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Discussion of Deep In-Situ Recycling (DISR)

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Discussion of Deep In-Situ Recycling (DISR)

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1.0 BACKGROUND

The mature road networks in most developed countries require rehabilitation more often than new construction. However, material sources are becoming scarce and traffic volumes on the major routes in these countries are high. There is an increasing international need for rehabilitation techniques that reuse existing paving materials with minimal traffic disturbance. The use of Deep In-Situ Recycling (DISR), particularly when used in combination with material stabilization processes, is gaining ground internationally as a viable option to meet these needs. The material stabilization options that have been successfully used with DISR include lime, cement, foamed bitumen, and emulsified bitumen treatment.

The 2003-04 Strategic Plan for the Partnered Pavement Research Program (PPRP) listed DISR as a current experimental strategy under evaluation by the California Department of Transportation (Caltrans) to become a standard strategy. This evaluation process started as a special forensic investigation, but has been identified as a full research goal (HVS Goal 10) in the 2003-04 Strategic Plan. The evaluation process will encompass the following issues:

- Selection criteria for identifying viable projects for DISR;
- Pre-design site investigation procedures including field and laboratory testing;
- Mix design procedures;
- Structural design procedures;
- Sound construction management procedures including specifications, planning, work methods and QC/QA; and
- Future maintenance strategies tied to life cycle cost analysis.

The DISR recycling process used in combination with foamed bitumen treatment, for example, is a fairly complex process with little room for error. The time available for mixing the material is limited and once the binder has been mixed in, no additional foamed binder can be applied. Hands-on training of the users of the technology is therefore of the utmost importance to ensure the successful deployment of this technology in Caltrans. The common thread that will therefore link all the above aspects is the transfer of the technology from experienced users to less experienced users. Although some expertise has already been developed in the use of DISR and foamed bitumen treatment in Caltrans District 3, it is not the primary function of the district personnel to provide training and they will probably lack the resources to do so. The Pavement Research Center (PRC) can provide the necessary resources to capture the existing expertise in Caltrans, expand it sufficiently, and develop and present practical, hands-on training courses on a statewide basis in addition to the further refinement of the technology through research.

This documents sets out a framework for addressing the above issues in terms of an overall approach as well as the short-term planning of specific activities.

2.0 RESEARCH, DEVELOPMENT, AND IMPLEMENTATION OF DISR IN CALIFORNIA

Figure 1 illustrates a generic Research, Development, and Implementation (RDI) cycle for pavement engineering technology. The process normally starts off with a new technology being introduced into the cycle through industry innovation or international technology transfer. The development of cold recycling machines with the capability to mill to a depth of 500 mm has spurred the interest and worldwide increase in the application of DISR on road rehabilitation projects. In the case of California, the DISR process used in combination with foamed bitumen treatment was introduced to District 3 through international technology transfer. The technology is, in turn, also being transferred to counties by Caltrans.

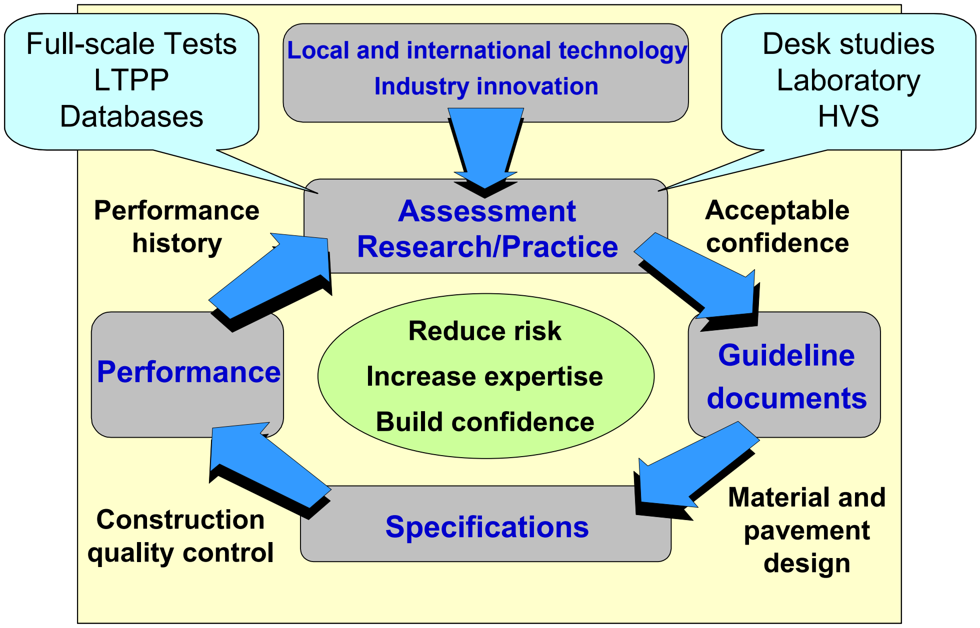

Figure 1. Research, development, and implementation cycle for pavement engineering technology.

Once the new technology has entered the RDI cycle, it must enter an initial assessment phase that should preferably be completed relatively rapidly. Laboratory and HVS testing provide the ideal tools for accelerating the initial assessment, but the limited application of the technology in practice is also valuable during the initial assessment, as long as the risk is acceptable.

Once a fair knowledge base has been assembled and acceptable confidence established in the use of the new technology, guideline documents should be prepared to assist in the application of the technology. These guidelines should contain sound engineering principles and procedures for all the implementation aspects identified in the previous section:

- Selection criteria for identifying viable projects for DISR;
- Pre-design site investigation procedures including field and laboratory testing;
- Mix design procedures;
- Structural design procedures;

- Sound construction management procedures including specifications, planning, execution and QC/QA; and
- Future maintenance strategies tied to life cycle cost analysis.

