AN ABSTRACT OF THE THESIS OF

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Saudi Arabia currently contains 31000 km (18600 mi) of paved roads and 42000 km (25200 mi) of agricultural roads, with the prospect of more roads to be constructed. The low population (6 million) compared to the large area of the country (2,253,300 km^2, 900,000 mi^2) coupled with the high cost of crushed aggregate makes maintenance and road building costs very high.

Local emulsified asphalt economics, plants, and uses were investigated in this study. Emulsified asphalt proved to be attractive when used for local road maintenance and road bases and low volume road construction, especially when used with dune sand and marl. Emulsified asphalts were evaluated for use with

dune sand and marl and at two portland cement contents. Three types of emulsified asphalts were used which included locally produced, laboratory prepared, and Chevron U.S.A. emulsions.

Emulsion treated mixes were tested for tensile strength, Poisson's ratio, resilient modulus, fatigue life, and rutting characteristics. Both diametral and beam fatigue tests were used and tests were conducted at 10°, 25°, 40°, and 55°C (50°, 77°, 104° and 131°F). The open-graded mix was tested for fatigue characteristics using beam flexure with a confining membrane.

Finite element methods were used to calculate beam bending moduli and the results were compared to beam equation results. These results together with local field experience were used to develop design charts for use of emulsions.

The results indicated that emulsified asphalts can be produced locally at relatively low cost. It also indicated that emulsified asphalts have a high potential for stabilizing local sands and marginal aggregates at low cost, especially for low volume roads and road base construction. Stabilized materials provided satisfactory fatigue and rutting results. They can be utilized to produce satisfactory, reasonable, economical road sections.

EVALUATION OF EMULSIFIED ASPHALT FOR USE IN SAUDI ARABIA

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EVALUATION OF EMULSIFIED ASPHALT FOR USE IN SAUDI ARABIA

1.0 INTRODUCTION

1.1. Problem Definition

Saudi Arabia is entering a new era of highway construction. Virtually thousands of miles of new and modern highways are under construction. A total of 31,000 km (186,000 mi) of highways and freeways and 42,000 km (25,200 mi) of agricultural roads have been constructed so far [51]. There will continue to be a great need for highways in the immediate future. Consequently, a large expansion in the asphalt industry has begun, and asphalt plants are more abundant now than ever. Since past construction has been confined to hot mixes rising fuel consumption, pollution, and safety hazards are becoming more common.

Dense-graded asphalt cement is widely used for highway construction. Cold mixes, which are limited to cutback asphalts, are used mainly for maintenance purposes and for secondary road construction. At present, emulsified asphalt is used only in tack and prime coats.

On the other hand, emulsified asphalt (see Appendix A) represents an attractive option for local use. The large network of roads compared to the low population (6 million) makes the maintenance cost of such a system very expensive, if only hot asphalt overlay is considered (as is the case now). There is a high demand for low volume agricultural roads; the use of emulsion represents an easy, quick way to construct such roads using local materials at minimum cost.

Further Saudi Arabian road construction is faced with the lack of good quality aggregates, especially in the eastern and northern part of the country. Coupled with the high cost of limestone aggregate ($35-45/cubic meter), the construction costs of roads may be expected to increase drastically. Use of emulsified asphalt allows for the use of locally available dune sand, marl and marginal aggregate which are less costly for road bases and low volume road construction. As a consequence, the construction costs would be cut tremendously.

Emulsified asphalt can be used to control the maintenance problem created on Saudi Arabian roads by sand dunes movement. Emulsified asphalt provides an easy means of stabilizing dunes for protection of roads and industrial areas. Moreover, emulsified asphalt can be used for preparation of industrial sites. Therefore, emulsified asphalt appears to be attractive for use in Saudi Arabia and deserving of further study.

1.2 Objectives

The overall purpose of this study is to evaluate the use of emulsified asphalt within the Kingdom of Saudi Arabia. Moreover, it is to evaluate the engineering properties of emulsified asphalt mixes for use in road construction and to develop suitable recommendations for its use. Specifically, the objectives are to:

1. Evaluate the existing emulsified asphalt industry and uses
2. Analyze economic viability of emulsified asphalt paving technology for commercial application in Saudi Arabia
3. Install a system for production of emulsified asphalt under laboratory controlled conditions at the University of Petroleum and Minerals, Saudi Arabia
4. Use emulsion produced with locally available materials and evaluate engineering properties of emulsion mixtures over the range of in-service temperatures
5. Develop design charts and recommendations for emulsified asphalt use with local materials

1.3 Anticipated Benefits

Emulsified asphalt mixes, both dense and open-graded mixes, are expected to have several benefits over hot mix and cut-back asphalts. They can be more economical, require less energy to produce, and have greater yields due to lower unit weight [47]. Dust pollution is minimized due to the absence of aggregate drying. Fire hazards to plants and workers are eliminated, and skid resistance is increased if open-graded mixes are used. Emulsion mixes may also be less susceptible to water effects [40]. Overall, emulsified asphalt mixes, particularly open-graded mix, have performance comparable to asphalt concrete, with many more benefits.

The use of emulsified asphalt should aid in the reduction of maintenance and construction costs by reducing the use of scarce high cost aggregate. Moreover, it has a high potential for sand stabilization for roads, industrial areas, agricultural areas, etc. and protection from sand dunes movements.

1.4 Study Approach

This research (Fig. 1.1) consists mainly of a laboratory study of mix properties as a function of variables such as aggregate type and gradation, mixing water content, portland cement content, degree of compaction and emulsion content. The influence of these variables on stability and stiffness will be evaluated, as well as the influences of temperature and cement

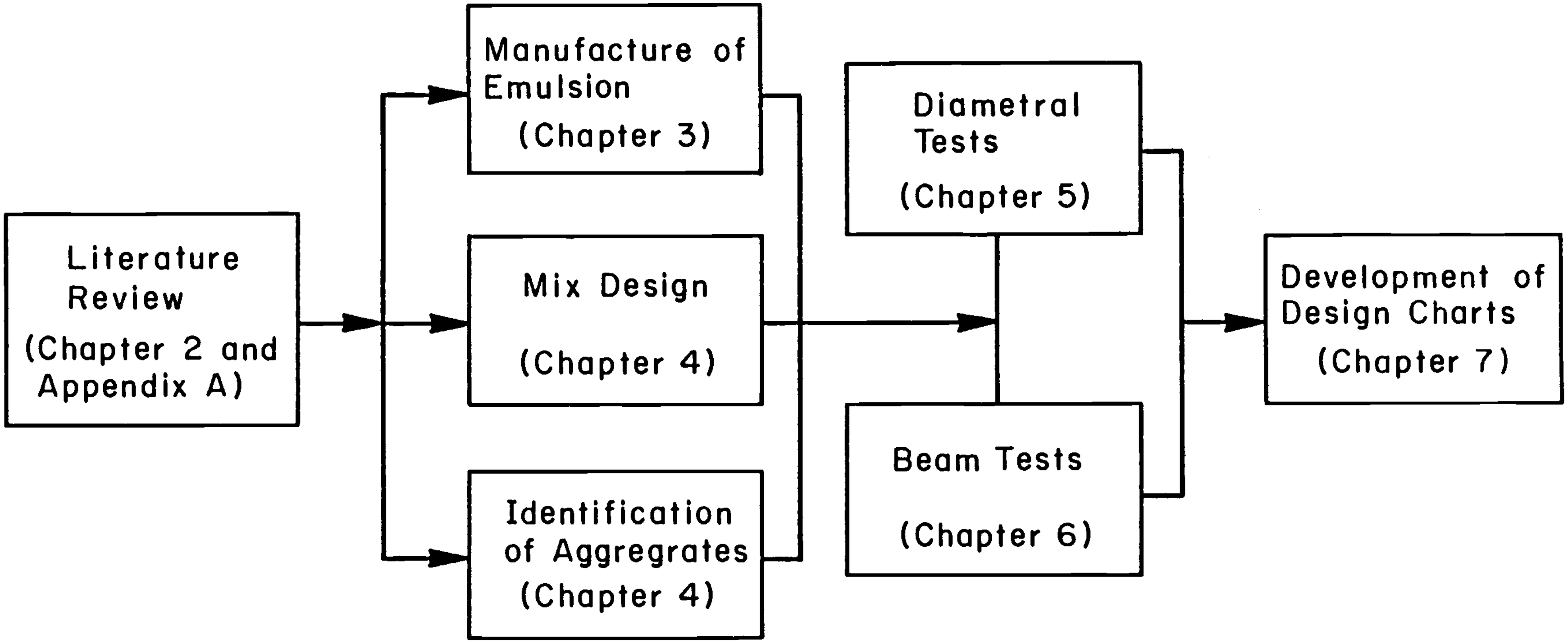


Figure 1.1. Study approach.

content on fatigue life and resistance to permanent deformation. Emulsified asphalts are prepared in the lab from locally available asphalt and, together with locally available emulsified asphalt, are compared with Chevron USA emulsified asphalt.

To satisfy the research objectives, it was necessary to undertake the five following tasks.

Task 1: Emulsified Asphalt Usage and Cost:

In this task, emulsified asphalt usage in Saudi Arabia was reviewed to establish its usage feasibility and to identify potential problems and benefits. This consisted mainly of a review of available literature and interviews with contractors and personnel from the Ministry of Transportation in order to identify:

1) Advantages and disadvantages of emulsified asphalt
2) Comparative economics of emulsified asphalt and hot asphalt cement
3) Expected performance problems
4) Economical viability of the emulsified asphalt industry

Results of this task are presented in Chapter 2.

Task 2: Production of emulsified asphalt:

Emulsified asphalts used were manufactured in lab from locally available asphalt (60-70 penetration grade). Since there is only slow setting emulsified asphalt

(CSS-1h) produced locally for sand stabilization purposes, CMS-2h emulsion was produced in the laboratory. Both types of emulsions were used with locally available materials (dune sands, marl, and limestone) and compared to a Chevron USA CSS-1h at 25°C (77°F).

An "Emul Bitume" emulsion plant (commercially available) was used for the preparation of emulsion under laboratory controlled conditions. The resulting emulsified asphalt was tested for properties. Details of this task are given in Chapter 3.0.

Task 3: Material Selection:

Materials were selected from a number of road construction projects. Three different types of aggregates, namely marl, limestone and sand were selected to represent different areas (locations) and material properties. Open-graded mix was investigated using limestone aggregate, while dense-graded mixes were investigated using the sand and marl aggregates. The aggregates were tested for physical properties, such as gradation, specific gravity, resistance to abrasion, sand equivalent and plasticity index, and were blended to meet gradations shown in Table 1.1. Chapter 4 presents these results.

Task 4: Mix Design and Property Evaluation:

Mix designs were prepared for the different materials to obtain optimum emulsion content. The

Table 1.1. Aggregate Gradations (22,40,41)

% Passing (by wt.)			
Sieve Size	Open Graded	Sand	Marl
3/4"	100		100
1/2"	60 - 70	100	
3/8"	20 - 55		
no. 4	0 - 10	75 - 100	(as received from the field)
no. 8	0 - 5	(as received from the field)	
no. 16			
no. 30			
no. 50			
no. 200	0 - 2	5 - 12	
sand equivalent		30 min.	
Los Angeles Ratler @ 500 revolutions	40 max		
Plasticity Index		Non Plastic	

Illinois method [56] of mix design was used to arrive at the optimum emulsion content for dense-graded mixes. The FHWA mix design procedure [55] was used for the open-graded mix design. A total of three mixes (sand emulsion, marl emulsion, and open-graded limestone emulsion) were designed. The optimum for each mix was used to test for mix properties including split tensile strength, Poisson's ratio, resilient modulus, fatigue resistance and rutting properties. Tests were conducted at two portland cement contents (2.0% and 5.0%) and three temperatures, 10°, 25° and 40°C (50°, 77° and 104°F) for the dune sand and open-graded emulsion mixes and at 25°, 40° and 55°C (77°, 104° and 131°F) for the marl emulsion mix (Fig. 1.2).

Two types of specimens were prepared:

1. Marshall specimens compacted by 75 blows. These were used to test for Poisson's ratio, tensile strength, resilient modulus for all mixes and diametral fatigue and rutting characteristics for the marl and sand emulsion mixes.
2. 3 in x 3 in x 16 in (7.5 cm x 7.5 cm x 40 cm) beams which were compacted to the same compaction level and were used to test for flexural fatigue for all mixes. Beams were supported on a rubber subgrade with a constant subgrade reaction modulus (k) of 110 pci

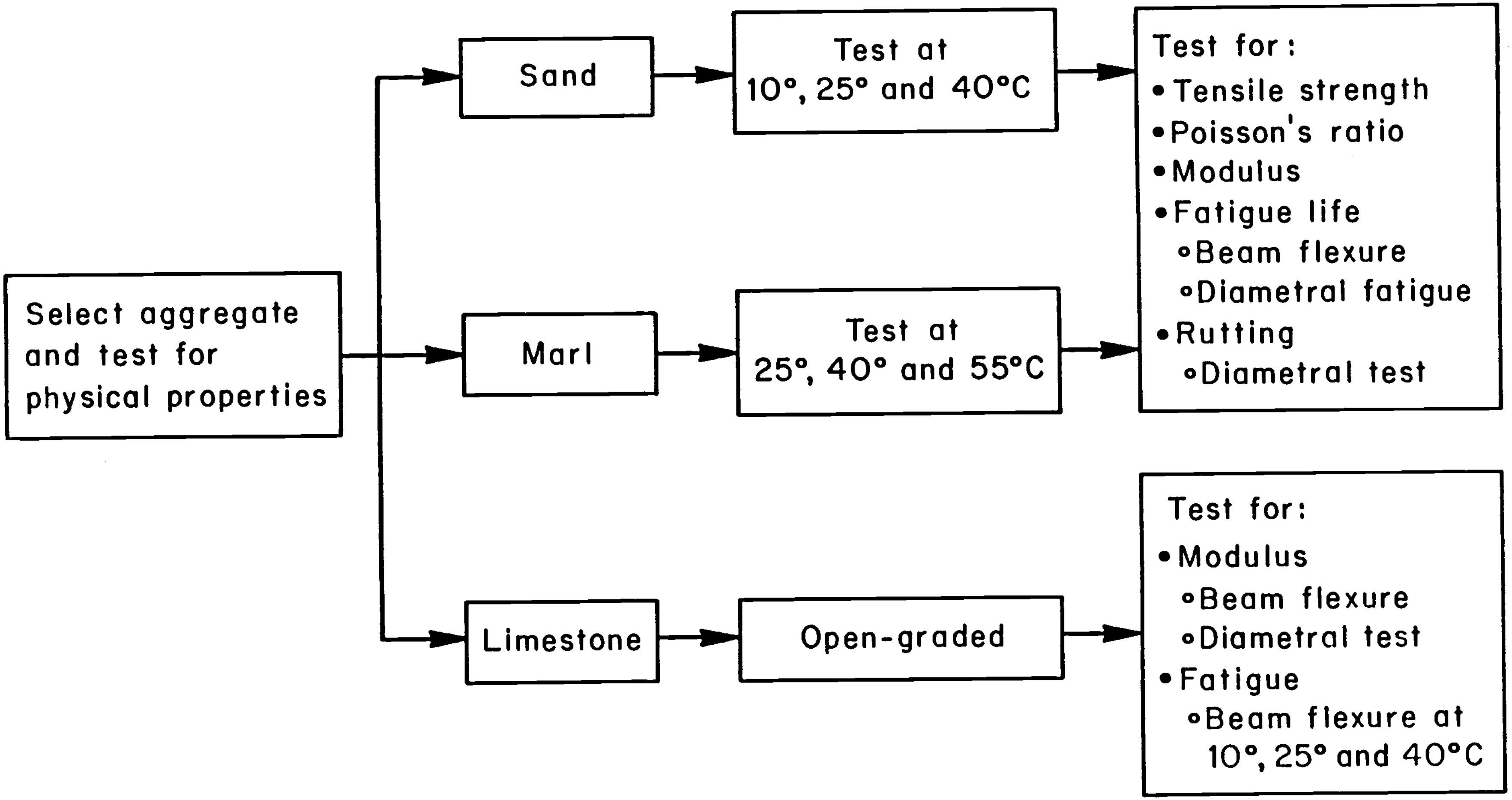


Figure 1.2. Task 4 flow chart.

($3288.9 \ g/cm^3$) and were failed by applying a repeated load at the center of the beam. center

The variables and levels of treatment considered for laboratory experiments are given in Table 1.2. The results of this task are given in Chapters 4, 5 and 6.

Task 5: Data Analysis and Final Report:

The results of previous tasks were evaluated and are presented in this final report. Test results were compared to establish the effects of temperature, loading, and type of mix and asphalt origin (Saudi and U.S.) on the split tensile strength, modulus, fatigue life and rutting properties. Standard statistical techniques were used to quantify the effects of strain level and temperature variations on the mix fatigue life and resistant to permanent deformation.

The results were utilized in developing design charts for local use. Fatigue life results were shifted to suit field conditions and were used together with rutting results and modulus values to predict pavement behavior in the field. Field conditions and local construction practices were also considered in the charts development as discussed in Chapter 7.0.

This final report summarizes the work done. It includes the results of the previous tasks. It presents

Table 1.2. Variables Considered in Test Program

Variable	Level of Treatment	Total No.
Material (aggregate)	Limestone Marl Sand	3
Mix types	Open graded Sand Marl	3
Cement content	2%, 5%	2
Asphalt content	Optimum	1
Level of compaction		1
Temperature	$10^{o}C$ $25^{o}C$ $40^{o}C$	
Strain levels	100 150 200	3
Replications	3	3
No. of Specimens		
Saudi Emulsion	66 beam, 117 Marshall spec.	
Chevron USA Emulsion	12 beam, 18 Marshall spec.	
Total:	78 beam, 135 Marshall spec.	

problems, data analysis and interpretation, and recommendations for implementation and further research.

2.0 APPLICATIONS OF EMULSIFIED ASPHALTS IN SAUDI ARABIA

The purpose of this chapter is to provide some information about the Kingdom of Saudi Arabia. It discusses the road systems and current practices with emulsified asphalts, including manufacturing, applications and economics.

2.1 Geography of Saudi Arabia

Saudi Arabia is one of the middle east countries and is bounded by Jordan and Iraq in the north, Yemen and Oman in the south, Qatar, Kuwait, United Arab Emirate and the Arabian Gulf in the east, and the Red Sea in the west (Fig. 2.1). Saudi Arabia has a land area of 2,253,300 km^2 (900,000 mi^2) (equivalent to the areas of France, Italy, and Spain combined) with a population of six million. The distance from Dammam, the major Arabian gulf seaport, to Jeddah, the major Red Sea port is 1528 km (917 mi). The north-south route in western Saudi Arabia is 2000 km (1200 mi).

