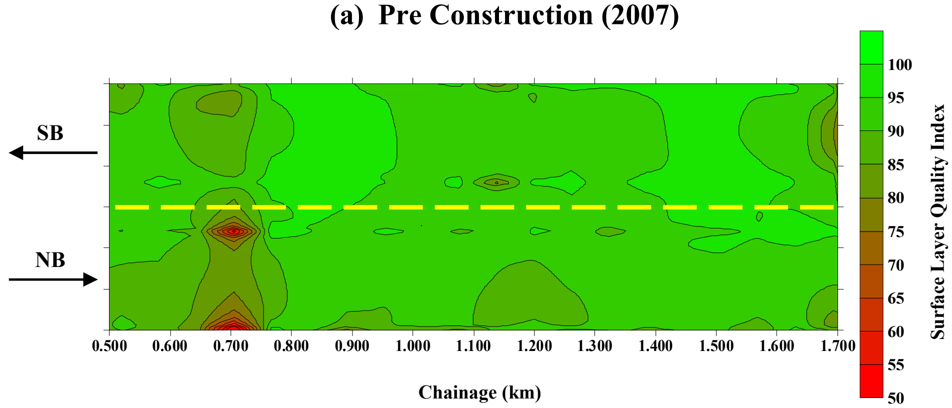


b) Granular Base Dielectric Permittivity

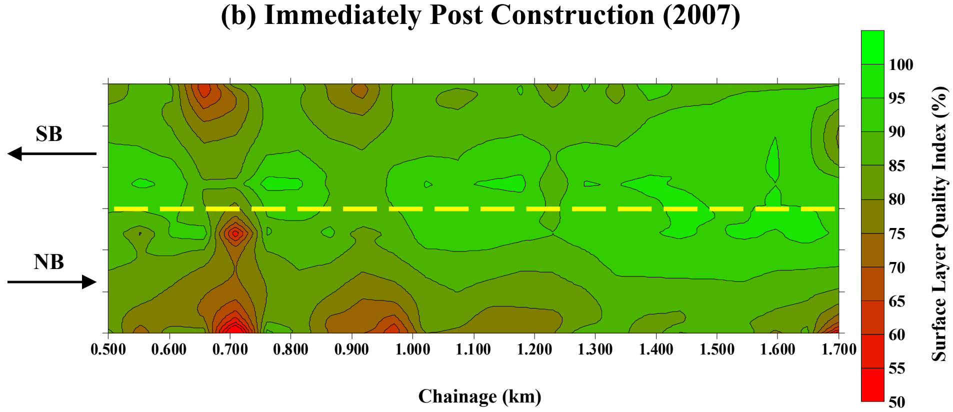
Figure 5 ***A Priori*** **Idylwyld Service Road GPR Properties (Pre Construction 2007)**



(a) Pre Construction (2007)



(b) Immediately Post Construction (2007)



(c) One Year Post Construction (2008)