The guideline documents are normally procedural documents and need to be supplemented by more specific mix and structural design methods that are prescriptive in terms of the procedures, test methods, and calculations to be done for design purposes. Some development has already been done in Caltrans District 3 regarding the site investigation, mix design, and construction management procedures. However, this information needs to be captured in formal guideline documents and transferred to other Caltrans districts. The mix and structural design procedures for foamed and emulsified bitumen treatment are not sufficiently developed and require further research.

In the short term, Caltrans prefers to continue with the current gravel factor design approach. However, the complex behavior of these stabilized materials are only captured realistically by a mechanistic-empirical design method. Such a mechanistic-empirical design method can be used to develop gravel factors. The characteristics, behavior, and performance of these materials must be investigated and accounted for in the design methods.

Specifications allow the design on paper to be translated to measurable items for construction. Current specifications for DISR seem to be largely method specifications and these should evolve into product and performance specifications. In addition to the construction specifications, specifications for construction equipment as well as field and laboratory testing equipment should be developed.

As experimental sections or trial projects are constructed, a track record of performance will be developed. The best way to capture the type of information needed for subsequent assessments of the new technology in the RDI cycle is to capture the design, construction (material and construction productivity data), and long-term performance of projects in databases. This information will supplement the information gathered during the initial rapid assessment and will be utilized in subsequent assessments.

The RDI cycle is in fact a continuous process of gathering more information to improve the procedures, design methods, and specifications related to the technology to increase the expertise, and thereby reduce the risk and improve the confidence with which the new technology is applied.

3.0 MEDIUM TO LONG-TERM PLANNING

The items that have been listed in the previous section for further research and technology transfer are:

- Selection criteria for identifying viable projects for DISR;
- Pre-design site investigation procedures including field and laboratory testing;
- Mix design procedures;
- Structural design procedures;
- Sound construction management procedures including specifications, planning, execution and QC/QA; and
- Future maintenance strategies tied to life cycle cost analysis.

The research and technology transfer requirements of these items are addressed in detail in this section of the document. The mix and structural design procedures require a basic understanding of the characteristics, behavior, and performance of pozzolanic (cement/lime), foamed bitumen and emulsified bitumen treated material, and these aspects are discussed before detailed discussions of the above items.

3.1 Characteristics, Behavior, and Performance of Treated Materials

The matrix shown in Figure 2 sets out the basic characteristics of common pavement materials and the interaction of these characteristics when combined into a foamed bitumen or emulsified bitumen treated material.

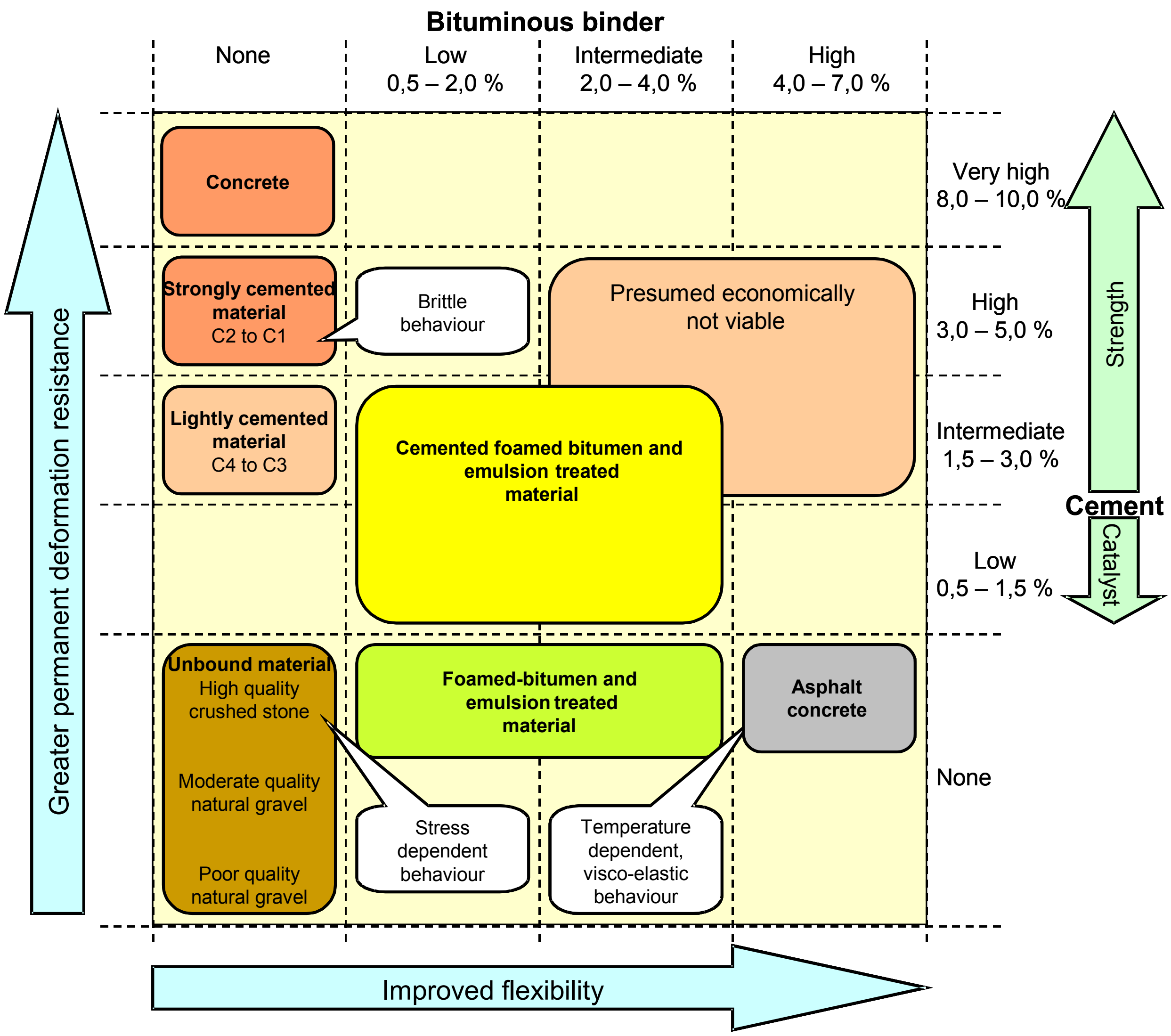

Figure 2. Matrix of the basic characteristics of road-building materials.