Saudi Arabia is a plateau sloping eastward from a mountain range extending along the western coast, usually within 15 to 25 km (9-15 mi) of the Red Sea Coast, from which it rises steeply to an average height of 4900 feet (1494 meter). The coastal plain rarely exceeds 50 km

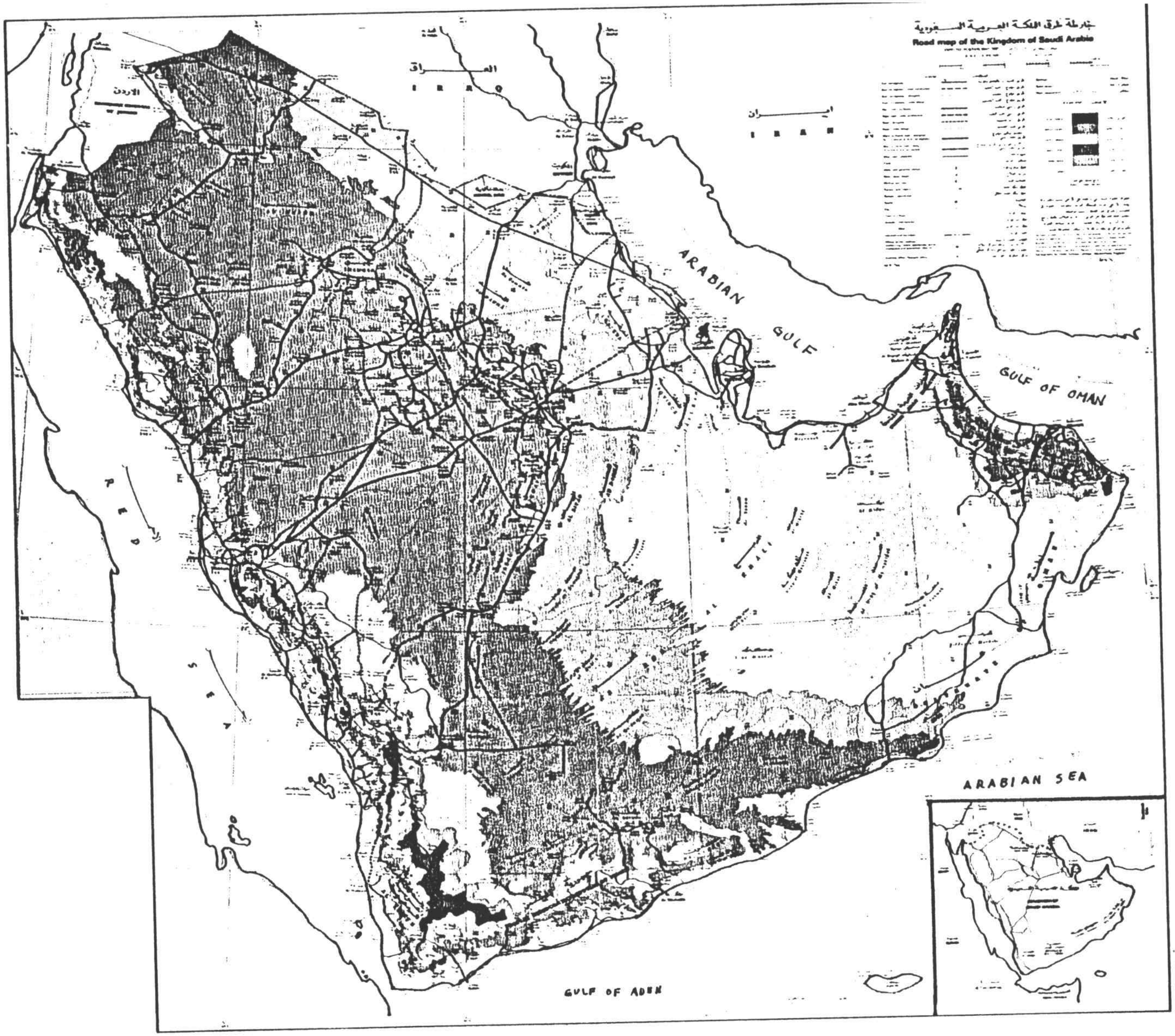


Figure 2.1 Map of the Kingdom of Saudi Arabia. (51)

(30 mi) in width. The country is generally arid and barren. The only area with significant regular rainfall is the high mountainous area in the southwest. The rest of the country is desert, with areas of numerous but widely scattered oases in dry stream beds that flood on a few rare occasions each year. There are no rivers, and only a few permanent pools, small lakes or natural springs.

The Arabian peninsula has three main natural divisions: (1) The Nejd, which is a central core of hard desert with many valleys and oases supporting a considerable permanent population; (2) an almost complete circle of sandy wasteland surrounding the central core and extending hundreds of miles outward to the north and south, known as the northern Nafud, the Dahna and the Rub'-al Khali, as shown in Fig. 2.2; and (3) an outer circle of steppes or mountains, in part barren and arid and in part populated and cultivated. Most of this outermost ring lies outside the borders of the Kingdom of Saudi Arabia.

Amid such terrains and different natural formations, housing complexes have been constructed from the Arabian gulf on the east to the Red Sea on the west, either in the form of big cities like Riyadh, the Capitol, with approximately one million people, or medium or small towns with populations which do not exceed a few hundred.

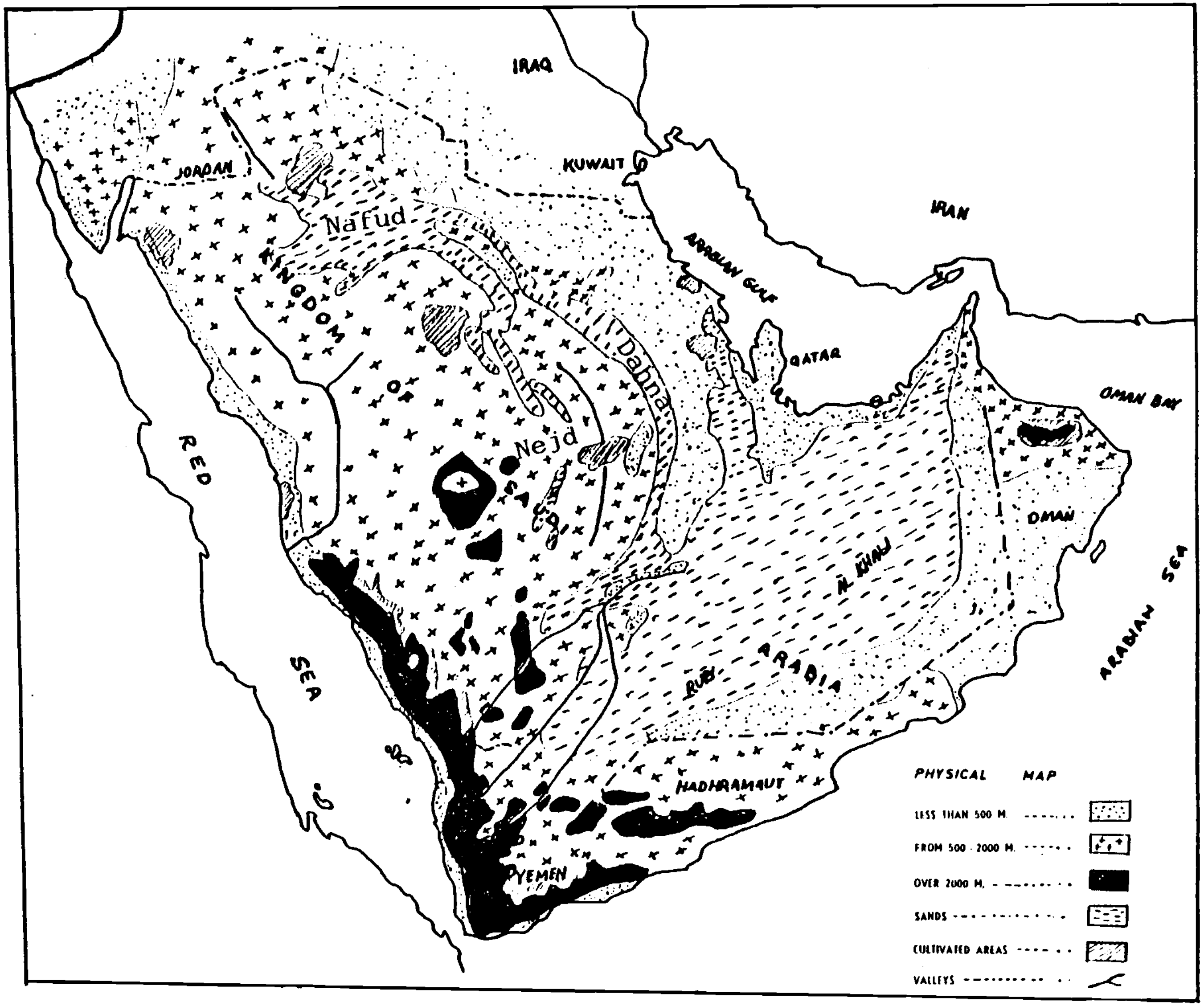


Figure 2.2 Physical map of The Kingdom of Saudi Arabia. (51)

2.2 Road System

Saudi Arabia's modern highway construction program dates from 1935, when the Public Works and Minerals Department was established [51]. Desert tracks had existed since ancient times, but in 1951 the first asphalt road construction project in the Kingdom represented a significant technological step forward.

The Ministry of Communications was formed in 1952 and took full responsibility for the nation's roads a year later. At that time there were only 239 kilometers (144 mi) of paved roads in the Kingdom. By 1963 the Ministry had expanded the network of paved roads to 4147 kilometers (2489 mi), despite a severe shortage of technical capabilities and specialized manpower.

In 1964, the Ministry launched a new road development program in the Kingdom. Based on its experience over the previous few years, and as a result of preliminary studies conducted throughout the Kingdom, the Ministry was able to initiate what was called the "Main Program" for developing roads and bridges. Its object was to construct a major network of modern two lane highways connecting all the population centers in every geographical and political area of Saudi Arabia. A set of General Specifications and General Conditions for Highway Construction Contracts and a set of Highway Design Standards were developed for use on all new projects [51].

The Ministry of Communications considered that the new road development program, or Main Program, should be implemented in four phases as follows:

<u>Phase I</u>: Completing the connection of main regions, and ensuring that roads would pass through the maximum number of towns and villages

<u>Phase II</u>: Shortening the travel distances between the main cities

<u>Phase III</u>: Widening and constructing roads where anticipated future traffic indicates that they would eventually be upgraded to dual carriage ways or expressways

<u>Phase IV</u>: Improving the standards of services, and developing safety features for the roads

In 1970, the Ministry of Communications prepared a comprehensive five-year road program. The first phase of Main Program continued under the five-year program, but with some modifications. Phase II of the Main Program was also introduced in 1970. Phase I had been concerned with connecting the maximum number of towns and villages. This objective often resulted in circuitous routes and long travel time. Phase II was concerned with constructing direct routes between major cities to reduce distances and travel times. In these two phases, most of the main regions and cities had been connected by primary and secondary asphalt roads whose total length had reached 12,169 km (7,300 mi) at the end of the plan (1975). The total of agricultural feeder roads was 8,077 km (4,846 mi).

In 1975, the Ministry of Communications began its second five year program, which continued the original Main Program to build a complete two-lane asphalt road network throughout the Kingdom. At the end of this phase (1980) 21,583 km (12,950 mi) of primary and secondary asphalt road projects had been completed, and 24,186 km (14,512 mi) of agricultural feeder roads had been completed.

The fourth phase, which started in 1980, included an increase in the total length of roads, 6,000 km (3,600 mi), together with the upgrading of existing roads to dual carriageways and expressways, and the construction of bridges and tunnels (Fig. 2.3).

To supplement the main program, the Ministry also initiated a separate program for low volume road construction in 1964. It involved the improvement and grading of the existing desert and mountain tracks, while expanding the network of unpaved roads to connect as many settlements as possible with the growing primary road network. The low volume roads program was continued and expanded since 1964. Ministry of Communications work crews build and maintain all low volume roads working through five zones and eleven districts, and using over

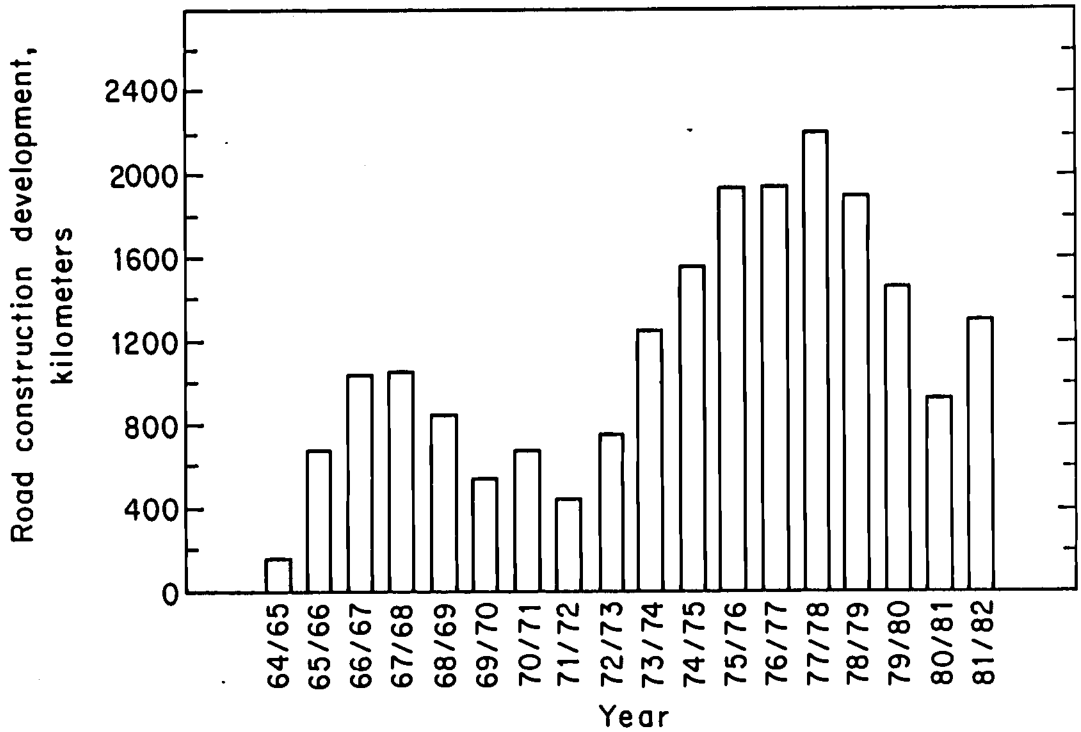


Fig. 2.3. Road construction/year.

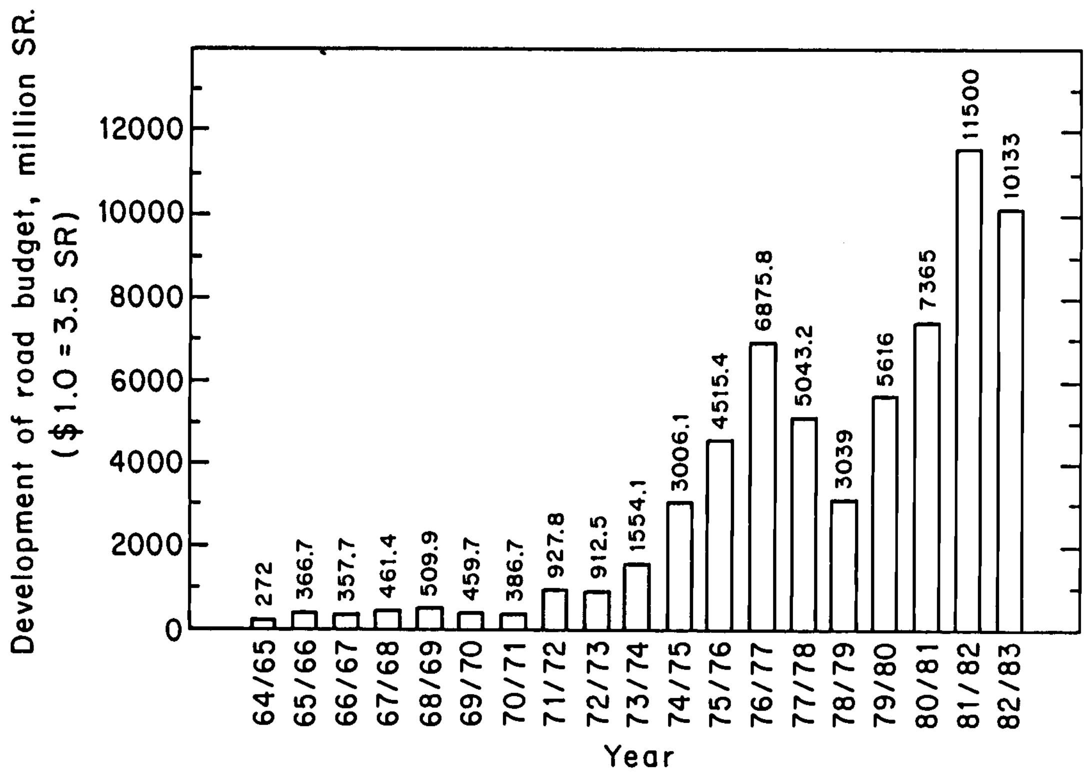


Figure 2.4. Road budget/year (51).

1500 pieces of construction equipment. There are currently 52 crews working, bringing the service to 4,579 villages [51].

The low volume network enabled the government to provide services to isolated areas, as well as giving greater mobility to agricultural produce and allowing the residents of isolated villages to communicate more easily with cities.

By 1984 there were 4,000 km (2,400 mi) of expressways, 24,000 km (14,400 mi) of dual way highways, 3,000 km (1,800 mi) of primary agricultural roads and 41,000 km (24,600 mi) of agricultural low volume roads connecting the various parts of populated areas in the northeast, central, northern and western sections of the country. The Ministry of Communications plans eventually to link up all villages in the Kingdom.

The increase in road construction led to an increase in road building costs (Fig. 2.4), which are funded by the government. Road construction cost the government the equivalent of $20 billion up to 1980. The government has earmarked $12,450.0 million for new roads and maintenance in the third Five-Year Plan (1980-1985).

The average cost of highway construction in Saudi Arabia has quadrupled in the years between 1972 and 1980 from a low of $155,000 per km ($258,300/mi) to over $650,000 per km ($1,083,300/mi) due to the increase in the costs of materials, labor, machinery and due to the improved roads' design features.

2.2.1 Types of Pavements in Saudi Arabia

As mentioned in the previous section, there are currently two types of roads. The first type consists of low volume, unpaved roads. These are constructed from compacted materials such as marl and are kept in condition by regular maintenance. There are currently 42,000 km (25,200 mi) of such roads, and the Ministry is considering upgrading some 20,000 km (12,000 mi) of these roads to oiled (or emulsion) surface roads.

The second type of roads uses dense-graded asphalt cement mix only for wearing course and base course. These roads include agricultural feeder roads, two lane roads, dual way carriage ways and expressways. There are currently 31,000 km (18,600 mi) of such roads (excluding intercity roads). These roads are usually constructed on a compacted sub-base of materials such as marl. Road construction specifications require that sub-base materials should have a CBR of 25 for two lane roads and a CBR of 40 for expressways. Stabilization with lime may be required to improve the CBR value of compacted sub-bases. Two lane roads usually have 12 cm (5 in) of hot asphalt base course and 6 cm (2.5 in) of wearing course while freeways have 15 cm (6 in) of asphalt cement (60-70 pen) base course and 10 cm (4 in) wearing course.

The crown cross-slopes are 1.5% to lessen the effects of the shifting sand dunes (reduce sand accumulation) and work well in this area of low rainfall and absence of snow. Side slopes of 4:1 are used for embankments of three meters or less. In sand dune areas, 6:1 side slopes are used for safety and to avoid sand dune accumulation on the roadway.

In the interest of safety, expressway medians are generally 20 meters wide except in mountainous and extremely difficult areas where they are reduced to 11.3 meters. In sand dune areas, the only way to avoid or minimize accidents is to have a wide median. Any obstruction in the median area such as a guard rail or New Jersey barrier or even light reflectors trap moving particles and result in accumulation of sand on the roadway.

Two-lane highways normally have a design speed of 110 km/hr (68 mph) while expressways are usually designed for 120 km/hr (75 mph). The minimum preferable horizontal radius for two-lane highways is 1200 meters, and 1650 meters is the preferred horizontal radius for expressways [52].

Sand dune areas prove especially difficult to negotiate. The best current solution is to go around sand dunes on the windward side. If it is impossible to bypass the dune, the next best solution is to go over the top. It is not always possible to go around or over every sand dune. Current experience indicates that if the roadway must go through a dune, a four meter level area should separate the outside edge of the shoulder from the toe of the slope. The cut slopes themselves should be 1:20 on the windward side, but in no case steeper than 1:10. The slope faces must be stabilized by applying a stabilizing solution such as cutback asphalt (MC-1) or slow setting emulsified asphalt (CSS-1h).

2.2.2 Type of Paving Construction Industry

The Ministry of Communications gives a great deal of attention and concern toward encouraging Saudi contractors to enter the field of road construction and related fields such as construction of bridges, tunnels, streets, and airports. Due to this policy, the participation of Saudi contractors in all types of construction projects has increased. There were 44 Saudi contractors and 52 foreign contractors in 1975. These figures have changed to 82 Saudi contractors and 17 foreign contractors in 1982. Saudi consultants increased from zero in 1961 to 20 in 1983 vs. 11 foreign consultants.

On the other hand, the Ministry of Communications has its own crews (52) working in different places in the country and using over 1500 pieces of construction equipment. The main job of these crews is to construct and maintain low volume (compacted earth) roads [51].

All roads (except low volume) are constructed using hot asphalt cement. Aggregates are produced locally where available from crushers. In other cases, where there is a lack of good quality aggregate, such as in the eastern and northern parts of the country, aggregate must be imported for road construction.

There are three types of aggregate available in Saudi Arabia: limestone, which is found in better quality as one moves from east to west, and granite and basalt, which are abundant in the western part of the country. Therefore, the good quality aggregates are limited to part of the central region and the western area. All locally used aggregates are supplied by privately owned sources.

2.2.3 Pavement Problems

All roads in Saudi Arabia are constructed with hot asphalt mix, using one asphalt grade (60-70 pen.) which is produced locally. Pavement associated problems can be classified in two categories: 1) aggregate associated problems, 2) load associated problems and 3) subbase problems.