Figure 6 Idylwyld Service Road Surface Layer Quality Index Contour Profile

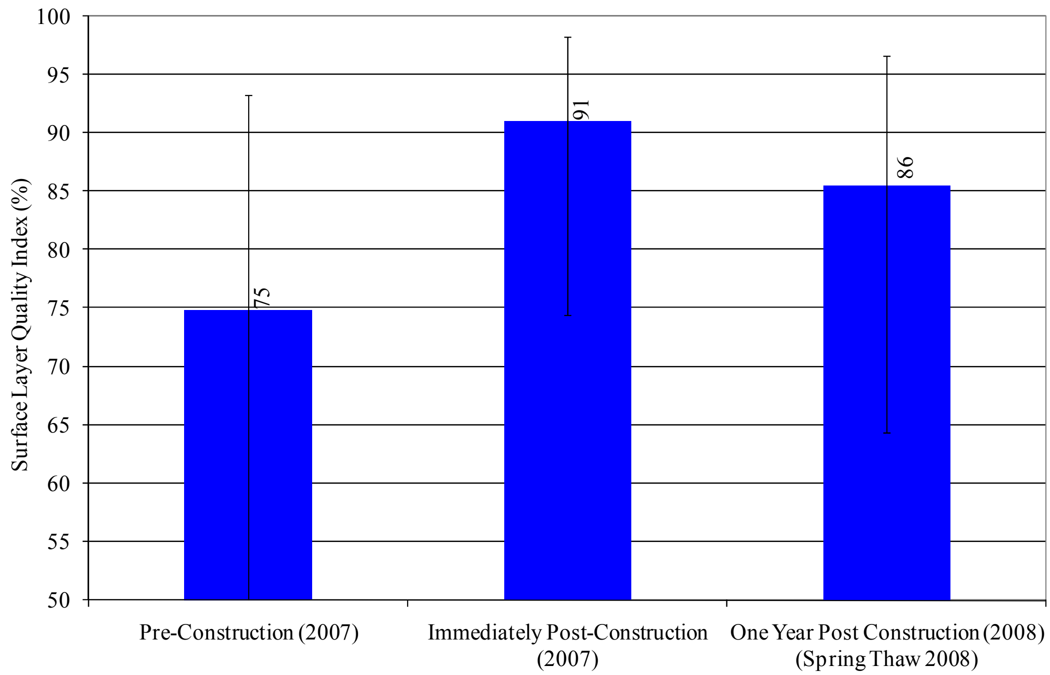


Figure 7 Idylwyld Service Road Surface Layer Quality Index Summary Statistics

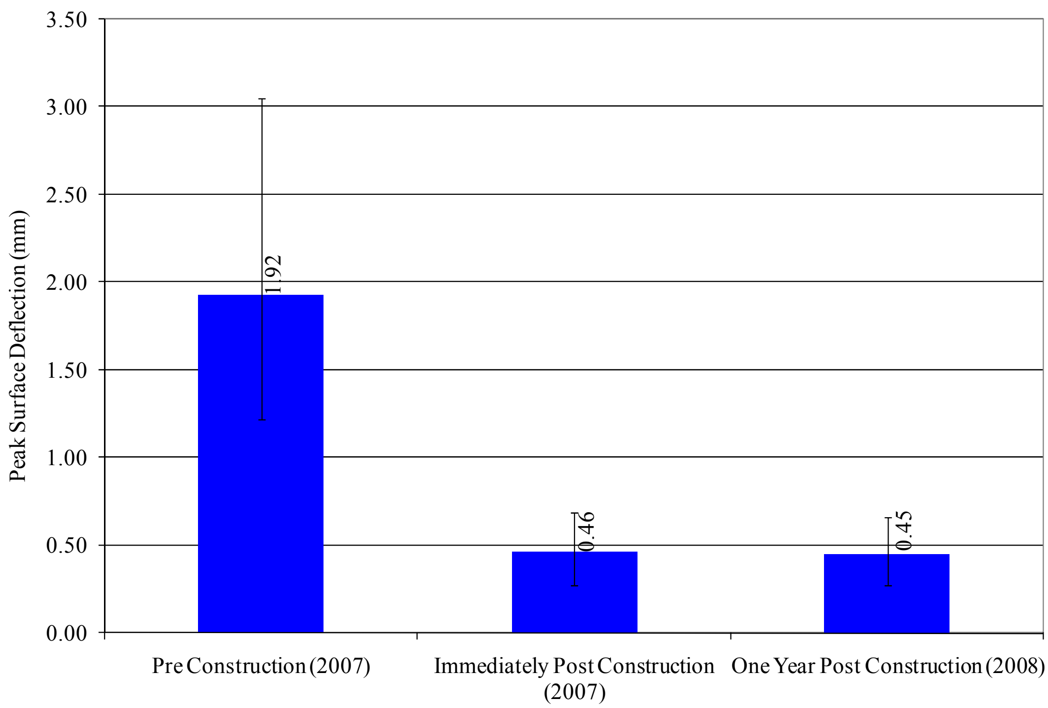