The unbound materials shown in the bottom left-hand corner of the matrix form the bulk of all road-building materials. In untreated form, these materials exhibit stress dependent behavior with an increase in resilient modulus under increasing confining stress and a reduction in resilient modulus under increasing shear stress conditions. The permanent deformation resistance of these materials increases with an increase in the material quality from poor quality natural gravels to high quality, highly compacted crushed stone products. In addition to a lack of permanent deformation resistance, especially under wet conditions, certain natural materials may exhibit durability problems. Materials containing active clays may be unsuitable for road construction, having extremely low permanent deformation resistance under wet conditions.

The undesirable properties of certain marginal natural materials may be modified and the permanent deformation resistance increased with the addition of moderate to high quantities of pozzolanic stabilization agents such as lime and cement. This pozzolanic treatment is represented by a vertical movement from the unbound materials in the lower left corner to the cemented materials and concrete at the top of the vertical axis on the matrix in Figure 2. The addition of pozzolanic stabilization agents results in the modification of the clay in the material and the formation of crystalline pozzolanic bonds in the material, resulting in a higher cohesion and increased permanent deformation resistance.

Because of the crystalline nature of the pozzolanic bonds, lightly cemented materials tend to be brittle, while strongly cemented materials may be prone to shrinkage, cracking, and pumping. In general, however, the addition of pozzolanic agents increases the resilient modulus, shear strength and permanent deformation resistance, and decreases the moisture sensitivity of the material but reduces the ability of the material to sustain flexural bending. This reasoning may be taken to the extreme by adding a high percentage of cement to a good quality crushed stone and sand mixture to produce concrete, with a high permanent deformation resistance, but little tensile strength and flexibility.

On the other hand, bituminous binder may be added to the unbound material in increasing quantities. Such treatment with bitumen is represented by a horizontal movement from the unbound materials in the lower left corner to asphalt concrete at the right-hand extreme of the horizontal axis on the matrix in Figure 2. The addition of bituminous stabilization agents results in the formation of pliable bituminous bonds in the material, resulting in a higher cohesion and increased permanent deformation resistance. However, because of the visco-elastic, temperature dependent behavior of these bituminous bonds, asphalt concrete may be prone to rutting under high temperatures and slow moving loads. In general, however, the addition of bitumen to the material increases the resilient modulus, tensile strength, ability to sustain flexural bending, and resistance to moisture damage.

Foamed bitumen and emulsified bitumen treated mixes may be produced by adding only the bituminous stabilizer to the material or by adding the bituminous stabilizer in combination with an inert filler. Pozzolanic filler is, however, often added to not only improve the permanent deformation resistance of the mix under high temperatures but also to assist in the early breaking of the emulsified-bitumen or to provide sufficient fines for foamed bitumen treatment. Foamed bitumen and emulsified bitumen mixes therefore often exhibit a combination of the stress dependent characteristics of the unbound aggregates; the brittle but permanent deformation resisting characteristics of pozzolanic stabilized materials; and the flexible characteristics of bituminous stabilized materials. The extent to which any of these characteristics dominate the mix behavior depends on the proportions in which the basic constituents are mixed and the properties of the individual constituents. If the unbound aggregate that forms the bulk of the volume of the mix had poor shear strength and permanent deformation characteristics, such as a sandy material, the shear strength and permanent deformation behavior of the mix will be dominated by either the pozzolanic or bituminous stabilizer depending on the relative quantities of these two stabilizers. If the pozzolanic stabilizer dominates in the mix, the mix will exhibit higher permanent deformation resistance but lower flexibility. If the bituminous stabilizer dominates in the mix, the mix will exhibit higher flexibility but less permanent deformation resistance. The ratio in which the pozzolanic and bituminous stabilizers are combined in the mix therefore largely determines the characteristics of the foamed bitumen or emulsified bitumen treated mix. This ratio and the balance between flexibility and permanent deformation resistance of the treated material should be reflected in the experimental design for all research investigations and should be carried through to the mix and structural design of these bituminous treated materials.

3.2 Detailed Discussion of Each of the Medium- to Long-Term Planning Items

Each of the previously identified research and technology transfer items are expanded into sub-items in this section to facilitate the discussion of each item. An attempt is made to list all the items that will require future investigation without entering into a discussion on any one of the items. Figures 3 to 8 show the breakdown for each of the 6 main aspects identified for further investigation.