Stripping of asphalt is a common problem in the eastern part of Saudi Arabia. Limestone aggregates usually contain weak particles which disintegrate when subjected to cycles of wetting and drying. These aggregates, when used in the wearing course, although anti stripping agents and admixtures are used, disintegrate (Fig. 2.5), creating holes in the pavement surface (Fig. 2.6) which are then increased by the traffic action, especially in the short rainy seasons (January-March). On the western coast where granite and basalt are used in road construction, aggregate polishing occurs and therefore creates a slick road surface.

Another problem facing roads in Saudi Arabia is the subbase problem. Subbases are usually constructed using marl stabilized with lime. These subbases when accessed by water, lose their supporting strength and cause excessive pavement failure (Fig. 2.7). This problem is common in cities where median irrigation is used. In coastal cities, this problem represents problem number one due to the closeness of the water table to the surface.

There is currently no axle load regulation enforcement. This allows most truck owners to exceed the legal axle limit (18 kip for single axle and 44 kip for tandem axle) by three times as much. This increase in axle load has generally resulted in major rutting problems (Fig. 2.8) for roads which are traveled by such trucks. The Ministry of Communications is considering the enforcement

Figure 2.5. Aggregate disintegration.

Figure 2.6. Raveling and stripping.

Figure 2.7. Subbase rutting, causing excessive surface failure.

Figure 2.8. Pavement rutting due to high axle loads.

of truck weights and dimensions by using fixed and mobile scales.

Other problems facing road construction and maintenance are the high cost of aggregates ($35-45/cubic meter) and sand dunes movements.

2.2.4 Needs for Emulsified Asphalts

From the discussion in the previous sections, it appears that there is a real need for considering use of emulsified asphalt, whether in maintenance, construction or stabilization. For example, emulsified asphalt can be used as slurry seal or surface treatment (instead of an overlay) to solve the problem of stripping and polishing. This will renew the skid resistance of pavement surfaces and will protect water-susceptible limestone aggregate. Moreover, emulsified asphalt can be used with locally marginal aggregate, marl or sand for base construction to eliminate water effect and to reduce the construction cost tremendously by eliminating the high cost of crushed aggregate. It also can be used for stablizing sand dunes to protect roads and industrial areas but without wasting the distillate, as is the case when using cutback asphalts.

2.3 Emulsified Asphalts in Saudi Arabia

The emulsified asphalt industry is relatively new in Saudi Arabia, beginning in 1981. There are currently four plants which produce emulsified asphalt (Table 2.1). The production from these plants is limited to the slow-setting types of emulsions which are needed for sand stabilization. Moreover, there are five licensed plants that are expected to produce emulsified asphalts in the near future (Table 2.2).

Use of emulsified asphalt in the Kingdom (prior to 1984) was limited to sand stabilization to protect industrial areas (Fig. 2.9). They were also used to stablize sand dunes to protect roads (Fig. 2.10) and to increase sand stability, as shown in Fig. 2.11, without affecting the growth of wild plants (Fig. 2.12). It has received limited use as mulch spray (Fig. 2.13) and fog sealing (Fig. 2.14).

Emulsified asphalt has the important advantage in that it can be colored green, blue, brown or golden as shown in Fig. 2.15. Therefore stabilized sand can be brown instead of black as shown in Fig. 2.16. Emulsified asphalt has also been used for paving sidewalks and finishing medians, as well as slurry sealing with different colors to give beautiful colors compatible with surroundings, as shown in Figs. 2.17, 2.18, 2.19, 2.20 and 2.21.

As discussed earlier, asphalt cement has been and still is the principal material used for road construction in Saudi Arabia. Use of emulsified asphalt

Table 2.1. Plants currently producing emulsified asphalts (1984).

Plant Name and Location	Type of Emulsion Produced	Uses
Esmat Al-saddy Sand Still F. "DAMMAM"	SS-1h CSS-1h	1) Stabilization 2) Slurry seal
Arabian American Asphalt Co. "JUBAIL"	CSS-1h	1) Slurry seal 2) Stabilization
Faleh Dahem Al-Dosarry EST. "JUBAIL"	CSS-1h	1) Stabilization 2) Fog seal 3) Mulch treatment 4) Steel, Timber and Concrete Protection
Saudi Project Development Office 'PSDO' "JEDDAH"	SS-1h	1) Stabilization 2) Slurry seal 3) Steel, Timber and Concrete Protection

Table 2.2. Plants Licenced to Produce Emulsified Asphalts in the Future.

Name of firm	Location	Licenced Production/ Year
Halalah Asphalt Industries Est.	Riyadh	6,440 tons
Saudi Emulsified Asphalt Factory	Jeddah	16,000 tons
Arabian Insulation Industry Co.	Jeddah	1,000 tons
Al-Dwail Factory for Bituminous Derivatives	Jeddah	11,925 tons
Soil Fixation Materials Factory	Jubail	33,000 tons

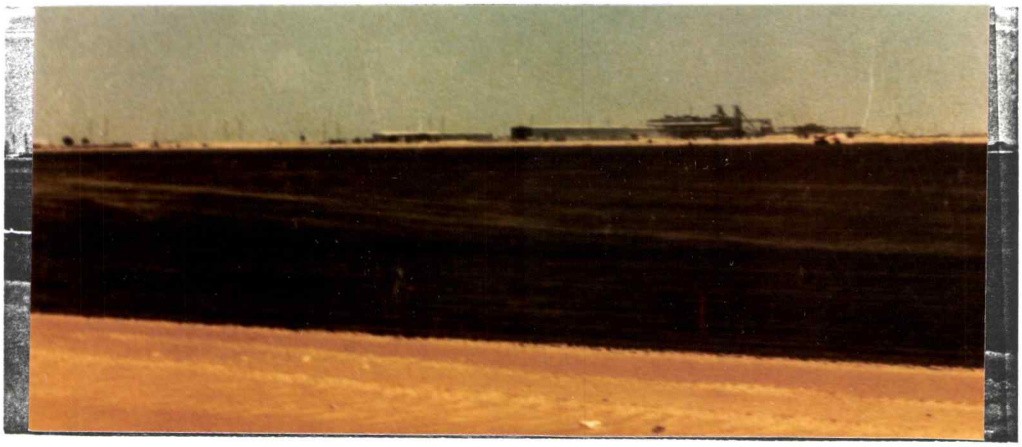


Figure 2.9. Sand stabilization to protect industrial areas. "JUBAIL"

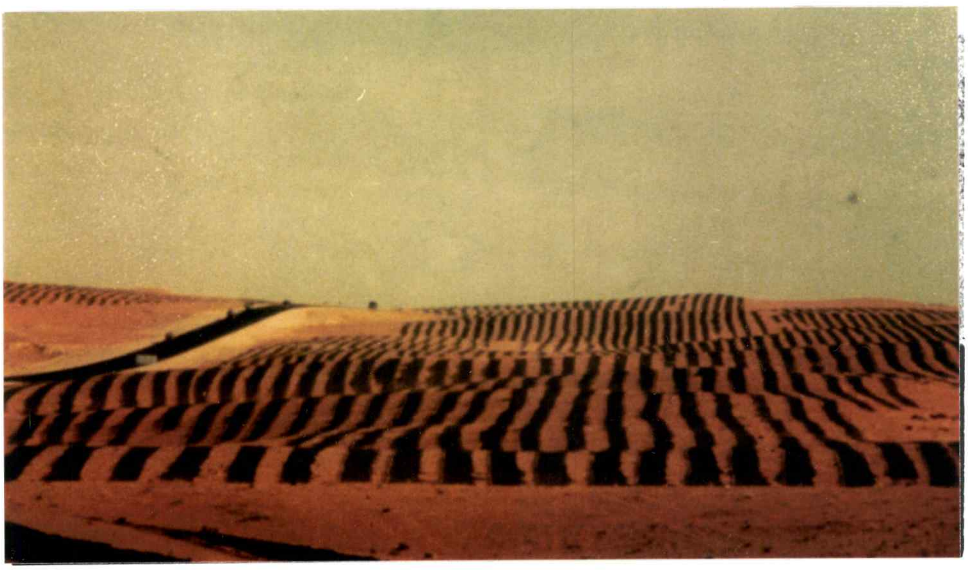


Figure 2.10. Sand dune stabilization to protect roads. "Al Majma'ah highway"

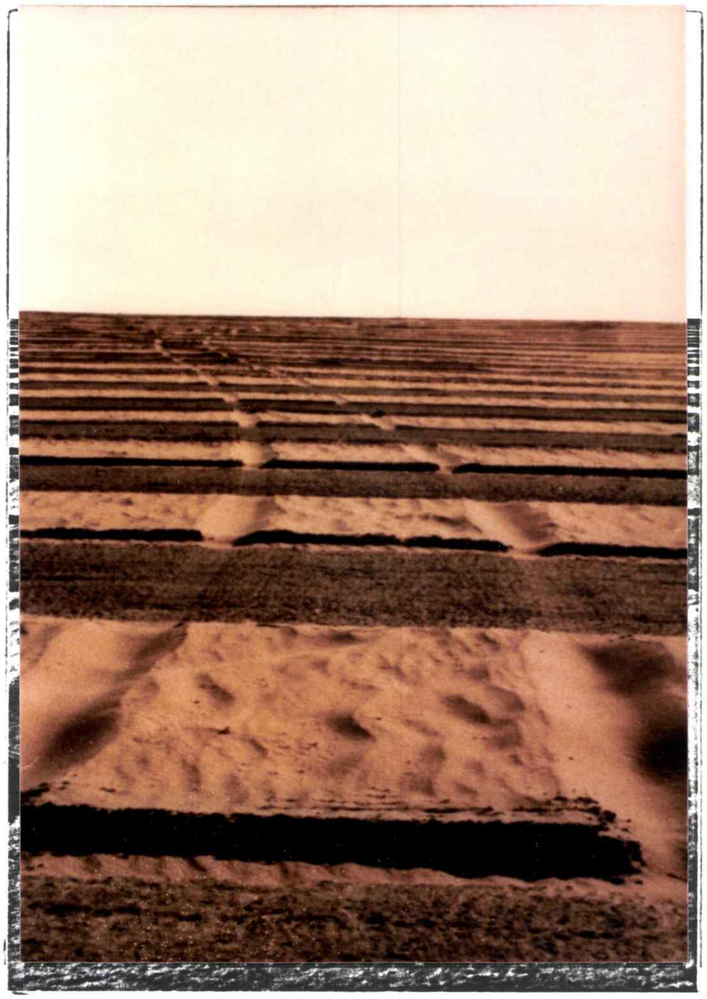


Figure 2.11. Effect on sand stability without compaction.
(DAMMAM)

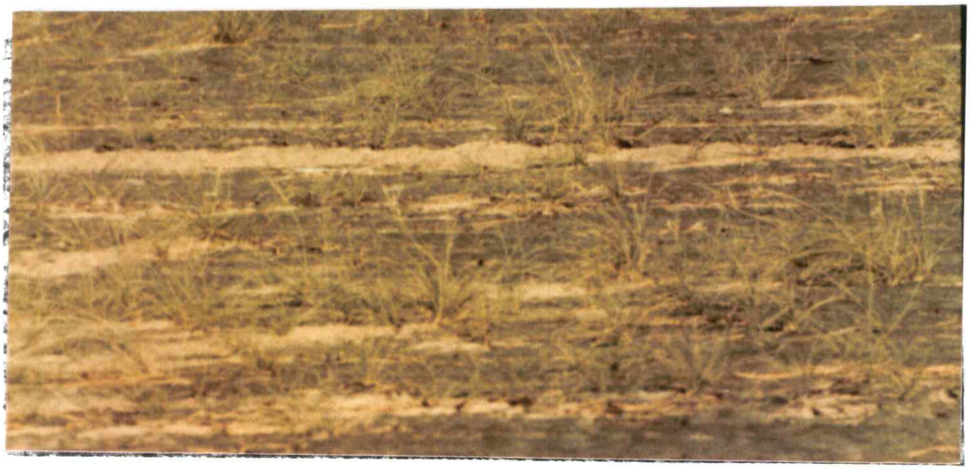


Figure 2.12. Use of emulsified asphalts does not affect wild plant growth. "JUBAIL"

Figure 2.13. Emulsified asphalt spray mulch for seed protection. "JUBAIL"

Figure 2.14. Fog sealing operation for surface protection. "JUBAIL"

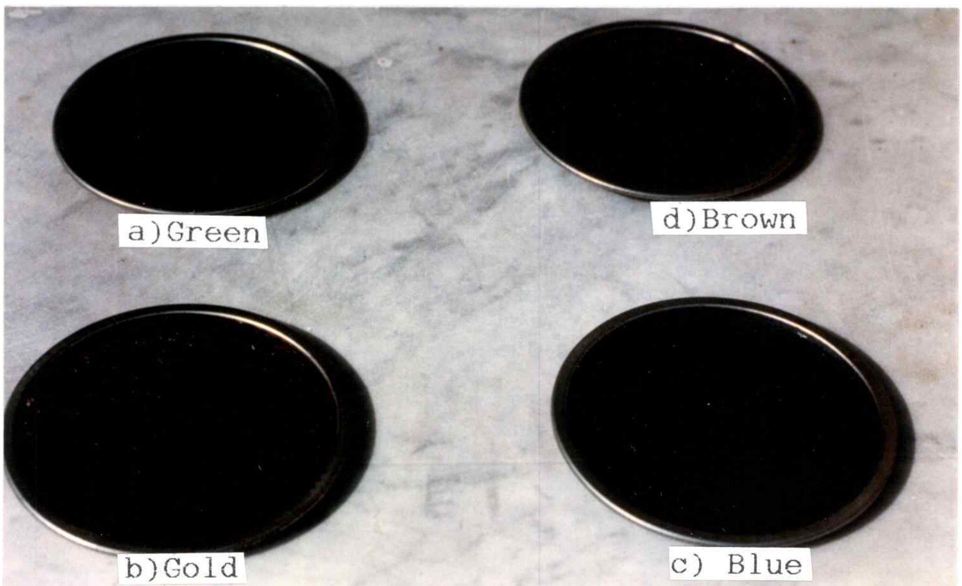


Figure 2.15. Asphalt emulsion can be colored to be green, blue, brown, or golden.

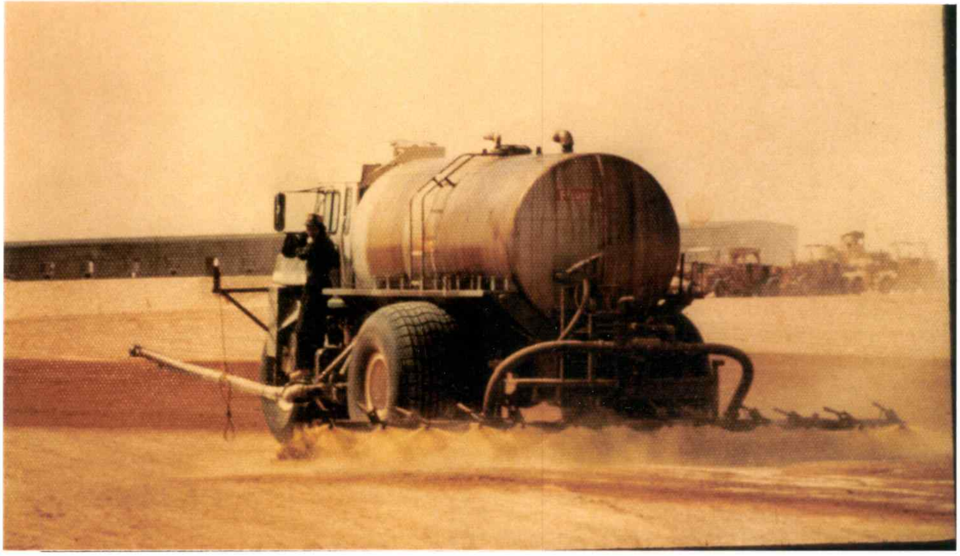


Figure 2.16. Asphalt emulsion (brown) spraying for sand stabilization. "JUBAIL"

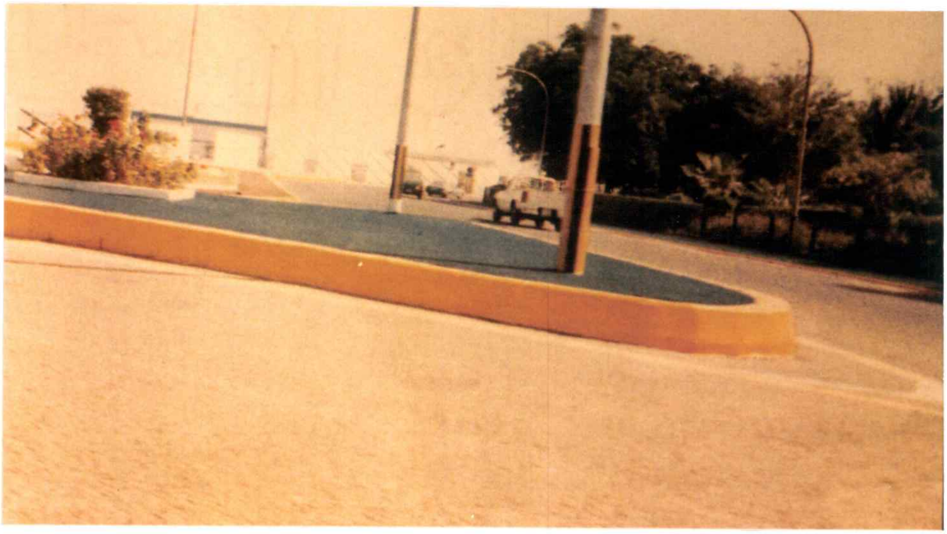


Figure 2.17. Dark blue asphalt emulsion used for median treatment. "JEDDAH"

Figure 2.18. Green asphalt emulsion used for sidewalk and median treatment. "JEDDAH"

Figure 2.19. Light blue asphalt emulsion used for sidewalk treatment. "JEDDAH"

Figure 2.20. Brown asphalt emulsion for median treatment. "JEDDAH"

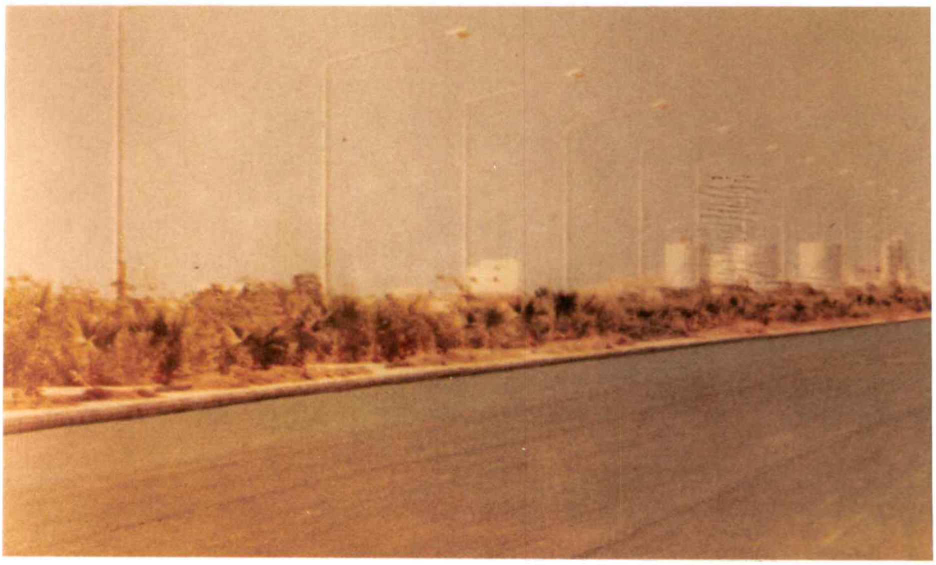


Figure 2.21. Green slurry seal. "JEDDAH"

has been limited to prime coats, tack coats and maintenance according to specifications [52, 53, 54]. As such, use of emulsified asphalt currently has no application in maintenance or construction of roads constructed by the Ministry of Communications. Moroever, the lack of good quality aggregate in areas such as eastern, northern and northwest Saudi Arabia increases the construction costs of roads (Table 2.3).

Use of emulsified asphalts would allow the utilization of the abundant dune sand and low cost marl in road construction. This will reduce road construction costs considerably due to the reduction of aggregates needed.

2.4 Emulsified Asphalt Production Cost

A comprehensive survey was carried out to evaluate the cost of emulsion production. The survey included plants currently producing, Keno Gard (major plant manufacturer), and local material costs and availability. Based on this survey, cost of emulsified asphalt emulsion produced locally was calculated (Table 2.4).