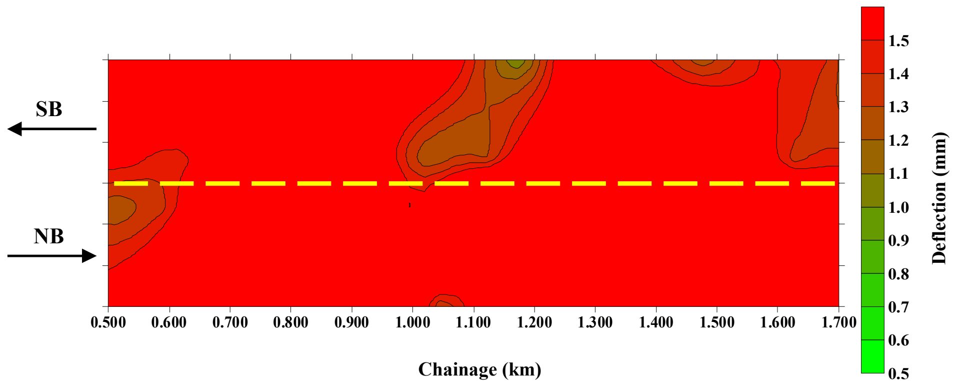
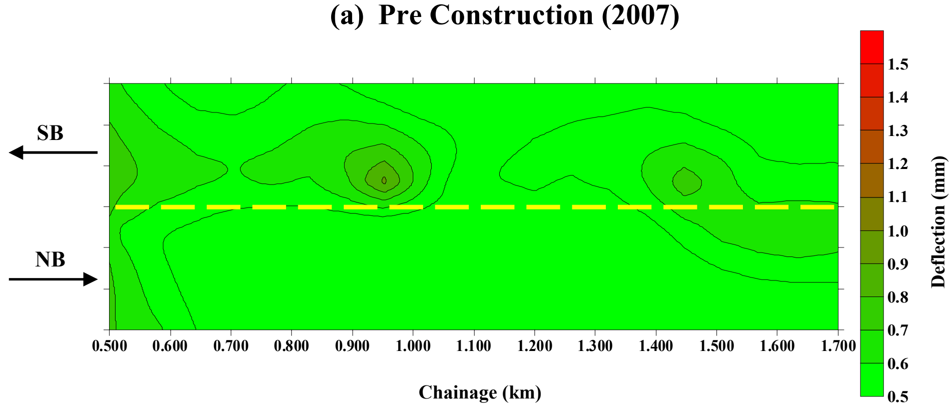


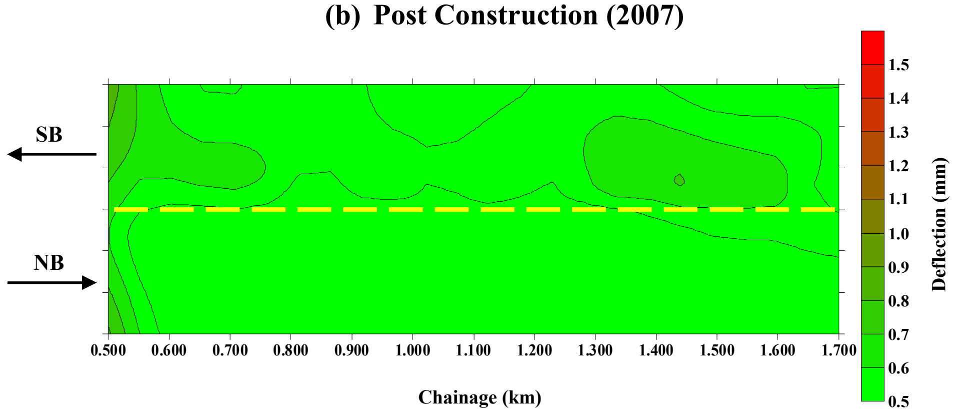
Figure 8 Idylwyld Service Road Peak Surface Deflection Summary Statistics (Primary Weight Limit + 50 %)