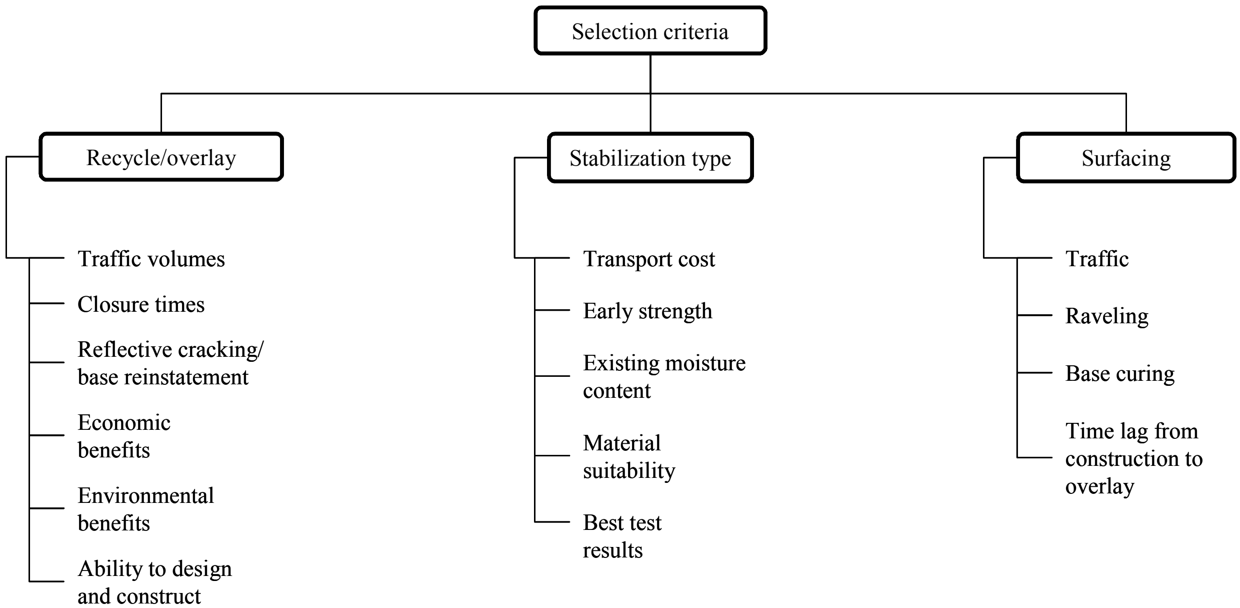

Figure 3. Selection criteria.

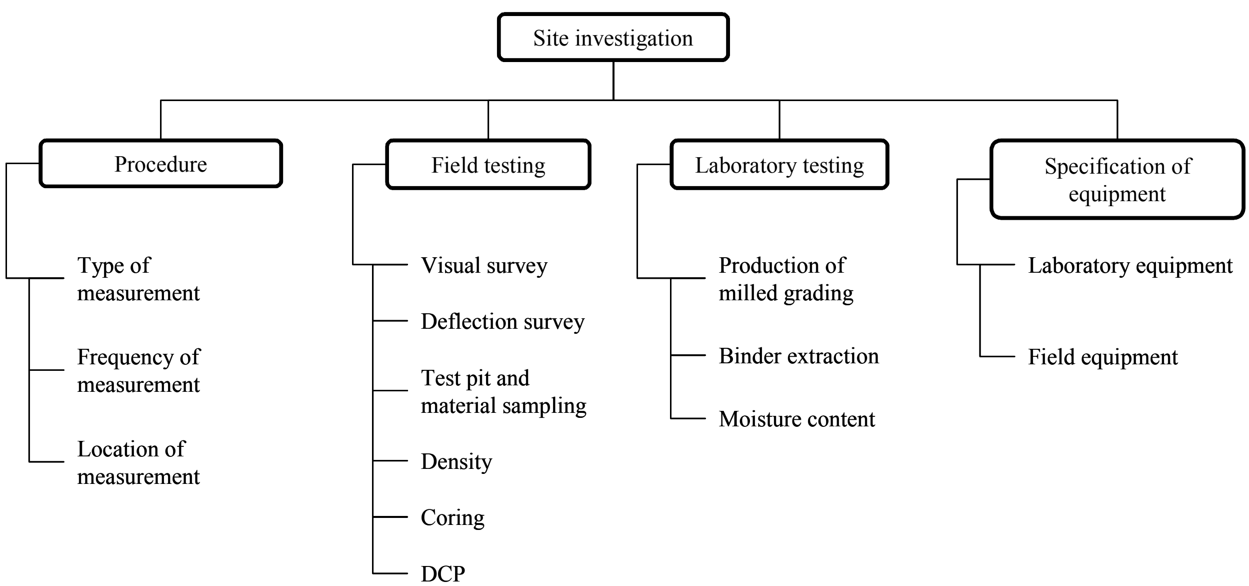

Figure 4. Site investigation.