All materials needed for emulsified asphalt are locally available at low prices. Water in Saudi Arabia does not represent a problem as it is available at a price of $0.5/cubic meter ($0.385/cubic yard). Asphalt cement and distilates are available at a cost of

Table 2.3. Material Costs in Saudi Arabia

Item	Cost (S.R.)*
Asphalt emulsion production	385/Metric Ton
Asphalt emulsion	450-900/Metric Ton
Asphalt cement	300/Metric Ton
Cutback asphalt	800/Metric Ton
Diesel fuel	90**/Metric Ton
Portland cement	200/Metric Ton
Crushed aggregate	130-170/Cubic Meter

* $1.0 = S.R. 3.5

** One ton of hot mix requires 5.4 liter of fuel for drying.

Table 2.4. Emulsion Cost Calculation.

(1) Equipment Cost:		
1 SEP-5	S.R.	310000.0
1 SPT-17	S.R.	105000.0
1 SST-34	S.R.	130000.0
1 SST-34E	S.R.	110000.0
1 SWT-10	S.R.	10000.0
Subtotal	S.R.	665000.0
(2) Freight Cost	S.R.	100000.0
(3) Interest, 10%	S.R.	76500.0
(4) Personnel:		
(a) One Chemist & One Marketing Engineer		
Salary at 6000	S.R.	2*72000.0
Housing	S.R.	2*25000.0
Car	S.R.	2* 8000.0
Travel	S.R.	2* 5000.0
Insurance	S.R.	2*10000.0
(b) Labor "5"		
Salary at 15000	S.R.	5*18000.0
Housing	S.R.	20000.0
Transportation	S.R.	10000.0
Subtotal (a+b)	S.R.	360000.0
(5) Construction	S.R.	400000.0
10% Interest	S.R.	40000.0
(6) Assuming (4000 ton/year) Production		
10% of Equipment Cost	S.R.	66500.0
Interest	S.R.	76500.0
10% of Freight Cost	S.R.	10000.0
Personnel	S.R.	360000.0
10% of Construction Cost	S.R.	40000.0
Interest	S.R.	40000.0
Bitumen, 60% at 300	S.R.	720000.0
Solvent, 3% at 90	S.R.	10800.0
Water, 37% at 2.0	S.R.	2960.0
Electricity at 2.0	S.R.	8000.0
Emulsifier (Cationic) 1% at 5000	S.R.	200000.0
Total	S.R.	1534760.0

Cost of ton production = 1534760.0 /40000
= S.R. 383.7

Selling Price (10% profit) = S.R. 383.7 * 1.1
= S.R. 425

$85/cubic meter ($66.0/cubic yard) and $25.7/cubic meter ($19.8/cubic yard), respectively.

It should be mentioned that the calculations presented are based on local practice for small industrial projects. In this regard, capital investment is assumed to be returned over the project period without compounding interest plus 10% constant profit/year on capital investment. The assumptions for calculation are as follows.

1) Design life for the plant is 10 years. Therefore capital investment is returned over 10 years without compounding interest
2) Return on investment is 10% per year (other than step 1)
3) Two engineers are required as follows
   a) one marketing engineer and director
   b) one chemist for emulsified asphalt formulation and testing
   c) five laborers for secretarial work, plant operations, minor maintenance work carried by plant crew, such as sand stabilization and fog sealing
4) Land is offered free by the government
5) 4000 tons of emulsified asphalt are produced each year
6) Calculation is for cationic emulsion which is

more expensive than anionic emulsion. Currently producing plants are shifting to cationic type due to its suitability with local aggregates

7) Emulsified asphalt selling profit is 10% of its production cost

All costs and prices represent the current costs in Saudi Arabia. They were obtained from a survey of the existing plants, and use market prices, as supplied by an emulsion plant manufacturer (Keno Gard). Calculations (Table 2.4) are based on the total cost (production and capital) per year during the ten year plant design life. Emulsified asphalt selling price is then calculated by adding 10% profit to the total cost. Calculations are shown in six steps as follows.

1) Equipment cost as given by Keno Gard = S.R. (Saudi Reyal) 665,000.0

2) Plant freight cost to Saudi Arabia from Sweden = S.R. 100,000.0

3) 10% interest/year (second assumption) on the above items = (0.10)(665,000+100,000) = S.R. 76,500.0

4) Personnel cost/year, for

   a) Two engineers

Salary @ S.R. 6000/month	= S.R.	144,000.0
Housing @ S.R. 25000/year	= S.R.	50,000.0
Car @ S.R. 8000/year	= S.R.	16,000.0

Travel @ S.R. 5000/year = S.R. 10,000.0

Insurance @ S.R. 10000/year = S.R. 20,000.0

b) Five Laborers

Salary @ S.R. 1500/month = S.R. 90,000.0

Housing @ S.R. 20000/year = S.R. 20,000.0

Transportation @ 10000/year = S.R. 10,000.0

Total Labor Cost/Year = S.R. 360,000.0

5) Construction cost of offices, plant facilities and fences = S.R. 400,000.0, and 10% interest/year (second assumption) on construction costs = S.R. 40,000.0

6) Based on current emulsion producers and experience of Keno Gard Company, 4000 tons of emulsion was used as a total production/year. Emulsified asphalt production cost/year was calculated based on assumption as follows.

a) Since the plant design life is 10 years, 10% return is expected for capital expenses (assumption 1); from items 1, 2 and 5, (0.10)(665,000 + 100,000 + 400,000) = S.R. 116,500.0

b) Based on assumption no. 2, interest on capital is 10%, interest from steps 3 and 5 above = S.R. 76,500 + 40,000 = S.R. 116,500.0

c) Personnel cost/year from step 4 above = S.R. 360,000.0

d) Emulsification costs based on 4000 ton/year production

- o Cost of bitumen which represents 60% of emulsion at a cost of 300 S.R./ton = (.6)(300)(4000) = S.R. 720,000
- o solvent which represents average of 3% at cost of 90 S.R./ton Cost (0.03)(90)(4000) = S.R. 10,800
- o Water, which represents 37% of emulsion at cost of 2.0 S.R./ton, cost (2)(.37)(4000) = S.R. 2,960
- o Electricity, where a production of 1 ton cost 2.0 S.R. as given by Keno Gard, cost = (2)(4000)= S.R. 8,000
- o Cationic emulsifier (which is far more expensive than anionic), where 1% is required for emulsification at 5000 S.R./ton, cost = (.01)(5000)(4000) = S.R. 200,000

Summing all the costs from item a to d yields the total cost of producing 4000 tons of emulsion/year including 10% profit on capital investments (S.R. 1,534,760.0). Calculating the cost of a ton (dividing by 4000) yields a cost per ton of S.R. 384 ($109) and selling price of S.R. 425 (1.1*384) ($122). However, the actual selling prices (1985) currently range between 450 - 900 S.R. (Table 2.3), i.e. with a profit of 20 to 140%, which presents one obstacle to emulsion usage in some areas. This is expected to decrease for two reasons:

1) The increase in competition, and
2) Ministry of Transportation does not approve any prices (for its projects) higher than S.R. 450.0.

2.5 Summary

Roads in Saudi Arabia have been constructed using hot asphalt cement. Portland cement concrete has never been used for road construction other than for bridges and tunnels.

Use of emulsified asphalts in Saudi Arabia is limited to sand stabilization, although it can also be used to solve current pavement problems. It can be used for base construction to reduce the usage of high cost aggregates. It can also be used for slurry sealing to reduce stripping and eliminate aggregate polishing and degradation problems. Use of emulsified asphalts with local sands for road base construction will reduce or eliminate the common base rutting problem when exposed to water. Therefore, it represents an attractive option for local road maintenance and construction. It can be produced from local low cost asphalt at relatively low prices. Consequently, it provides an alternative for local roads construction and maintenance.

3.0 PRODUCTION OF EMULSIFIED ASPHALTS IN THE LABORATORY

Since only one type of emulsified asphalt (CSS-1h) is currently produced in Saudi Arabia for sand stabilization, lab trials were carried out at the University of Petroleums and Minerals, Saudi Arabia, to produce cationic medium setting emulsion (CMS-2h) for use with local materials. This emulsion was used with dune sand and open- graded limestone to produce road mixes and to evaluate their properties.

This chapter presents a description of the emulsion plant and the procedures used to produce emulsified asphalt in the laboratory.

3.1 Plant Description

"Emul Bitume" plant was used to produce emulsion in the lab (Fig. 3.1). The plant is based on the batch plant principle (Fig. 3.2) where asphalt cement is heated in a bitumen tank with solvent while water and emulsifier are mixed and heated in another tank and then mixed together in a colloid mill to produce emulsified asphalt. This plant is designed to produce 500 liters an hour of emulsified asphalt. An overall diagram of the emulsion plant is shown in Fig. 3.3. The various elements and their functions are discussed below.

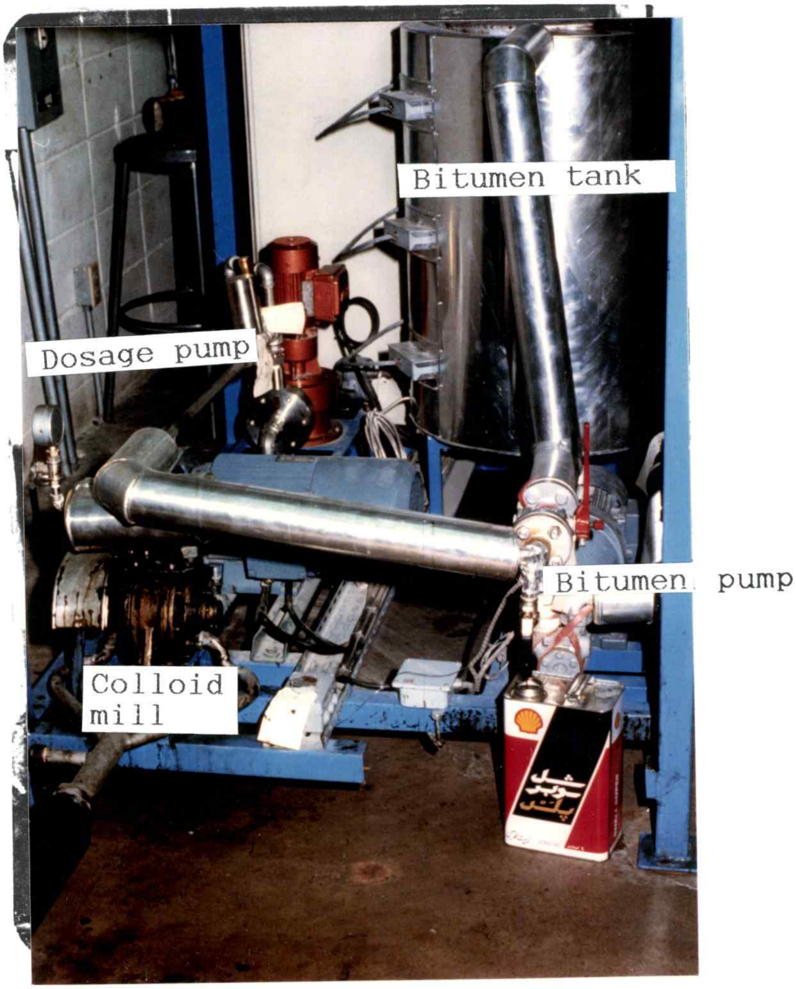


Figure 3.1. 'Emulbitume' emulsion plant

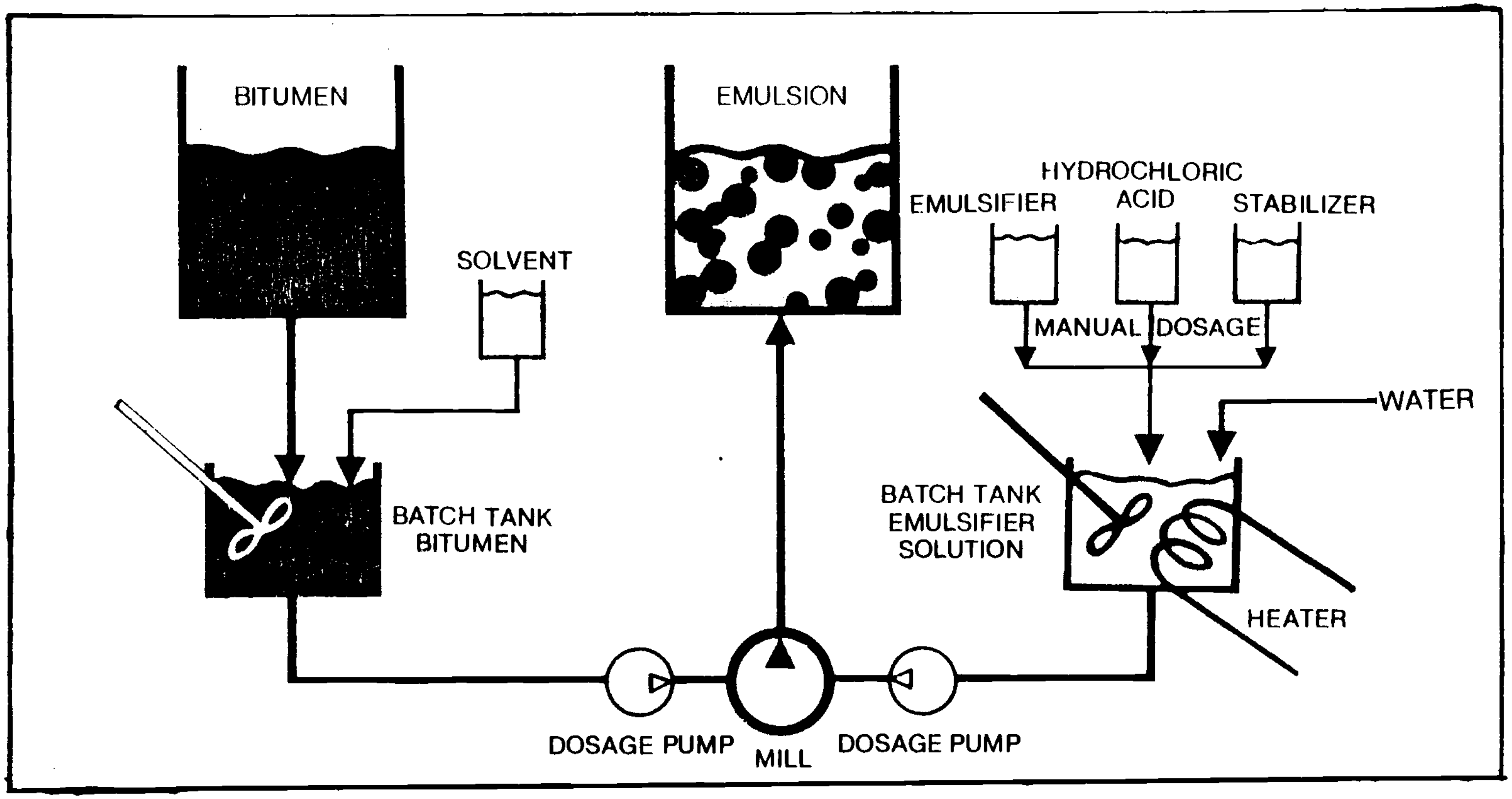
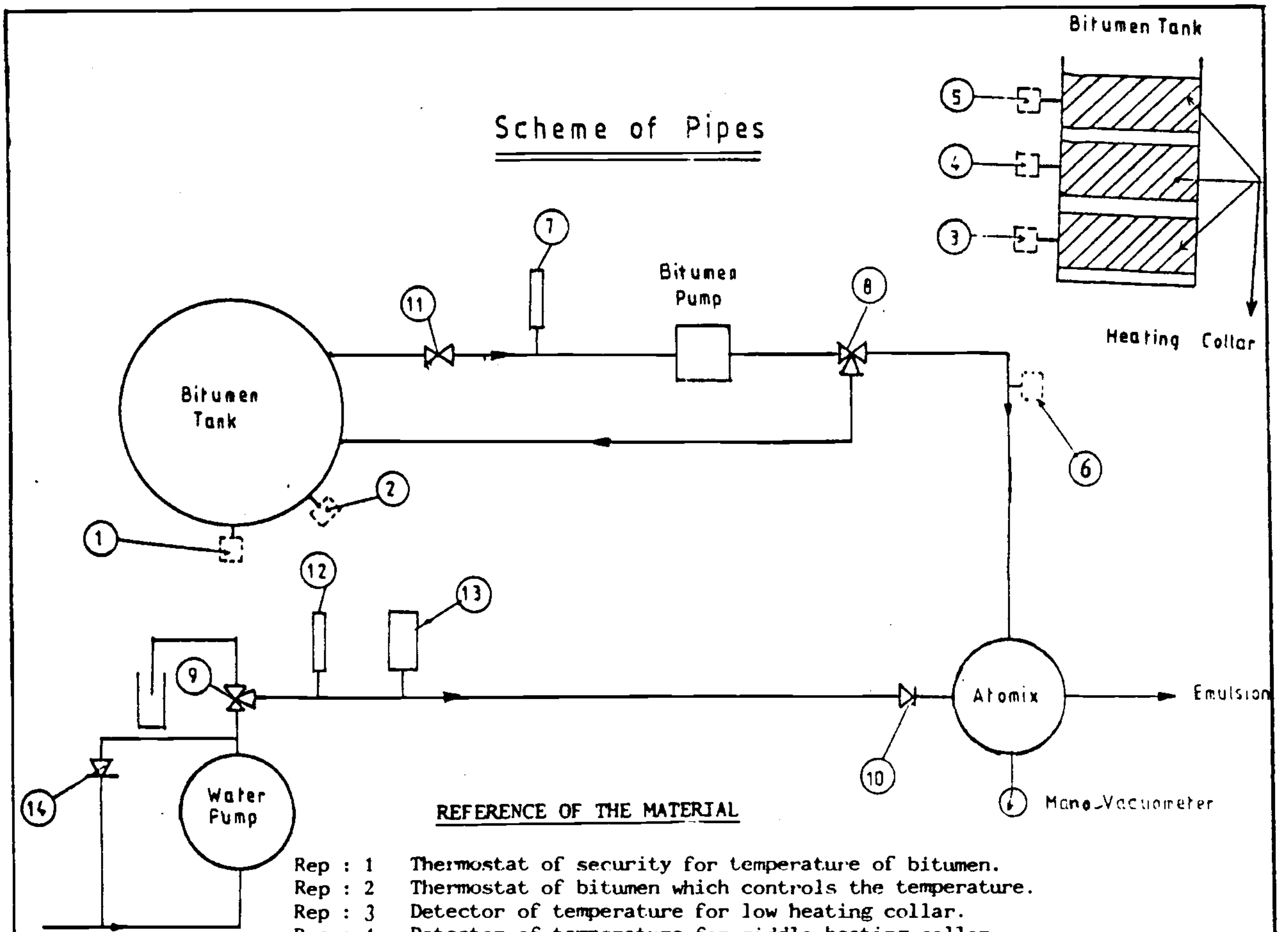


Figure 3.2. Priciple diagram of a batch plant.(Courtesy KenoGard Co.)



REFERENCE OF THE MATERIAL

Rep : 1 Thermostat of security for temperature of bitumen.
Rep : 2 Thermostat of bitumen which controls the temperature.
Rep : 3 Detector of temperature for low heating collar.
Rep : 4 Detector of temperature for middle heating collar.
Rep : 5 Detector of temperature for upper heating collar.
Rep : 6 Thermostat which controls the heating of bitumen pipes.
Rep : 7 Thermometer giving the temperature of bitumen in the pipe at the succion of the pump.
Rep : 8 Tap with 3 ways in I for bitumen.
Rep : 9 Tap with 3 ways in I for soap solution to test the flow of water pump.
Rep : 10 Non return valve.
Rep : 11 Tap at the bottom of bitumen tank.
Rep : 12 Thermometer giving the temperature of soap solution .
Rep : 13 Regulator of pressure.
Rep : 14 Valve discharge for water pump at pressure of 3 bars.
Rep : 15 Thermometer of regulation of bitumen temperature.

Figure 3.3. Emulsion plant diagram.(Courtesy Emulbitume co.)

3.1.1 Bitumen Pump

The purpose of this pump is to supply and regulate bitumen flow to the mill. The speed of the pump can be varied from 90 to 910 revolutions/minute. This is obtained with the variable rheostat located on the front panel (Fig. 3.4) and can be monitored by the speedometer located on the front panel. Pump speed is used to regulate the flow of bitumen (flow varies linearly with the pump speed). For example, at a speed of 260 RPM, flow rate is 30 gallon/hr (115.4 liter/hr) and increases by 0.115 gallon/hr (0.442 liter/hr) when increasing the pump speed by one (i.e. 0.115 gallon/revolutions/hour). Flow rate is displayed on the front panel by a digital counter, in gallon/hr.

3.1.2 Colloid Mill

At the mill, the hot asphalt and water with emulsifier are mixed together to form emulsified asphalt. The motor driving the mill has a maximum speed of 3130 revolutions/minute (100%). Because the ratio of the diameters between the pulley of the motor and the pulley of the mill is two, the maximum speed of the mill is 6260 turn/minute and the peripheral speed of the rotor is 43 meter/sec. The variation of this speed is obtained with a variable rheostat which is located on the front panel (Fig. 3.4).