(a) Pre Construction (2007)



(b) Post Construction (2007)



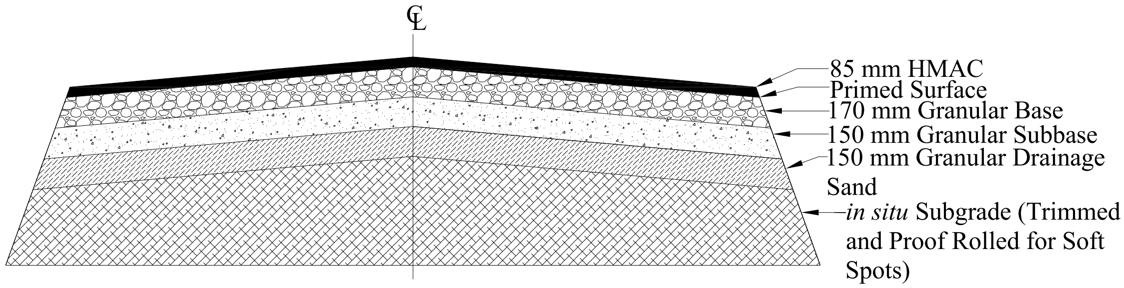
(c) Post Construction (2008)

Figure 9 Idylwyld Service Road Peak Surface Deflection Profiles at Primary Weight Limit + 50 %