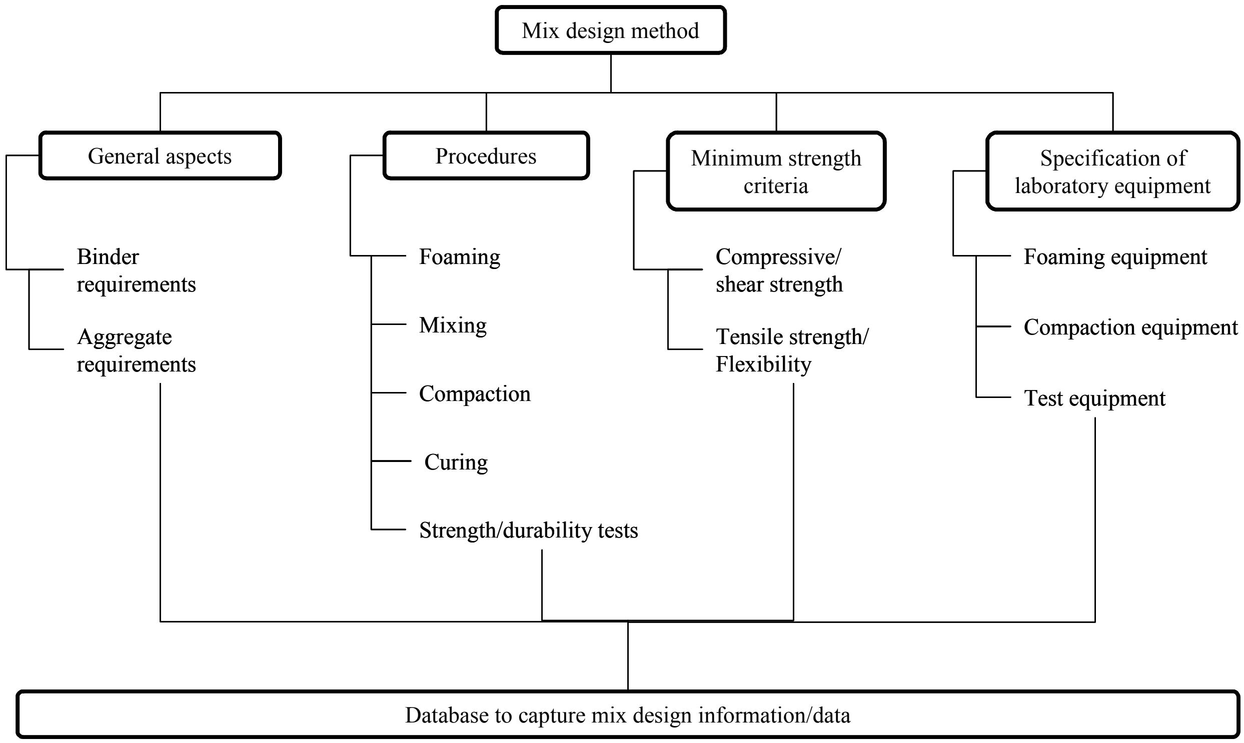

Figure 5. Mix design.

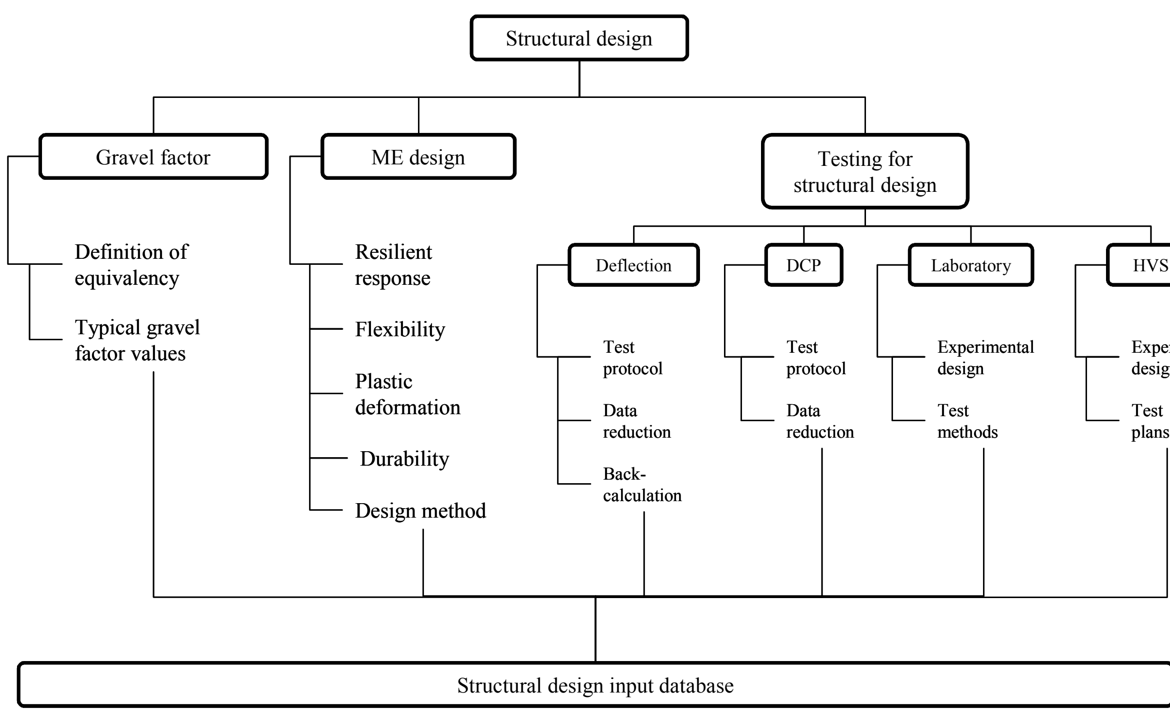

Figure 6. Structural design.