3.1.3 Bitumen Tank

In this tank, asphalt with solvent (diesel) is heated to emulsification temperature of 145°C (294°F) prior to milling. The bitumen tank (Fig. 3.5) has the following dimensions:

1) Diameter = 500 mm (19.7 in)

2) Height = 800 mm (31.5 in)

3) Total Capacity = 200 liters (52 gallons)

4) Utilization Capacity = 170 liters (44.2 gallons)

The tank is heated with three electrical collars each having a height of 200 mm (7.9 in) and a power of 4 KW. The temperature of the bitumen is verified by a detector which is located at the bottom of the tank (Fig. 3.3). This detector transmits the temperature to an adjustable thermometer which controls the three heating collars.

To avoid overheating of the collars, particularly as the tank approaches empty, a detector is provided between each collar and tank. These detectors transmit the temperature to the thermostat which is adjustable between 0° and 300°C (32°F and 572°F). These thermostats (Fig. 3.3, Representations 3, 4 and 5) are normally set at 280°C (536°F) to prevent the deterioration of heating collars.

A thermostat for security (Fig. 3.3 Rep. 1) has been attached at the bottom of the tank. This thermostat prevents activation of the pumps and the mill if the temperature is below 95°C (203°F).

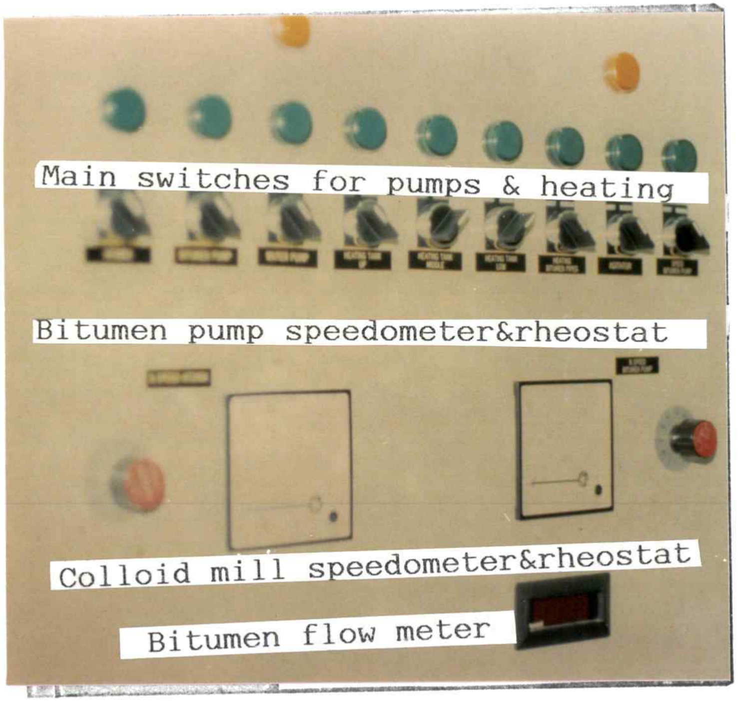


Figure 3.4. Front panel showing main switches, rheostats, speedometers, and flow meter.

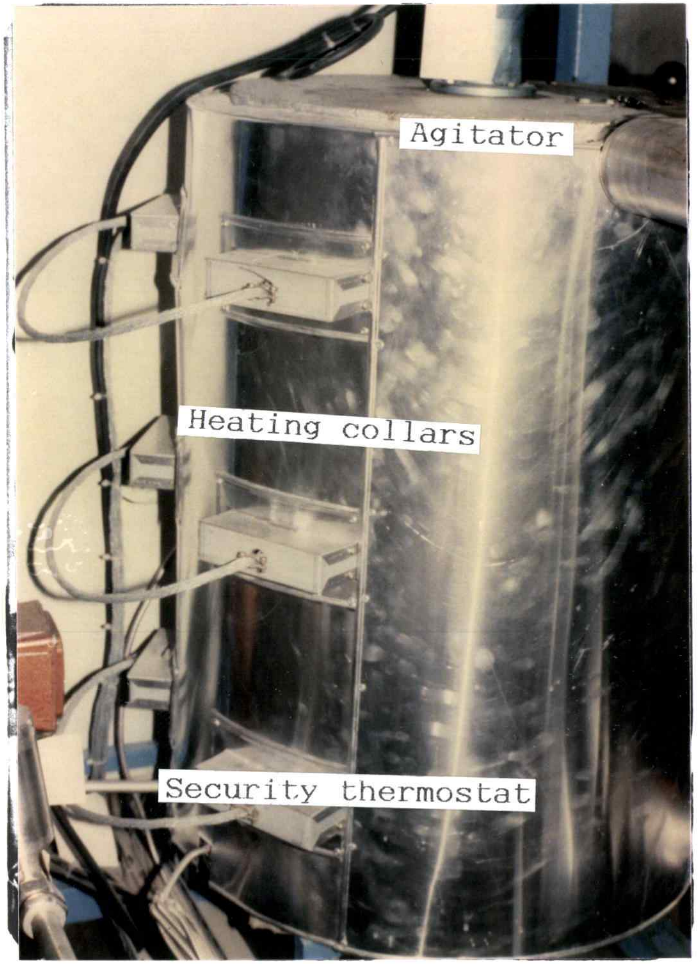


Figure 3.5. Asphalt heating tank showing agitator, heating collars, and security thermostat.

3.1.4 Bitumen Pipes

All the bitumen pipes between the tank and mill are preheated with an electrical cables. The temperature is controlled with a thermostat adjustable between 0° and 300°C (32°F and 572°F). This thermostat is normally set at 100°C (212°F).

3.1.5 Soap Solution Dosage Pump

The soap solution dosage pump is used to pump and regulate the flow of water with emulsfier to the mill. The flow of this pump varies linearly with the graduation of the flow vernier (Fig. 3.6). The vernier has 25 graduations for one round. The vernier can make 4 rounds which gives a graduation from 0 to 100. There is no flow when the vernier is set to zero. The flow can be increased by a rate of 2.1 liter/hr (0.546 gallon/hr) by increasing the vernier graduation by one (i.e. 2.1 liter/hour/graduation). The maximum flow of ths pump is 210 liters/hour (54.6 gallon/hr).

3.1.6 Soap Solution Tank

Water and emulsifier agent are mixed in the soap solution tank. It has a capacity of 120 liters. The soap solution can be heated and agitated at the same time using an immersion heater. The temperature of the soap solution can be controlled by a thermostat from 0°C to 80°C (32° to 176°F) which is set at 40°C (104°F).

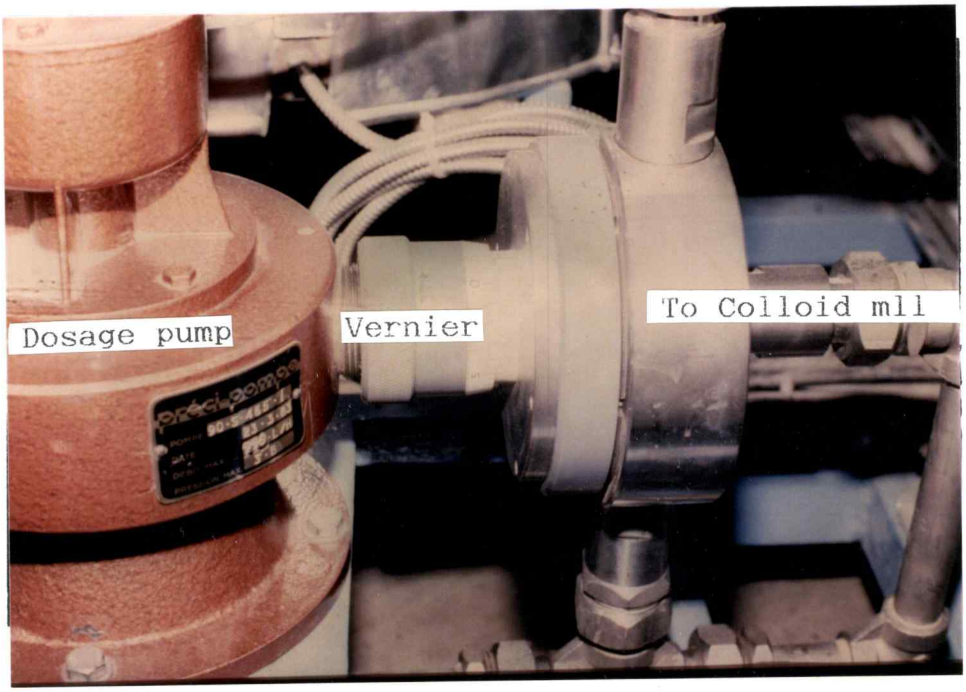


Figure 3.6. Dosage pump with vernier for the adjustment of soap solution flow.

3.2 Emulsion Production

Emulsified asphalt used in this study was produced using the following steps:

1) Preheat the bitumen pipe at least one hour before the test
2) Make certain that the bitumen temperature reaches the set value (140°C, 1284°F). The pump will not start if temperature is less than 100°C (212°F).
3) Check if the bitumen pump can be turned manually (not jammed)
4) Start the bitumen pump in recycling position to recycle the bitumen in the tank
5) Increase the pump speed until the desired flow is obtained
6) Begin the soap solution pump to provide the mill with soapy water
7) Start the mill at a low speed and increase its speed until 6200 R.P.M.
8) Introduce bitumen into the mill, turning the three-way tap (Fig. 3.3, Representation 8)
9) Collect emulsified asphalt in containers with covers.
10) Asphalt/water proportion can be controlled by the speed of bitumen pump and the gradation of the soap solution dosage pump vernier

To stop the system, the following steps are followed to clear the mill of asphalt which could plug it in the future:

1) Set the bitumen pump in position of recycling to the bitumen tank,
2) Allow the mill to operate an additional minute provided only with a cleaning soap solution before reducing its speed, and
3) Stop all pumps and clean bitumen from all the pipes and pumps with petrol solvent such as kerosene.

3.3 Materials

3.3.1 Bitumen

Asphalt cement (60/70 pen.) from Ras Tanura Refinery, Saudi Arabia, was used in this study. Properties of this bitumen are given in Table 3.1. It has a very high viscosity which makes it necessary to add 1.5% solvent (diesel) to soften it for the emulsification.

3.3.2 Water

Standard tap water (drinking water) from Dhahran was used for the emulsification.

3.3.3 Emulsifier

"Lilamuls EM71," Quantenary salt of tallow monamine, supplied by Keno Gard Co., was used as the emulsifier.

Table 3.1. Properties of Bitumen* used to produce emulsified asphalts

Test	Unit	Method	Result
Penetration at 25°C	mm/10	ASTM D5	60
Softening point R & B	°C	ASTM D36	48
Viscosity at 60°C	Ns/m^2	ASTM D2171	322
Viscosity at 135°C	mm^3/S	ASTM D2170	558
Tests on residue from thin-film oven test			
Loss of heating	%	ASTM D1754	-0.68
Penetration % of org.	%	ASTM D5	40
Ductility at 25°C	cm	ASTM D113	<100
Density at 25°C	g/cm^3	IP 59 D	1.0273
Sulfur content	%	ASTM D2622	5.3

* 60-70 pen bitumen produced by Aramco, Ras Tanura refinery, Saudi Arabia (54)

It is a water soluble yellow liquid which can be used at acid or neutral pH without addition of hydrochloric acid. It is used primarily for medium set emulsions and is a powerful adhesive agent giving improved adhesion to most aggregates.

While the bitumen phase had to be heated to 140°C (284°F) to make it pumpable, the temperature of the water phase was adjusted so that the temperature of the resulting emulsion did not exceed 100°C (212°F), which could result in the evaporation of water phase and setting of the emulsified asphalt.

The emulsifier agent was added to water which was heated at 40°C (104°F) and mixed with 140°C (284°F) asphalt to produce CMS-2h emulsion. The production data are shown in Table 3.2. The resulting emulsion was stored in 20 liter tins (5 gallons) at 45°C (113°F), and was tested and compared with ASTM Specifications. The test results are shown in Table 4.2 and will be discussed further in Chapter 4.

3.4 Summary

CMS-2h emulsion was produced under laboratory controlled conditions. An "Emul Bitume" laboratory plant was used to produce emulsified asphalt from local asphalt with no problems. Produced emulsion, together with CSS-1h emulsion supplied by Sand Still Company of Saudi

Table 3.2. Production Data for CMS 2-h

Formulation %	
Bitumen	67
Diesel	1.5
Lilamulus EM 71	1.0
Water	30.5
Emulsification Data	
Temp °C:	
Water	40
Bitumen	145
Emulsion	93

Arabia, was used with local materials and was compared with CSS-1h supplied by Chevron U.S.A. All emulsions were tested and compared with ASTM specs as will be discussed in Chapter 4.

4.0 EXPERIMENT DESIGN FOR TESTS ON EMULSIFIED ASPHALT MIXES

This chapter describes the experiment design for emulsified asphalt treated mixes. The research program for evaluating emulsified mixes is shown in Fig. 4.1 and consists of six main phases as follows:

1) Selection of aggregates and determination of their basic properties
2) Selection and characterization of emulsified asphalts
3) Emulsified asphalt mix design
4) Dynamic testing, diametral and beam fatigue
5) Analysis of test results, and
6) Development of design charts for local use

These phases are discussed in greater detail in the following sections and chapters.

4.1 Selection of Aggregates

Three types of aggregates were selected for this study: 1) dune sand, 2) marl and 3) limestone. Marl and dune sand were chosen due to their abundance at low cost in Saudi Arabia. If found to be suitable in performance they would be attractive substitutes for the more costly crushed aggregates, which are most widely used in local road construction. Limestone was selected from an

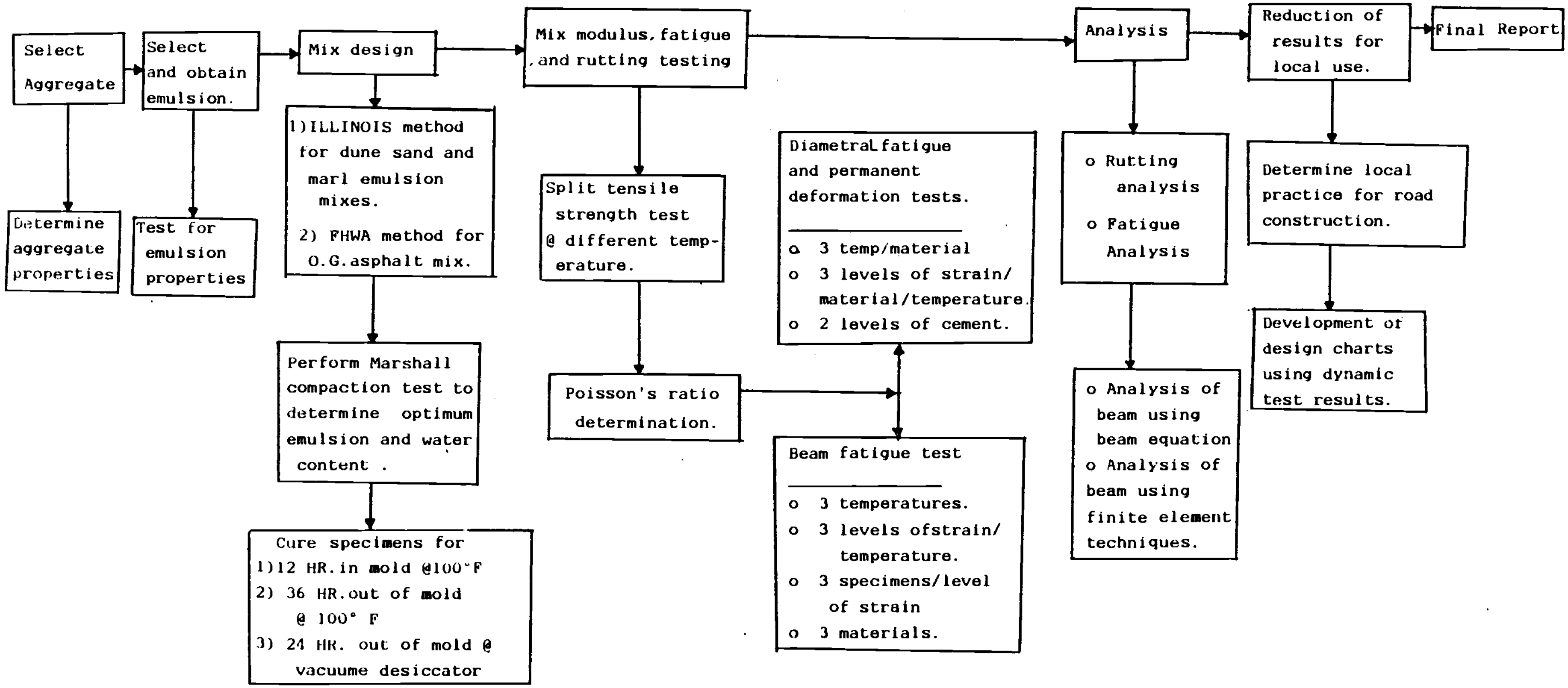


Figure 4.1. Laboratory program for evaluating use of emlsified asphalt mixes.

on-going highway project near Dammam City. Marl was selected from the same project where it was used for subbase construction. Dune sand was sampled in the Dhahran area. Selected aggregates are shown in Fig. 4.2.

4.1.1 Aggregate Tests and Results

Table 4.1 shows the various tests performed on each aggregate along with the test designations from AASHTO Specifications [9]. These tests were concerned mainly with the identification of basic physical properties of the materials for use in mix design. The test results shown are within specification limits with the exception of the marginal abrasion and soundness and high absorption exhibited by the coarse portion of marl.

Aggregate gradations are shown in Figs. 4.3 and 4.4. The gradation of dune sand and marl is as received from the field, while the gradation of open-graded limestone aggregate is in accordance with FHWA specifications for open graded emulsion mixes [55].

It should be noted that marl was mixed with 30% of dune sand in order to modify its mixing properties with emulsified asphalt. Marl when mixed with emulsion by itself tended to form muddy lumps, preventing uniform mixing. Addition of dune sand prevented such a condition. This will be discussed further in the following section. All aggregates were oven dried and

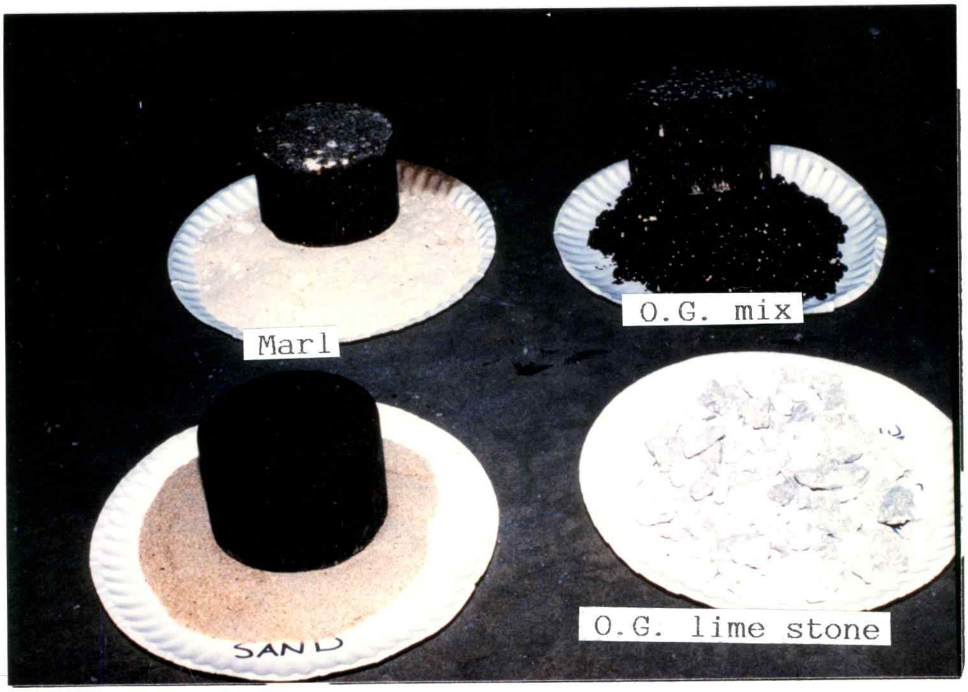


Figure 4.2. Dune sand, marl, and open graded limestone before and after treatment.