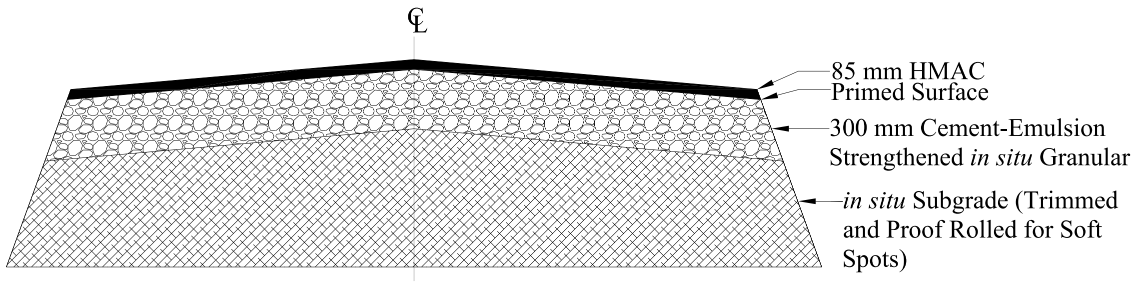
a) Pre Construction 2006

b) Post Construction 2006

Figure 10 Shannon Road Typical Photos

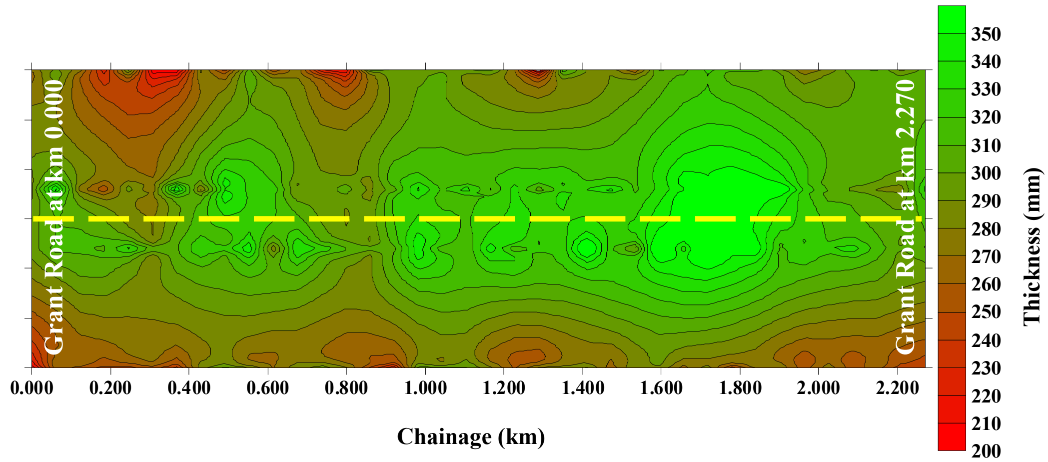


a) Conventional Urban Structural Pavement Cross Section

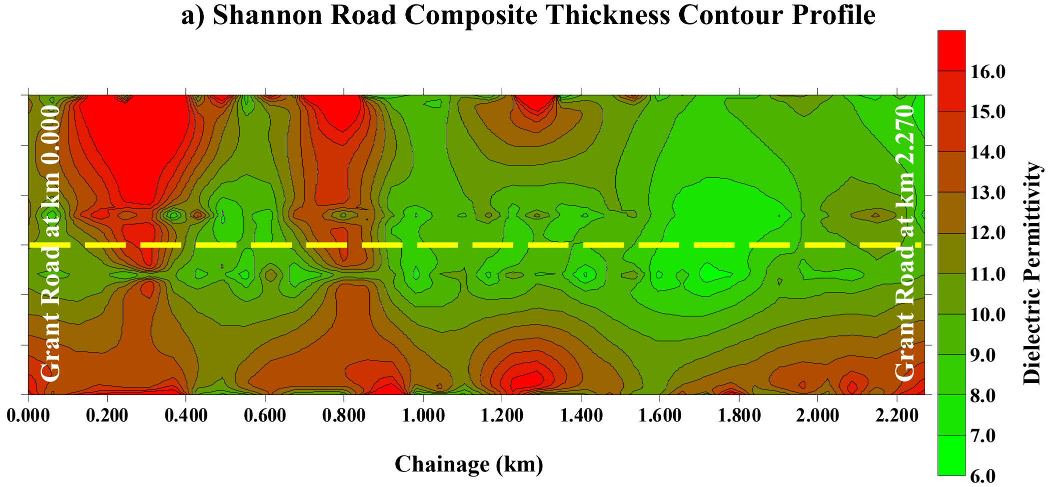


b) Full Depth Reclamation Strengthened Structural Pavement Cross Section

Figure 11 Shannon Road Proposed Design Conventional and FDR Strengthened Design Cross Sections