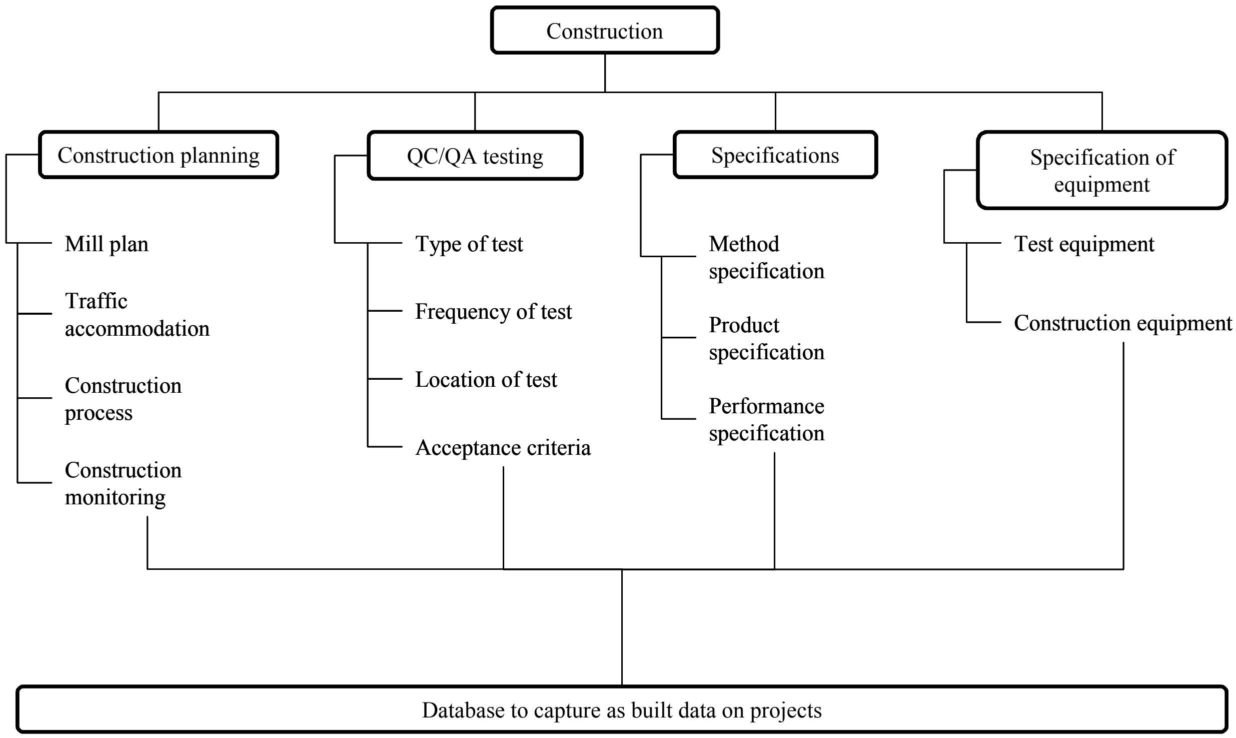

Figure 7. Construction management.

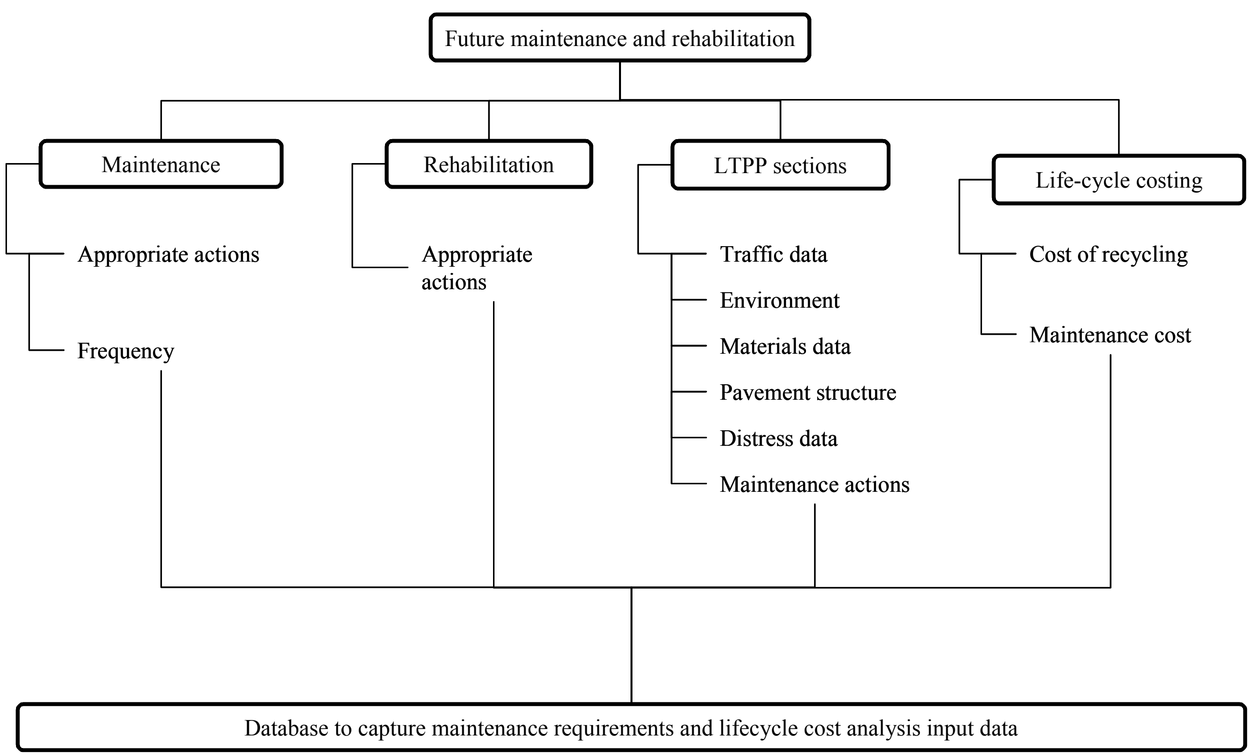

Figure 8. Future maintenance, rehabilitation and lifecycle costing.

3.2.1 Selection criteria for identifying viable projects for DISR

The selection criteria should be geared towards identifying first, the projects that are suitable for recycling, and second, what type of stabilization (pozzolanic, foamed bitumen, or emulsified bitumen), if any, would be the most appropriate. The diagram in Figure 3 lists some deciding factors but is not a comprehensive list. A decision framework should be developed based on a comprehensive investigation of the benefits of recycling and stabilization. The decision tree should probably include factors such as traffic, condition, materials, pavement structure of the existing pavement, and acceptable traffic closure times. Although the final decision to select the most viable rehabilitation option will probably be based on economics, there are many intangible benefits of recycling that may not be readily quantified in economic terms. These benefits will probably have to be accounted for in a decision tree. The selection of the type of stabilization treatment to use, if any, will depend on the transport cost and suitability of the different type of stabilization agents. The final selection of the appropriate treatment option should, however, be based on the treatment option that provides the best test results.

It is foreseen that the selection criteria will tie in closely with the future maintenance and rehabilitation requirements and lifecycle cost analysis. As such, it is recommended that research efforts on these two aspects should be combined or at least closely coordinated.

Research recommendations:

- Investigate the intangible benefits of recycling in terms of saving resources and lower energy requirements;
- Investigate the published benefits and selection criteria for recycling, and pozzolanic, foamed bitumen, and emulsified bitumen treatment; and

- Develop a decision tree for selecting candidate projects for recycling and stabilization.

3.2.2 Site investigation

The aims of the site investigation are to:

- Characterize the pavement subgrade that will provide support to the recycled layer;
- Obtain samples and characterize the material that will be recycled; and
- Capture layer thickness and material variability that will impact on the mix designs and on the construction process. .