Table 4.1. Aggregate Characteristics

Test Type	Limestone	Marl +30% Sand	Sand	Typical Saudi Specs.
Specific gravity				
Coarse agg. AASHTO T-85	2.54	2.5	--	--
Fine agg. AASHTO T-84	--	2.8	2.64	--
P.I.	--	N.P.	N.P.	N.P.
Abrasion AASHTO T-96	29	35	--	30
Absorption AASHTO T-85	2.3	4.9	0.3	--
Sand equivalent AASHTO T-176	--	25	80	min. 30
Sodium sulphate soundness AASHTO T-104	3.9	8.5	0.5	9.0
K_c*	2.7	9.0	--	--
C.K.E.**	--	7.4	1.8	--

* Surface constant for coarse material (size 3/8" x 4)

** Centrifuge Kerosene Equivalent

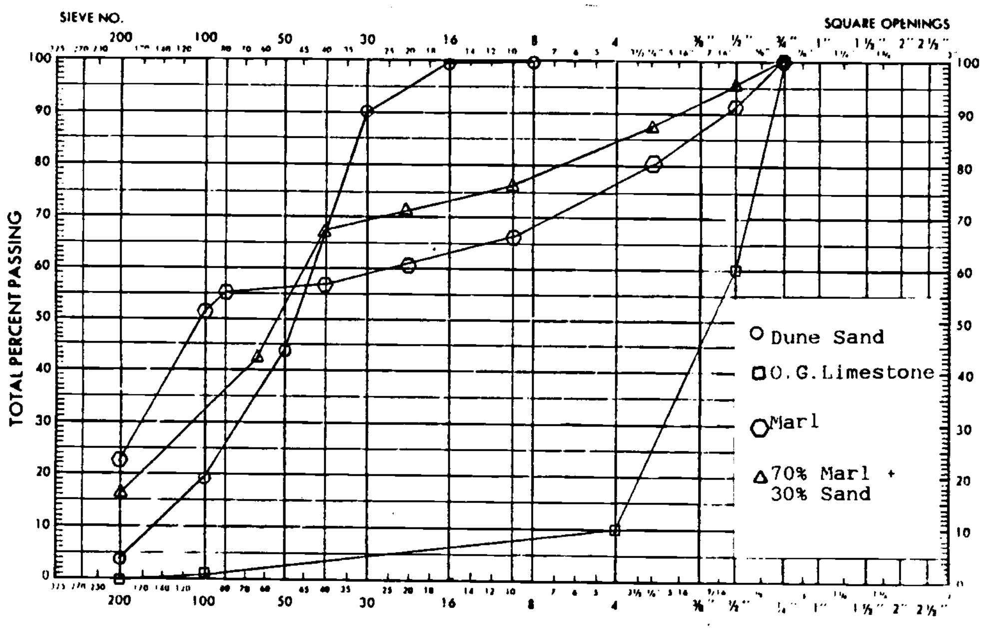


Figure 4.3. Gradation for aggregates evaluated (AASHTO T-27, ASTM C-136).

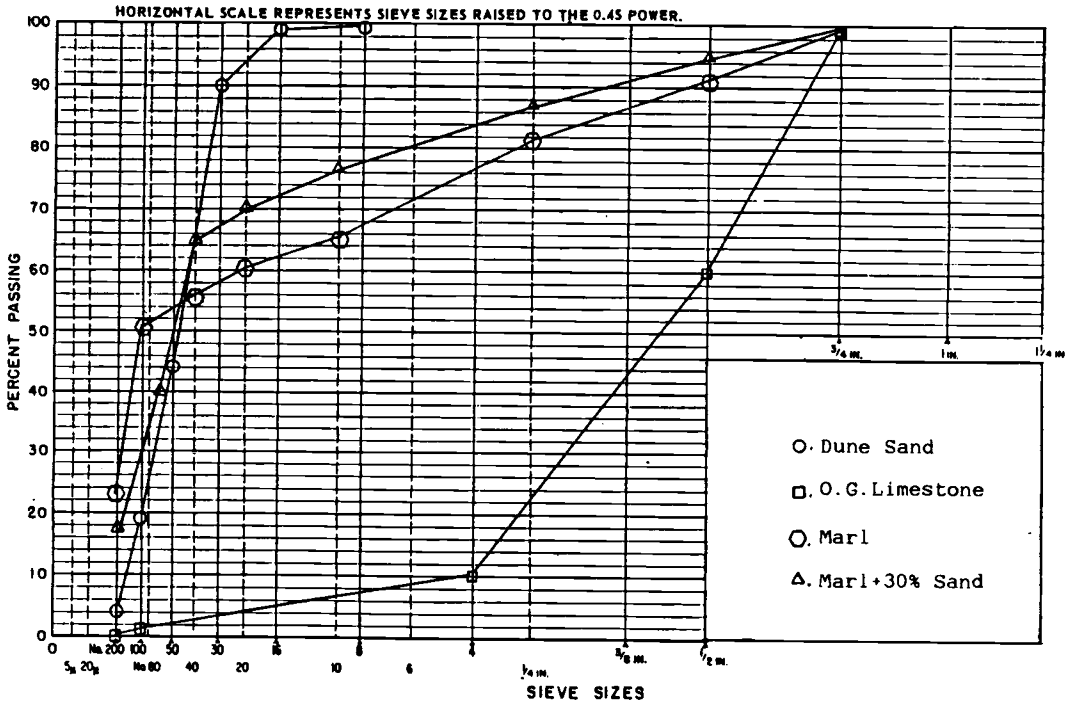


Figure 4.4. Gradation for aggregates evaluated (AASHTO T-27, ASTM C-136).

separated according to size and stored in plastic bags for later use.

4.2 Emulsified Asphalts

Three types of emulsified asphalts were used in this study: 1) locally produced CSS-1h; 2) CSS-1h from Chevron, U.S.A.; and 3) CMS-2h. CMS-2h, which is not locally available, was prepared in the lab for use with the open-graded limestone aggregate (refer to Table A-8). Results of tests are given in Table 4.2 and compared to ASTM Specification D-2397, Table 4.3. Test results indicated that emulsified asphalts were within specification limits. The significance of these tests is discussed below.

4.2.1 Viscosity Test

The viscosity of emulsified asphalt should be low enough to enable easy handling (pumping, spraying, mixing, etc.). If the viscosity is too high, spray-nozzles may clog, giving uneven distribution of the binder. The emulsion may also have difficulties in penetrating dust layers and wetting the stone surfaces. It will also resist mixing with aggregate, reducing workability of the mix.

Results from Table 4.2 indicate that all viscosities were in the ASTM limits.

4.2.2 Storage Stability Test

This test provides an indication of the stability of

Table 4.2. Emulsified Asphalts Test Results.

Property	CMS-2h	CSS-1h	
		Saudi	Chevron
Viscosity			
50°C	53		
25°C		32	30
Storage Stability %	1.2	2.0	1.6
Coating (%):			
Dry aggregate	95		
After spraying	90		
Wet aggregate	100		
After spraying	60		
Sieve Test %	0.1	0.1	0.1
Residue %	66.3	58.7	60.5
Cement Mixing Test %	--	0.8	0.5

Table 4.3. ASTM D2397 Specifications for Emulsified Asphalts (74).

Property	CMS-2h	CSS-1h
Viscosity (sybolt Furol)		
25°C		20-100 sec
50°C	50-400 sec	
Storage stability	max 1%	max 1%
Coating ability		
Dry aggregate	good (>95%)	
After spraying	fair (>50%)	
Wet aggregate	fair (>50%)	
After spraying	fair (>50%)	
Sieve Test	max 0.1%	max 0.1%
Residue	min 65%	min 57%
Cement Mixing Test %	--	max 2%

an emulsified asphalt during storage. Bitumen particles either will slowly sink to the bottom of the sample (or rise) due to gravity or the difference in density between the bitumen and the aqueous phase.

The degree of settlement is measured as the difference in bitumen content at the top and bottom of a sample which has been left standing for 24 hours. It is also important to determine if the bitumen drops can be redispersed after they have settled, to see if the emulsion has the capability to be remixed if settlement happened during storage.

This test did not pass as the residue percentage was 1.2-2.0 as against the specified value of 1% max. This is not a problem if emulsified asphalt is not stored for a long time.

4.2.3 Sieve Test

In this test, the amount of larger particles is measured. It is important that the emulsified asphalt does not contain such particles as they reduce the stability and may result in problems such as clogging of spray nozzles. Usually a No. 20 (850 m) sieve is used. All test results met this test limit which is 0.1% max.

4.2.4 Residue by Evaporation Test

This property is used when the amount of asphalt is to be measured. The result of these tests indicated that values are within specification limits.

4.2.5 Coating Ability and Water Resistance Test

This test is used for open-graded mixes where the emulsion is mixed with an aggregate and the area covered with binder is estimated before and after spraying with water. For this test, a limestone aggregate from Dhahran area was used. The results indicated good coating ability with CMS-2h.

4.2.6 Particle Size Distribution Test

Three samples, CMS-2h and CSS-1h (Saudi and Chevron U.S.A.) were tested for particle distribution using Coulter Counter, which gives both particles frequency distribution and cumulative frequency distribution. The results, which are shown in Figs. 4.5, 4.6 and 4.7, indicate that all emulsified asphalts have a mean particle size of about 6.5 micrometer. The minimum particle size is 1.5 micrometer and maximum particle size is 15 micrometer. These results indicate a good particle distribution since most emulsions normally have a mean particle size of 2 to 8 micrometer [41].

4.3 Emulsified Asphalt Mix Design

The purpose of the mix design test is to determine the optimum emulsified asphalt and added water contents for a compacted mix. Two types of mix design procedures were used:

1. FHWA method for open-graded mixes [55], and
2. Illinois method for dune sand and marl mixes [56]

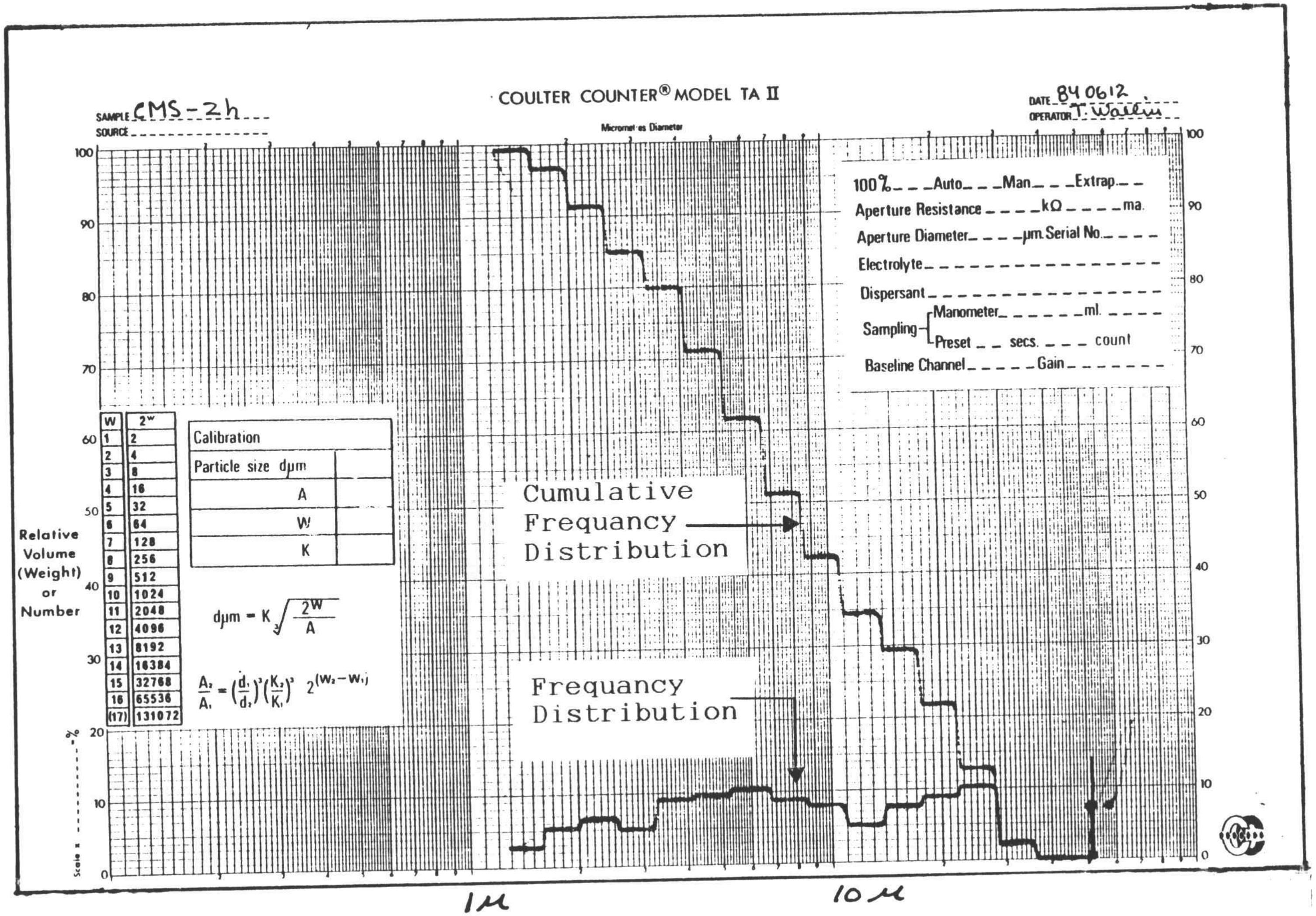


Figure 4.5.CMS-2h emulsified asphalt size distribution.

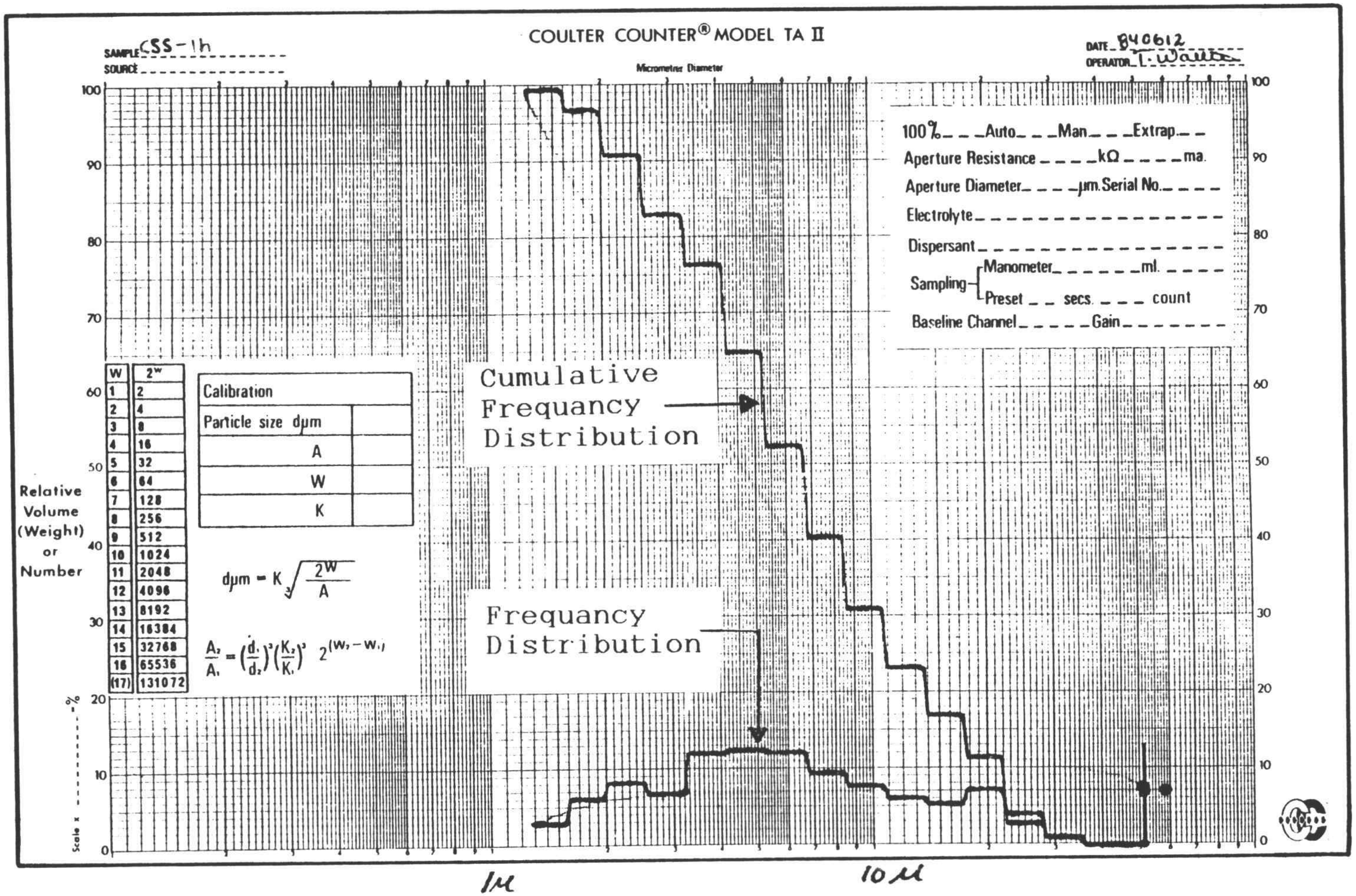


Figure 4.6 CSS-1h emulsified asphalt size distribution(Saudi).

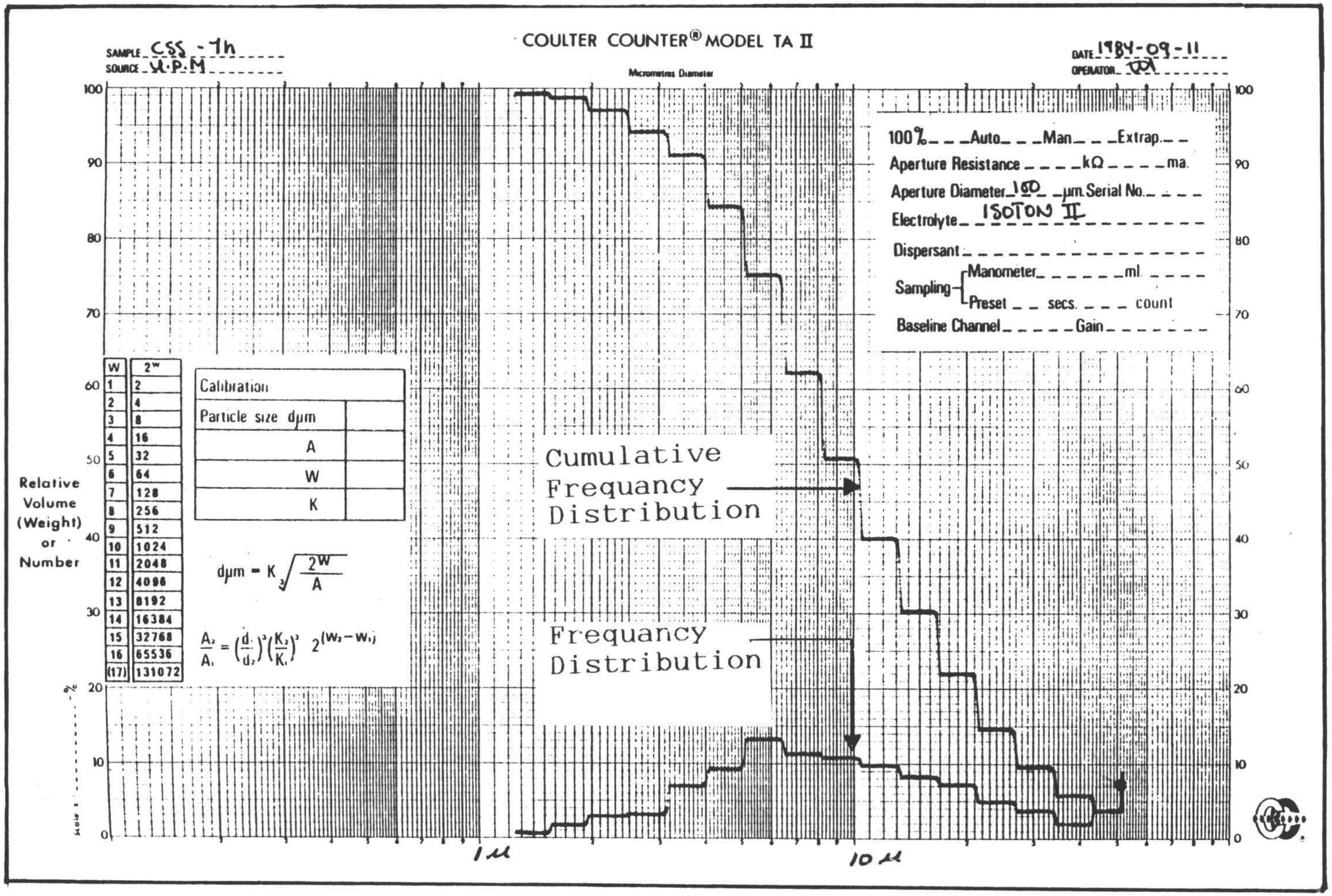


Figure 4.7. CSS-1h emulsified asphalt size distribution(Chevron USA).