a) Shannon Road Composite Thickness Contour Profile



b) Shannon Road Subgrade Dielectric Permittivity Profile

Figure 12 ***A Priori*** **Shannon Road GPR Properties (Pre Construction 2006)**

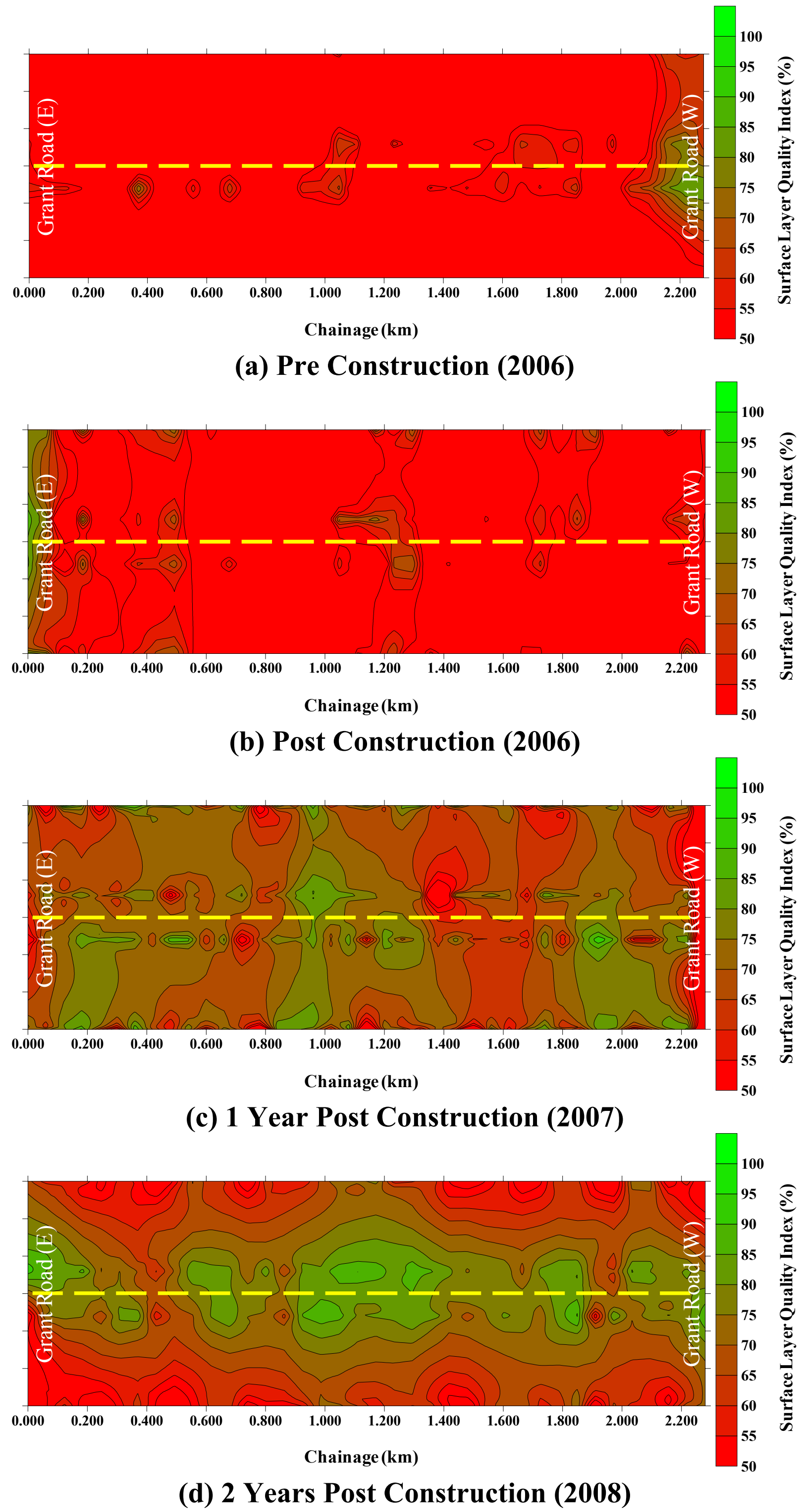


Figure 13 Shannon Road Surface Layer Quality Index Contour Profiles