Research should aim to give guidance on the type, frequency and location of testing to be done during the site investigation. Current site investigation procedures applied in Caltrans District 3 should be captured and incorporated in a Guideline on site investigation. This site investigation procedure should include deflection surveys, test pit and material sampling, density measurements, coring, and Dynamic Cone Penetrometer (DCP) tests if not already included in the procedure used by District 3. Methods of replicating the recycled grading from the test pit material samples should be investigated and other laboratory tests should be considered for inclusion in the site investigation procedure. Specifications for the field and laboratory testing equipment should be developed, if not available.

One of the concerns at Caltrans is the extent and cost of the site investigation for recycling compared to site investigations for conventional construction. It must, however, be stressed that scaling down on the site investigation to reduce effort and cost will result in a higher design risk. Different site investigation strategies may be developed for different road categories, each with an acceptable level of risk for the specific road category.

Research recommendations:

- Capture the existing site investigation procedure used by Caltrans District 3. Supplement with additional appropriate field and laboratory tests, if required. Investigate the cost of doing extensive site investigations to capture the variability of recycling projects;
- Develop a site investigation guideline document setting out different levels of effort and cost associated with the site investigation that could be applied to different road categories. The effort and cost of the site investigation should be set of against the risk of not fully quantifying the variability on the recycling project;
- Investigate and develop a method for replicating recycled gradings from test pit samples;
- Develop specifications on field and laboratory equipment for site investigation;
- Develop a training module on site investigation for recycling including documentation, multi-media content and hands-on practical training.

3.2.3 Mix design procedures

Mix design for foamed bitumen and emulsified bitumen treatment still requires extensive research. The mix design procedure and material classification system should incorporate the permanent deformation resistance and flexibility aspects of the treated material. A mix design guideline document should be developed for pozzolanic, foamed bitumen, and emulsified bitumen treatment providing guidance on general aspects such as binder and aggregate requirements, procedures for doing the mix design, and minimum strength criteria. Specifications should be developed for the laboratory foaming, mixing, and compaction equipment.

Mix design data needs to be collected for all testing done in the research environment as well as for each project carried out in practice. The best way to assimilate this data is in a materials database.

Research recommendations:

- Capture the existing mix design procedure used by Caltrans District 3. Supplement with additional appropriate laboratory procedures and tests, if required;
- Test the foaming characteristics of a range of bitumens used in California;
- Investigate appropriate test methods to optimize and balance the mix design;
- Investigate appropriate laboratory curing techniques and relate to equivalent field curing;
- Develop appropriate performance related strength criteria;
- Develop specifications for the laboratory equipment used for mix design;
- Develop a materials database to capture mix design data from research and construction projects;
- Develop a training module on mix design for recycling including documentation, multi-media content and hands-on practical training.

3.2.4 Structural design procedures

Two options are available for structural design. Currently, the preferred Caltrans method is to develop gravel factors for recycled stabilized materials. However, the mechanistic-empirical design of these materials should also be investigated for future application. A definition of "equivalency" will have to be formulated to enable the development of gravel factors. This definition may be formulated in terms of DCP penetration (DN), elastic response, or bearing capacity. A process of collecting comparable data will then have to be carried out for the gravel factors to be calculated. Gravel factors could also be calculated using a mechanistic-empirical design approach.

In terms of mechanistic-empirical design, the following aspects of material behavior and performance should be investigated:

- Resilient response;
- Flexibility;
- Permanent deformation resistance; and
- Durability

The delivery mechanism for the mechanistic-empirical design method may consist of design catalogues, design charts or design software.

Recent research in South Africa has highlighted the effect of the bitumen to pozzolan contents ratio on the characteristics, response, and behavior of foamed bitumen and emulsified bitumen treated mixes. It is therefore recommended that the experimental design for research projects in the field of mix and structural design should be based on the test matrix set out in Table 1 whenever possible. Although Table 1 indicates an "optimum" binder content, recent research seems to indicate that a "minimum required" binder content is more appropriate.

Table 1 Recommended Experimental Design Matrix for Research Projects in the Field of Mix and Structural Design

Aggregate	**Pozzolanic filler content**	**Bituminous Binder Content**			
		None	Below "optimum"	"Optimum"	Above "optimum"
	None	Y		Y	
	Below ICS*	Y	Y	Y	Y
	Above ICS			Y	

*ICS = Initial consumption of stabilizer

Table 2 provides a list of recommended tests to be considered for research project in the field of mix and structural design. Test and data reduction procedures will need to be developed for field tests such as the FWD and DCP tests, and the laboratory tests listed in Table 2, if not already available. The experimental design of laboratory projects will require special attention and test plans will have to be developed for HVS testing. Changes in the mechanical

Table 2 List of Recommended Laboratory Tests for DISR Research Proejcts

Test Category	Type of test	Material		
		Binder	**Aggregate**	**Stabilized mix**
Engineering parameters	Origin/mineralogy	Y	Y	
	Classification	Y	Y	
	Grading [a]		Y	
	Atterberg limits		Y	
	MDD/OMC		Y	
	ARD/BRD		Y	
	ICS		Y	
	Microscopic images		Y	Y
	R-value		Y	Y
	Penetration	Y		
	Foaming Index	Y		
Engineering strength tests	CBR		Y	Y
	UCS			Y
	ITS			Y
Mechanical tests	Static triaxial		Y	Y
	Mr triaxial		Y	Y
	Plastic strain triaxial		Y	Y
	Flexural beam test			Y
	Fatigue test [b]			Y
Durability tests	Retained ITS			Y
	Retained UCS			Y
	Erosion		Y	Y
	Mechanical brush			Y
	Permeability		Y	Y
	Shrinkage		Y	Y

Notes: a) Pre- and post-milled
b) Only high binder content mixes

characteristics and response of stabilized materials under loading do, however, require that the HVS tests plans are continually evaluated and revised during any specific HVS test.