4.3.1 Open-Graded Emulsion Mix Design

The design method used for open-graded emulsion mixes was developed by the Federal Highway Administration [55]. To determine the starting emulsified asphalt content, the oil ratio (Kc) for the aggregate was determined from the CKE test and found to be 2.7. The starting emulsion content is given by (Kc x 1.5) + 3.5 or 7.5%. Samples of 500 gm were recombined to meet the recommended gradation and mixed with different amounts of emulsified asphalt. Trials included 6% emulsion by weight of aggregate which was raised in increments of 1% up to 12% (Fig. 4.8). Water was added at ratios of 0, 1 and 2% to each emulsion content. Mix properties evaluated visually included:

1. Percentage of coated aggregate
2. Asphalt film thickness (thin, moderate, heavy)
3. Workability, and
4. Percentage of excess fluids

Mixture workability was determined in the first 30 to 45 seconds of mixing. Workable mixes should not be stiff before 30 to 45 seconds of mixing. An acceptable mix should have little or no excess fluids, have moderate to thick coating and more than 90% of aggregate coated (Table 4.4).

Trials indicated that addition of water considerably affects fluidity and therefore reduces film thickness.

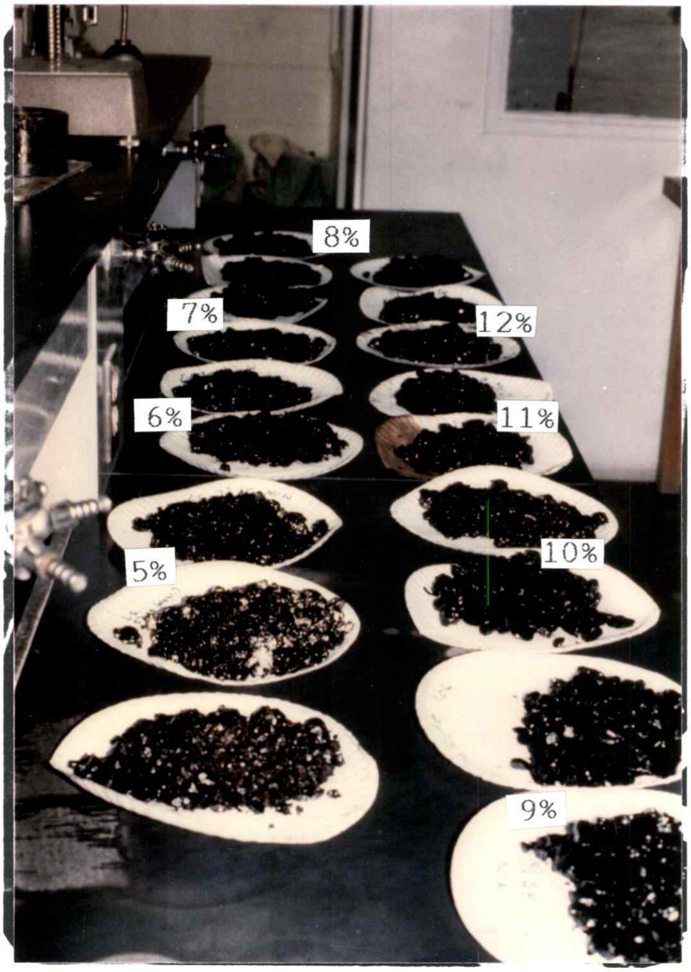


Figure 4.8. Open graded asphalt emulsion mix trials showing different emulsion contents (water content varied from 0-2%).

Table 4.4. Open Graded Emulsion Mix Design Results

Emulsion Content %	Water Content %	% of Coated Agg.	Film Thickenss	Worka-bility	Excess Fluids
6	0	60	med-thick	poor	none
	1	90	medium	fair	none
	2	100	thin	fair	none
7	0	80	med-thick	fair	none
	1	95	medium	fair/ good	none
	2	100	thin	good	slight
8	0	95	thick	good	none
	1	100	med-thick	good	slight
	2	100	thin	good	considerable
9	0	100	thick	good	slight
	1	100	med-thick	good	considerable
	2	100	medium	good	excessive
10	0	100	thick	good	considerable
	1	100	med-thick	good	excessive
11	0	100	thick	good	considerable
12	0	100	thick	good	excessive

Therefore water addition was stopped and emulsion trials were carried out using only CMS-2h emulsion. The optimum asphalt emulsion was found to be 9.0% (high absorption). The asphalt film thickness was calculated using the formula [55],

$$\text{Film thickness in microns} = \frac{48.7 * \text{effective asphalt (in \%)}}{\text{surface area (from CKE)}}$$

At the optimum asphalt content of 9%, the film thickness was approximately 26 microns (surface area = 10.96 ft^2).

Several specimens were also prepared for diametral modulus (ASTMD 4123) using a Marshall compactor (Fig. 4.9). The open-graded mix was placed in the mold using two lifts, each receiving 20 rod tamps in the center and edge using a bullet nosed steel rod. The mix was then covered with a 4 in (10 cm) diameter and 0.2 in (0.5 cm) thick, rubber cover to minimize degradation during compaction. Each specimen was compacted using 75 blows on each side.

Specimens were cured for 48 hours in the mold at 100°F (278.8°C) [56] and for 24 hours in a vacuum desicator cabinet (at 25 in Hg) to reduce curing time (Fig. 4.10). Specimens were then extracted and the specific gravity determined. Each sample was then confined using a rubber membrane prior to testing.

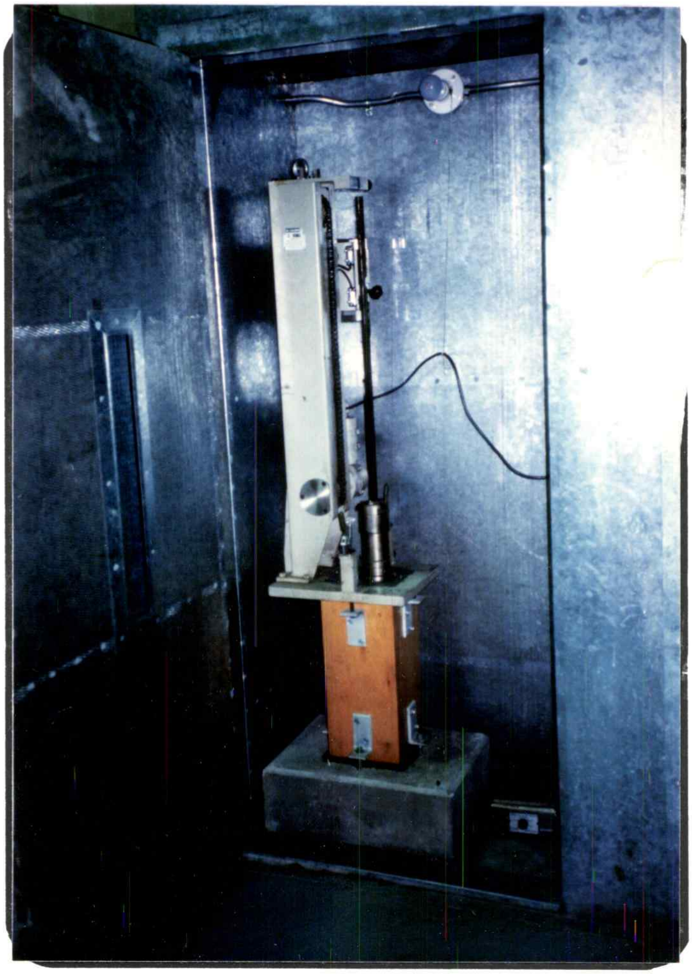


Figure 4.9. Marshall compaction hammer used to prepare emulsion treated mixes.

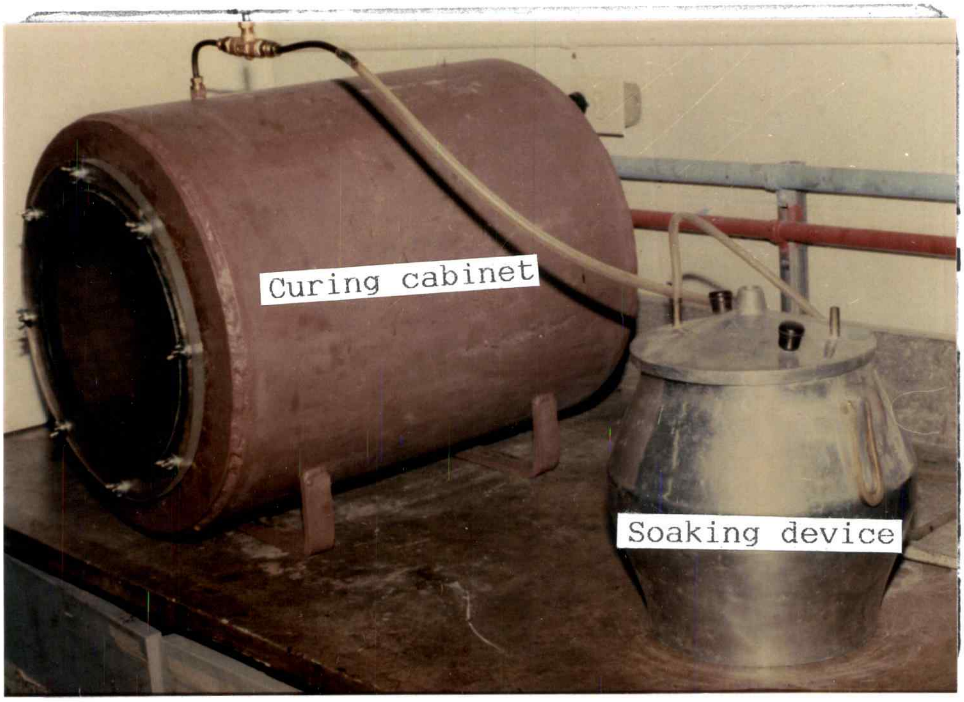


Figure 4.10. Vacuum curing cabinet and soaking device.

Figure 4.11. Effect of mixing time on dune sand emulsion.

4.3.2 Dune Sand Emulsion Mix Design

The Modified Illinois Method [56] was used to determine the optimum emulsion content for the dune sand. To determine the starting emulsion content, the C.K.E. value of the aggregate was measured and the trial emulsion content determined to be 6.0 (based on the Hueem method of design). Thus mix trials were made for different emulsion ranges (6% and 14% of dry sand weight). Water added was varied between 1% and 5% (Table 4.5). Portland cement was added for early curing (2% and 5% were used). Materials were added in the following order: water, cement and then emulsion. Mixing time was limited to 30 seconds to avoid stripping problems which were observed for mixing time of 60 seconds and more (Fig. 4.11). Stripping problems could be eliminated by increasing distillate (naphtha) in the emulsified asphalt to 10-15% [34]. Increasing distillate results in the modification of the asphalt phase cohesion (i.e. cohesion development delayed). This provides a chance for fine sand particles coating without strong cohesion forces which will counteract adhesion and result in stripping of asphalt film. Dune sand emulsion mix was then compacted using the Marshall compactor; 75 blows were applied to each side. Five specimens for each emulsified asphalt content and water content were compacted.

All specimens were cured for 12 hours in the mold at 100°F (37.8°C), extracted and cured for another 36

Table 4.5. Mix Design Results for Dune Sand

Emulsion Content %	Water Content %	Workability	% Coating	Excess Fluids
6	1	poor	50	none
	3	fair	70	none
	5	fair-good	80	none
8	1	fair	80	none
	3	good	95	none
	5	good	100	slight-none
10	1	good	100	slight-none
	2	good	100	slight
	3	good	100	slight/ considerable
	4	good	100	considerable
	5	good-fair	100	considerable
12	1	good	100	slight/ considerable
	3	good	100	considerable
	5	fair-good	100	considerable
14	1	good	100	considerable
	3	fair	100	considerable
	5	fair	100	considerable

hours at 100°F [56]. Specimens were then cured for 24 hours in a vacuum desicator cabinet (at 25 in Hg) to reduce curing time [77]. This curing procedure was found to reduce water content to about 0.05%.

Since dune sand is composed of silicon (negatively charged), cationic emulsified asphalt was selected for its treatment. Both slow and medium setting (CSS-1h, CMS-2h) emulsified asphalts were tried. When CMS-2h was used for dune sand treatment, higher stability was obtained than that for CSS-1h (due to thicker coatings). Therefore, CMS-2h was used for dune sand stabilization.

Three specimens were tested for Marshall stability after specific gravity determination. Another two specimens were tested for Marshall stability after vacuum soaking (Fig. 4.10). These samples were vacuum saturated for an hour under 100 mm of Hg (3.95 in) vacuum, after which the vacuum was slowly released, and the specimen allowed to soak in water for one hour. The specific gravity was determined, and the amount of absorbed water was recorded. The specimens were then tested for stability, and the loss in stability recorded.

<u>Tests and results</u>: Volume relations were calculated for the compacted mix using the procedures given in Table 4.6. Final results are shown in Figs. 4.12 to 4.17. The criteria shown in Table 4.7 were used to determine the optimum mix as follows:

Table 4.6. Volumes Calculation Formulas (56).

1) $V_a = 100 - (V_b + V_{ag})$

2) $V_b = \frac{W_b}{S \cdot G_b} * \frac{100}{V_m}$

3) $V_{ag} = \frac{W_{ag \cdot}}{S \cdot G_{ag}} * \frac{100}{V_m}$

4) $V_m = \frac{W_m}{S \cdot G_m}$

5) $W_b = \frac{W_e R_e}{100}$

where,

V_a = volume of air (% of total mix)

V_b = volume of asphalt in mix (% of total mix)

V_{ag} = volume of aggregate (by apparent specific gravity, % of total mix)

V_m = bulk volume of compacted mix

W_b = weight of asphalt

$S \cdot G_b$ = specific gravity of asphalt

W_a = weight of dry aggregate

W_m = weight of dry compacted mix

$S \cdot G_m$ = bulk specific gravity of dry compacted mix

$S \cdot G_{ag}$ = aggregate apparent specific gravity

W_e = weight of emulsion

R_e = % residue of emulsified asphalt, as a whole number

Table 4.7. University of Illinois Method Design Criteria (56).

Property	Min	Max
Stability, lb at 72°C paving mixtures	500	-
Total voids, % compacted mix (not required for sand mix)	2	8
Stability loss, % after 4 days soaking* at 72°C	-	50
Absorbed water, % after 4 days soaking* at 72°C	-	4
Aggregate coating, %	50	-

*Modified to one hour vacuum saturation followed by one hour immersion by Puzinauskas & Jester (56).

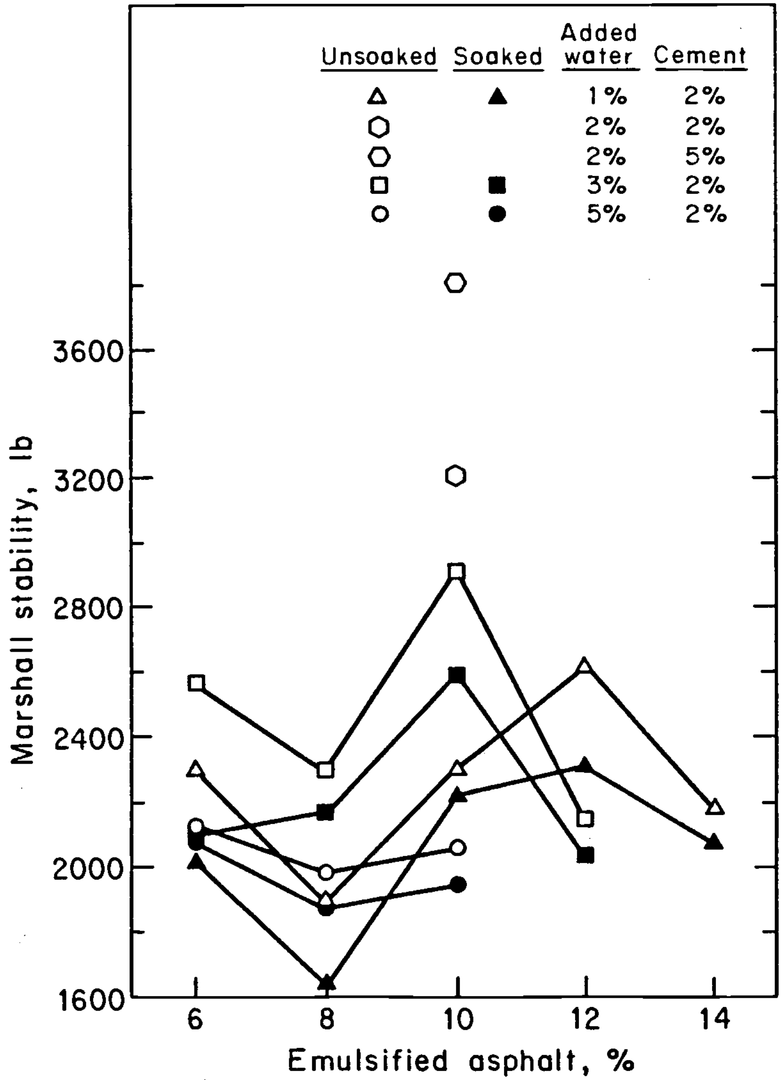


Figure 4.12. Effect of emulsified asphalt and added water on stability of dune sand emulsion mix.

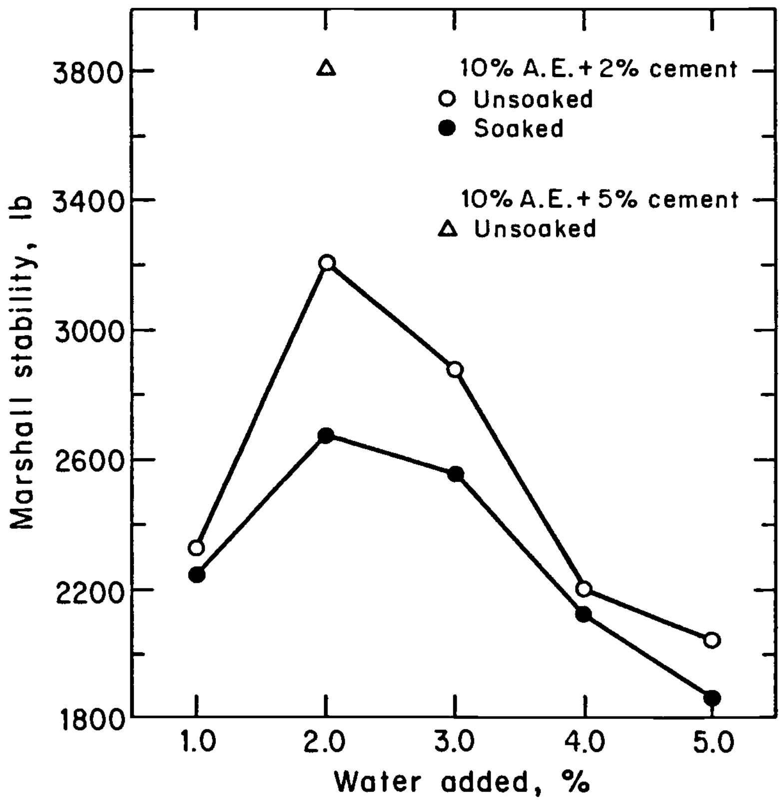


Figure 4.13. Relation between added water and Marshall stability of dune sand emulsion.

1) <u>From Fig. 4.12</u>; With increasing water content, stability tended to increase up to 3% water then it tended to decrease. The same trend was true for stability loss (Fig. 4.13). Peak stability was reached at 10% emulsion with 3% water added. At this point, soaked stability also peaked.

2) <u>From Fig. 4.13</u>; At 10% emulsion, stability (dry and soaked) peaked at 2% added water content (optimum coating). Further water content increases tended to reduce film thickness.

3) <u>From Fig. 4.14</u>; Stability loss seems to be negligible for dune sand. For example, maximum stability loss is 80% at 5% added water and 6% emulsified asphalt. Lowest stability loss occurred at 10% emulsified asphalt and 1% added water. Stability loss tends to decrease by increasing asphalt emulsion content.

4) <u>Figs. 4.15, 4.16, 4.17</u>; Dry density increases with increasing asphalt content while total voids and water absorption decrease by increasing asphalt content.

All above results indicated that maximum stability, lowest stability loss, and reasonable density and water absorption are observed at 10% emulsified asphalt and 2% water added. Therefore, these values were used.