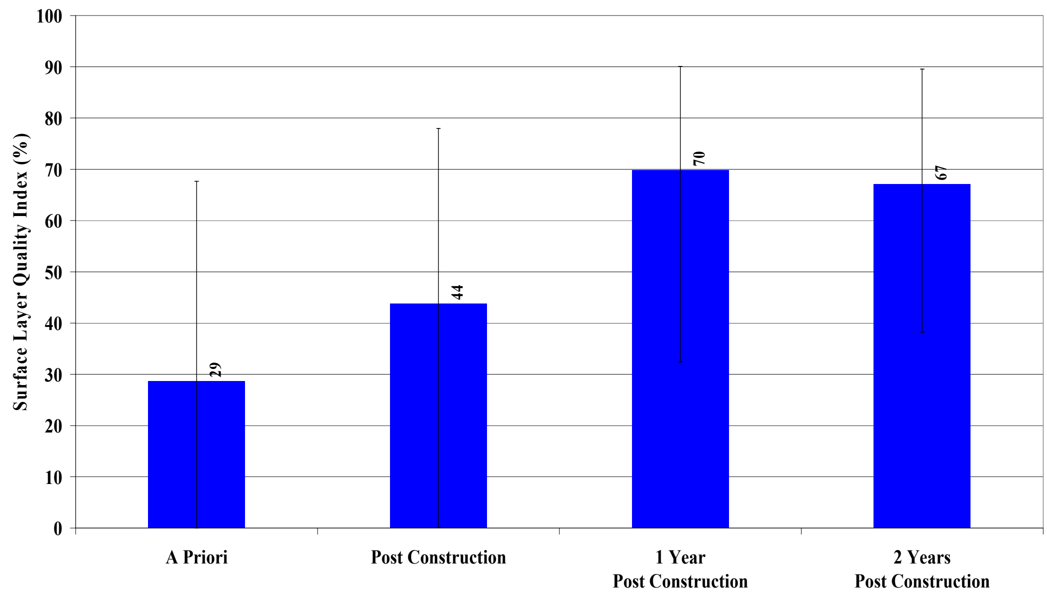


Figure 14 Shannon Road Surface Layer Quality Index Summary Statistics

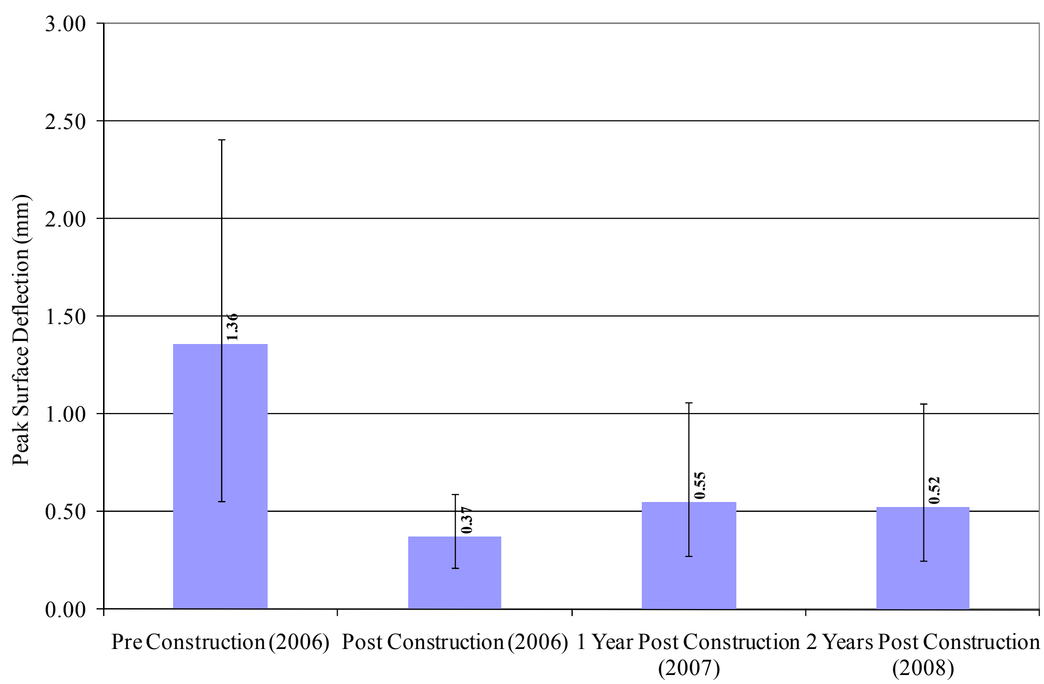


Figure 15 Shannon Road Peak Surface Deflection Summary Statistics (Primary Weigh Limit+25%)