Research recommendations:

- Develop a definition of material equivalency, collect the required data and calculate gravel factors for foamed bitumen and emulsified bitumen treated materials;
- Investigate the mechanical characteristics, basic behavior, distress mechanisms and failure mechanisms of foamed bitumen and emulsified bitumen treated materials including the effect of the bitumen to pozzolan contents ratio using HVS and laboratory testing;
- Formulate a mechanistic-empirical design model for foamed bitumen and emulsified bitumen treated material;
- Incorporate the mechanistic-empirical design model into the design delivery mechanism.
- Develop testing and data reduction procedures for field and laboratory tests;
- Develop a structural design database to capture all the data generated from the research process to be used later as input to the design models;
- Develop training material on structural design (this will probably only be meaningful once a first version design model is available).

3.2.5 Construction management procedures

A guideline document for construction management will have to be prepared. This document should address aspects such as the preparation of a DISR mill plan, traffic accommodation, the daily construction process, sound construction practices, and a method for monitoring construction productivity. Guidelines on the type, frequency, and location of QC/QA testing should also be included in the document as well as acceptance criteria for quality acceptance.

The construction specification for DISR is currently a method specification and will have to evolve to a product and performance specification. To achieve this, some insight will have to be gained into the minimum strength criteria and material classification system from the mix design component and the performance associated with these minimum strength requirements as obtained from the laboratory and HVS testing programs.

Specifications will have to be developed for construction equipment and QC/QA testing equipment.

Research recommendations:

- Investigate construction management practices on DISR projects and develop guidelines on construction management, QC/QA testing, and acceptance criteria;
- Capture existing expertise on the DISR construction specification used in Caltrans District 3 and supplement, if necessary, to develop a construction specification for statewide application. Initially the construction specification is foreseen to be a method specification, but, should be revised in future towards a product and performance specification;
- Supplement existing or develop new specifications for construction equipment and QC/QA test equipment;
- Develop a database to capture as built data on construction projects.

3.2.6 Future maintenance strategies

Guidelines for the future maintenance and rehabilitation requirements of DISR projects are required to enable a fair economic comparison to normal overlay rehabilitation strategies over the full lifecycle of the road. The maintenance requirements are often dictated by functional deterioration and are therefore difficult to assess from laboratory testing, HVS testing, and structural design models, although some indication of the extension of the surfacing fatigue life because of recycling may be obtained from mechanistic-empirical modeling. It is anticipated that Long-Term Pavement Performance (LTPP) sections may be a suitable method of capturing the future maintenance requirements of DISR projects. The LTPP study will need to capture, traffic data, environmental data, materials data, pavement structure data, distress data, and maintenance actions and associated costs. A database of the LTPP data will need to be maintained.

Research recommendations:

- Identify appropriate maintenance and rehabilitation strategies for DISR projects;
- Investigate the potential benefits in terms of extending the fatigue life of surfacing layers by means of mechanistic-empirical modeling of the reflective cracking of overlaid, cracked pavements compared to the fatigue life of surfacing layers on DISR projects;
- Establish and monitor LTPP sections to capture performance and future maintenance requirements data;
- Develop a LTPP database to capture the LTPP data.
- Recommend procedures and typical input values to perform life cycle cost analyses.

4.0 SHORT-TERM PLANNING ITEMS

This section lists items that require immediate attention. Each item is briefly discussed to define the scope of the work but detail work plans will have to be developed for each topic as separate documents.

4.1 Scope of DISR in California

The Pavement Standards Team (PST) group of Caltrans expressed the need to have a survey done to estimate the number of candidate projects for DISR in California at the meeting on 14 May 2003. A set of criteria to decide the suitability of roads for DISR will, however, have to be developed before such a survey is conducted.

4.2 Establishment of Foaming Capabilities at the Pavement Research Center (PRC)

The laboratory capability to foam bitumen and to simulate the fast mixing action of recycling machines is a prerequisite to establishing a successful mix and structural design research program as well as a training program for DISR used in combination with material stabilization. The preparation of cemented, foamed bitumen treated, and emulsified bitumen treated laboratory specimens require experience in the preparation, mixing, compaction, and curing of specimens. If the PRC is required to do research and provide training on DISR and material stabilization, these capabilities will have to be well established. It is recommended that the Council for Scientific and Industrial Research in South Africa (CSIR) prepare a proposal for the transfer of this technology to the PRC. This work will be done under the current contract agreement between the PRC, Dynatest, and the CSIR and the cost of the project will not be in addition to the current contract amount. Caltrans District 3 personnel experienced with laboratory foaming will be consulted. The PRC will need to acquire a laboratory foaming plant and twin shaft, pug-mill type mixer. CSIR can provide some guidance on these acquisitions.

4.3 HVS Testing of SR89 in District 3

The decision has already been taken to move the HVS to SR89 in District 3 towards the middle of June 2003. Although the PRC is well experienced in HVS testing, the testing of stabilized materials requires a specific approach to and dynamic adaptation of the HVS test plan during a test to track the changes in response of the stabilized material. CSIR will provide the PRC with the approach and HVS test plans currently used for HVS testing of stabilized materials in South Africa including recommendations on the type of construction and pre-HVS site investigation data to be collected. It is also recommended that CSIR personnel should assist in the daily monitoring and analysis of HVS test data and provide input on the adaptation of the test plan during the actual HVS testing. Again, this work will be done under the existing contact and within the existing contract budget.

4.4 Field Surveys on Existing Trial Projects

A number of candidate DISR projects have been identified for immediate inclusion in a monitoring program. These are roads SR20, SR36, SR70, SR 89, SR95, and US395. The PRC will include these roads in their seasonal monitoring program but the site investigation design and construction data of these sections will have to be collected.