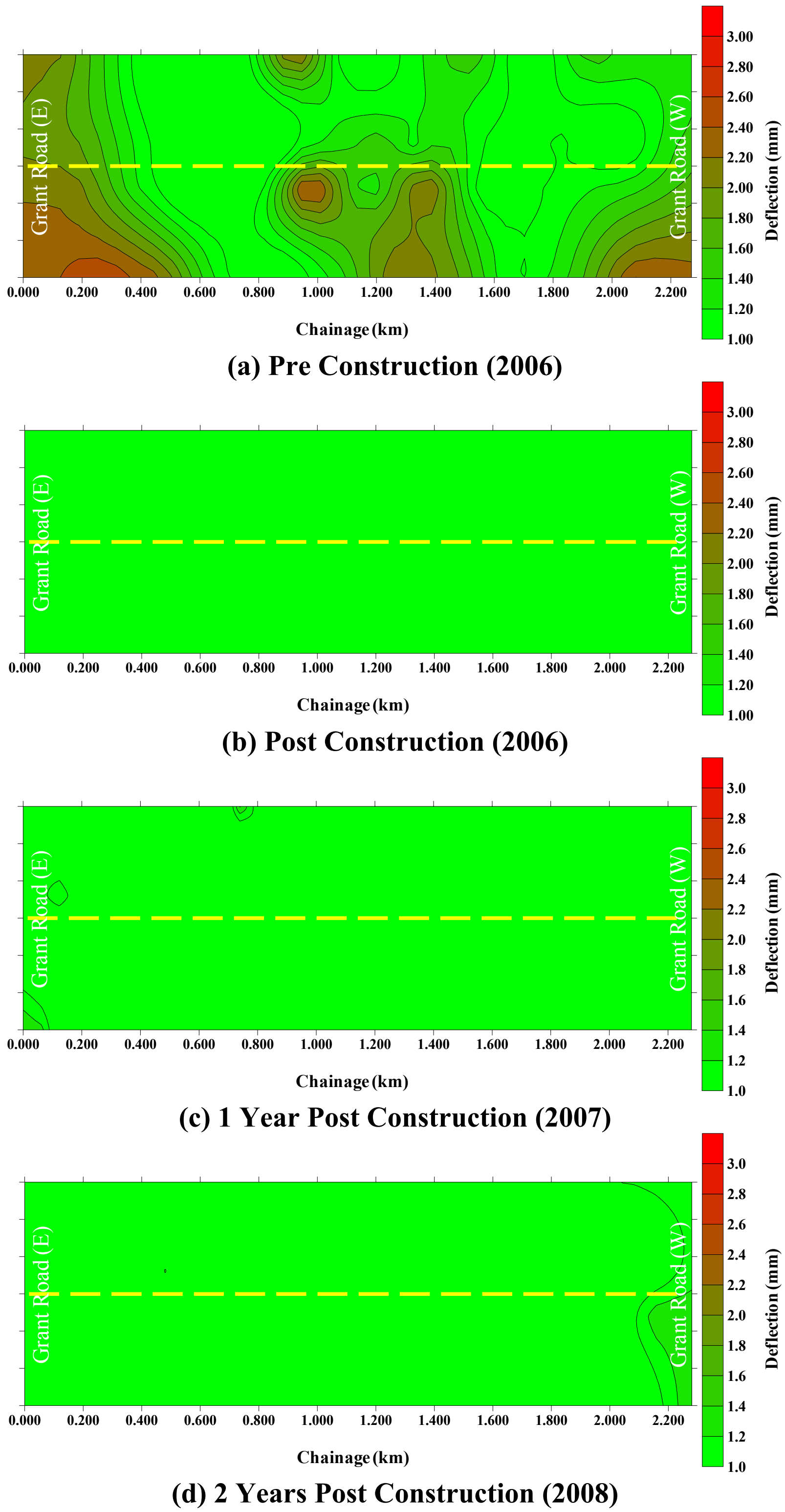


Figure 16 Shannon Road Peak Surface Deflection Profiles at Primary Weigh Limit+25%