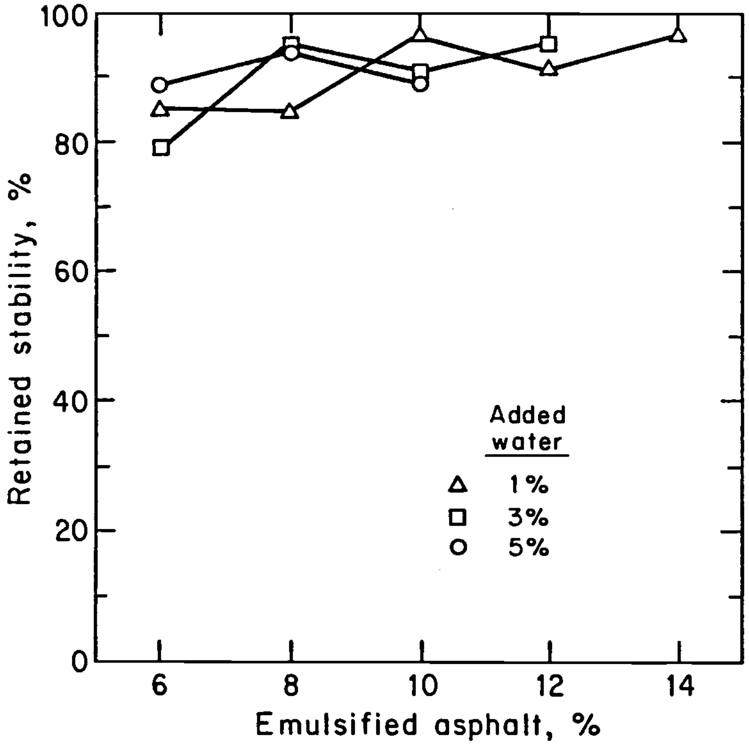


Figure 4.14. Relation between emulsified asphalt content and retained stability for dune sand emulsion+2% cement.

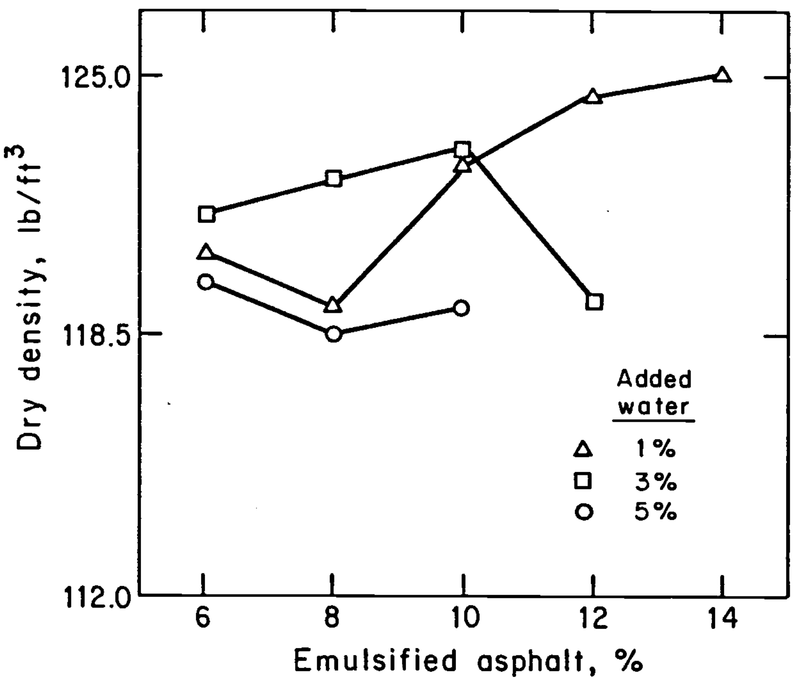


Figure 4.15. Relation between emulsified asphalt and dry density of dune sand emulsion+2% cement.

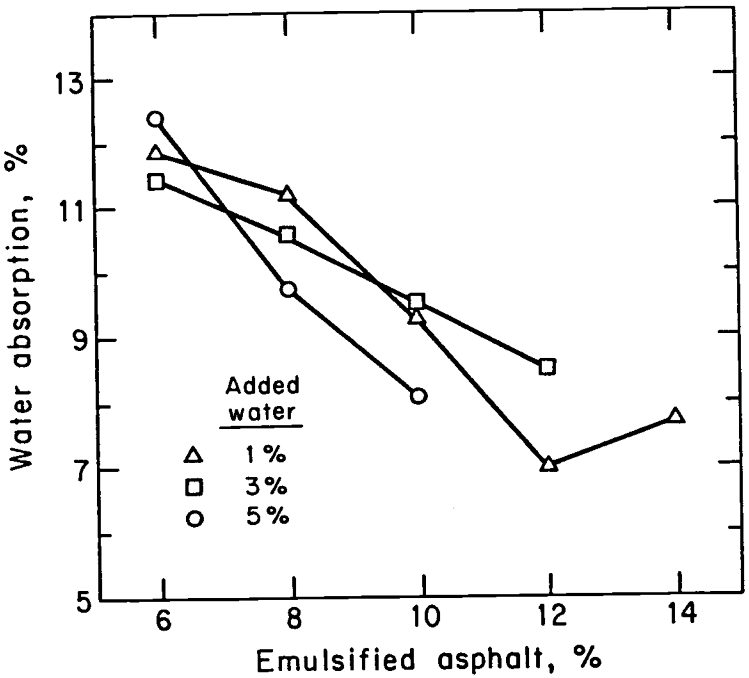


Figure 4.16. Effect of emulsified asphalt content on water absorption of dune sand emulsion+2% cement.

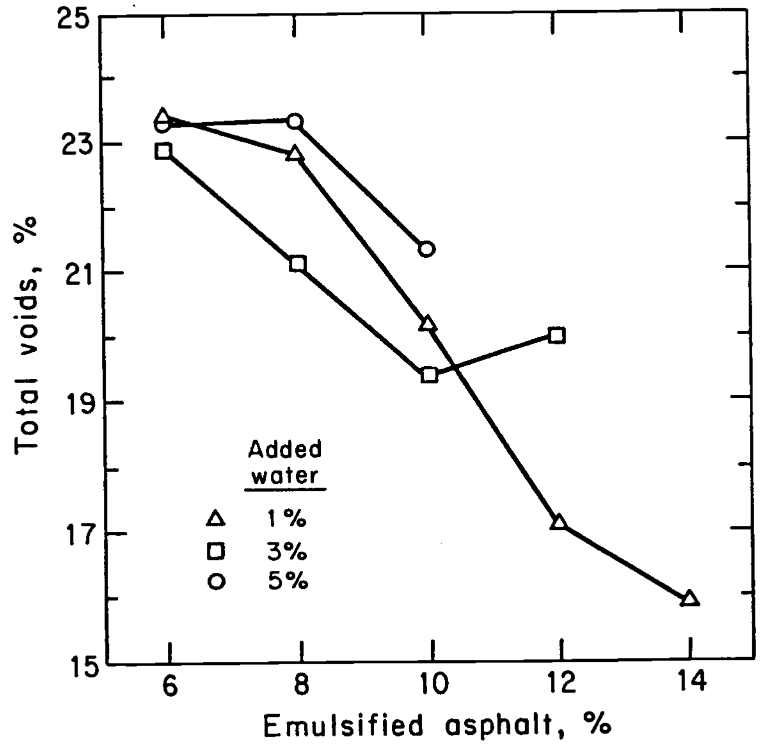


Figure 4.17. Effect of emulsified asphalt content on the total voids of dune sand emulsion.

4.3.3 Marl Emulsified Asphalt Mix Design

Marl is a common name for a wide variety of soils which includes carbonate sands, limestone silt, and silty sands. Marl used in this experiment is a siliceous carbonate sand (mixed charge). Therefore, cationic emulsified asphalt was selected for its treatment due to its ability to work with a wider type of aggregates than the anionic type. A locally produced CSS-1h was used for marl treatment.

A similar procedure to that used for the dune sand mix design was used here; however, the marl was initially mixed with sand to modify its mixing properties. This was because marl alone tended to form muddy lumps which prevent uniform mixing when water or emulsion is added due to its fine gradation. Various amounts of marl were mixed with sand (Fig. 4.18) at different percentages to evaluate its effect on marl-emulsion mix workability and stability. A decision was made to mix marl with 30% dune sand which provided reasonable workability without much loss of stability.

Premixing water was omitted in the marl case because adding water directly to the marl tended to form lumps which are difficult to coat. Adding water to emulsified asphalt first and then adding this mixture to marl resulted in better coating and higher stability.

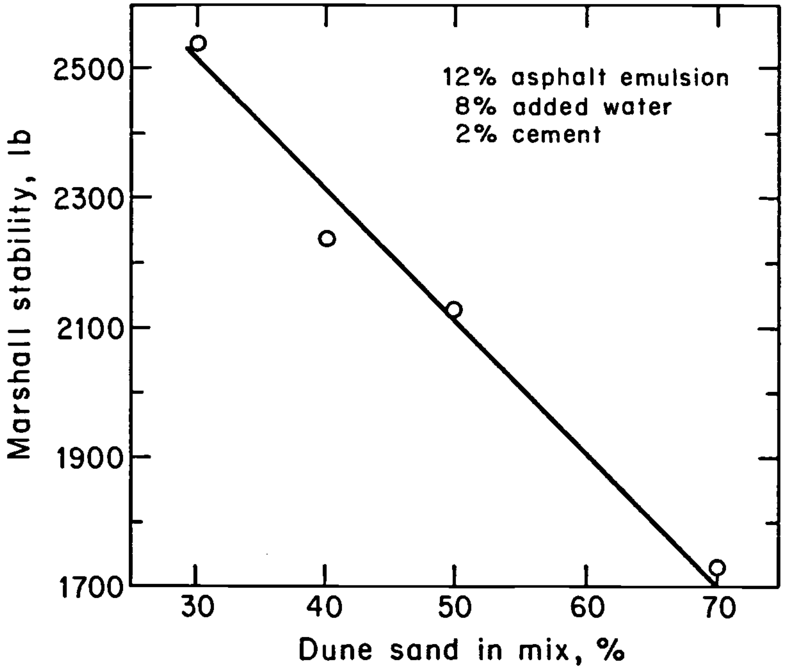


Figure 4.18. Effect of dune sand on the stability of dune sand-marl emulsion mix.

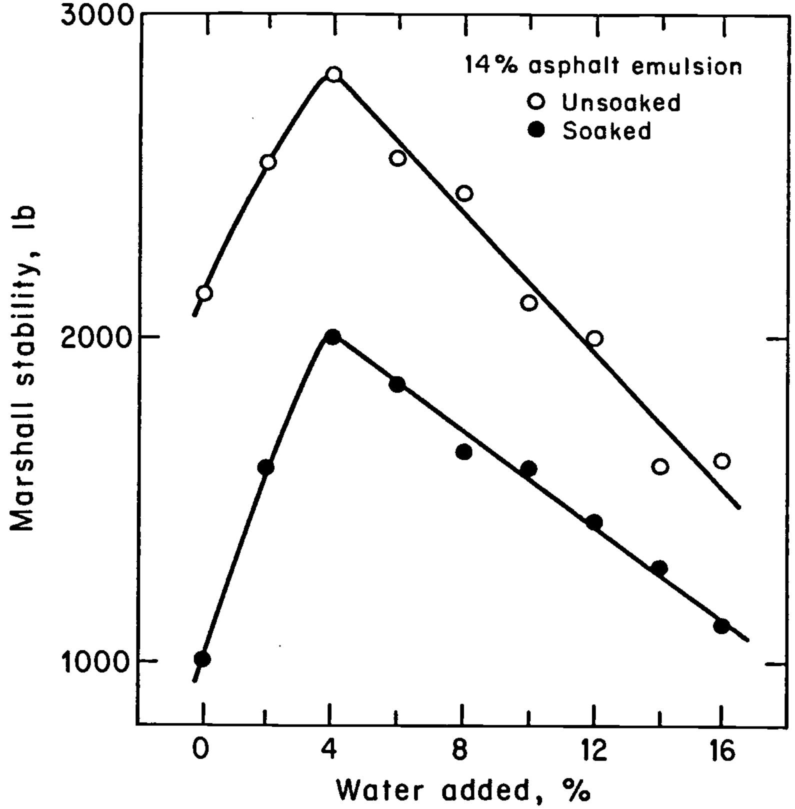


Figure 4.19. Effect of water added on the stability of marl emulsion mixture.

Therefore, 2% portland cement was mixed with marl (for early curing) and then water-emulsion added to the mix.

Tests and results: To determine the starting trial values, the CKE test was used to determine the surface capacity of fine and coarse aggregates (Table 4.1). This test indicated the initial oil ratio to be 10. Trial emulsion contents are obtained by multiplying oil ratio by 1.1, 1.4 and 1.7.

A starting emulsion trial of 14% emulsified asphalt (10% residual asphalt) was considered. The first step is to determine the optimum added water content. This was determined by preparing several specimens at different water contents but having the same emulsion asphalt content (14%). These tests (Fig. 4.19) indicated that a total water content of 10% is required for the optimum mix (4% added water + (14%)(1-0.59)).

Once the optimum water content was determined, the water content was held constant and residual asphalt content was varied between 3 and 12% as shown in Fig. 4.20. These results indicate that 8.25% residual asphalt content is optimum. Specimens were compacted using the Marshall compactor; 75 blows were applied to each side. Five specimens for each residual asphalt content were (3%-12%) were compacted.

Specimens were cured for 12 hours in the mold at 100°F (37.8°C); extracted and cured for another 36

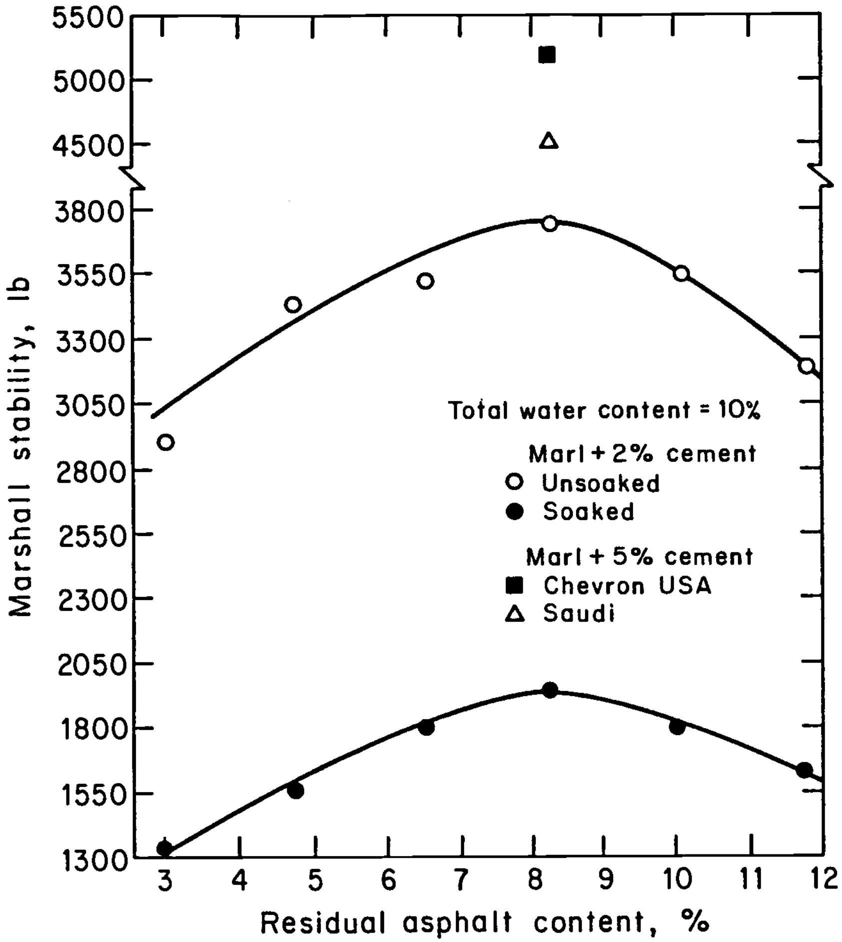


Figure 4.20. Effect of residual asphalt content on Marshall stability of marl emulsion mixture.

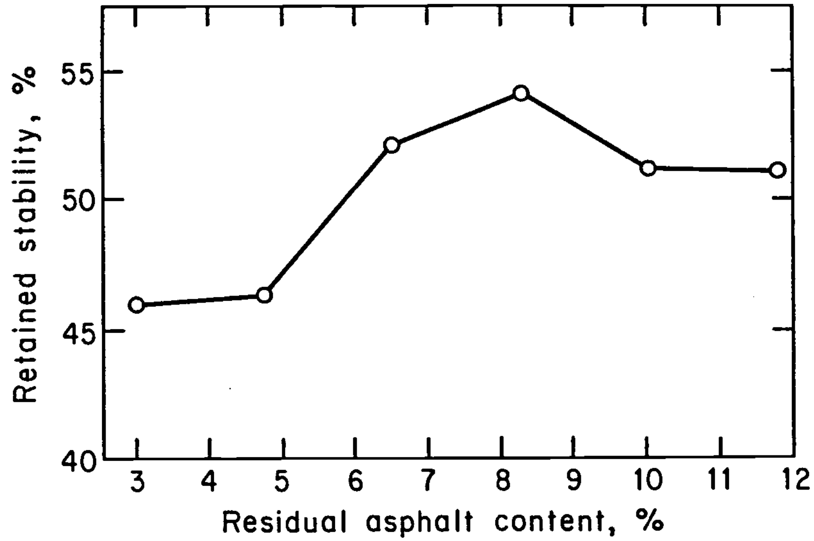


Figure 4.21. Effect of residual asphalt content on retained stability of marl+2% cement.

hours at 100°F [56]. Specimens were then cured for 24 hours in a vacuum desicator cabinet at 25 in Hg (63.5 cm).

At each residual asphalt content, three specimens were tested for Marshall stability after specific gravity determination. Another two specimens were vacuum saturated for an hour under 100 mm of Hg; the vacuum was slowly released and the specimens allowed to soak in water for one hour. The specific gravity was then determined and the amount of absorbed water recorded. Specimens were then tested for stability, and the loss in stability recorded.

Optimum emulsified asphalt content was determined as follows:

1) Fig. 4.19 indicates that at 14% emulsion, stability increases by increasing added water content up to 4%; after that stability reduces by increasing water content.
2) Fig. 4.20 indicates that, at a constant water content, stability tends to increase by increasing residual emulsified asphalt content up to 8.25%, after which stabiity tends to decrease by increasing residual emulsion content. The trend is the same for vacuum saturated stability.
3) Fig. 4.21 shows that the maximum retained stability peaks at 8.25% residual asphalt emulsion content.

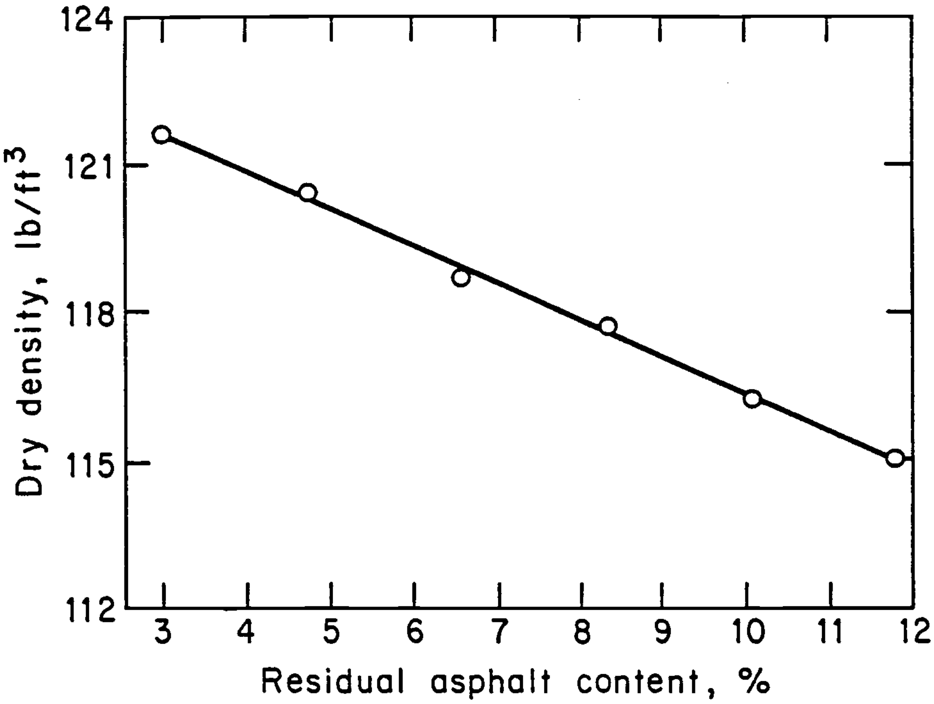


Figure 4.22. Effect of residual asphalt content on dry density of marl emulsion mixture.

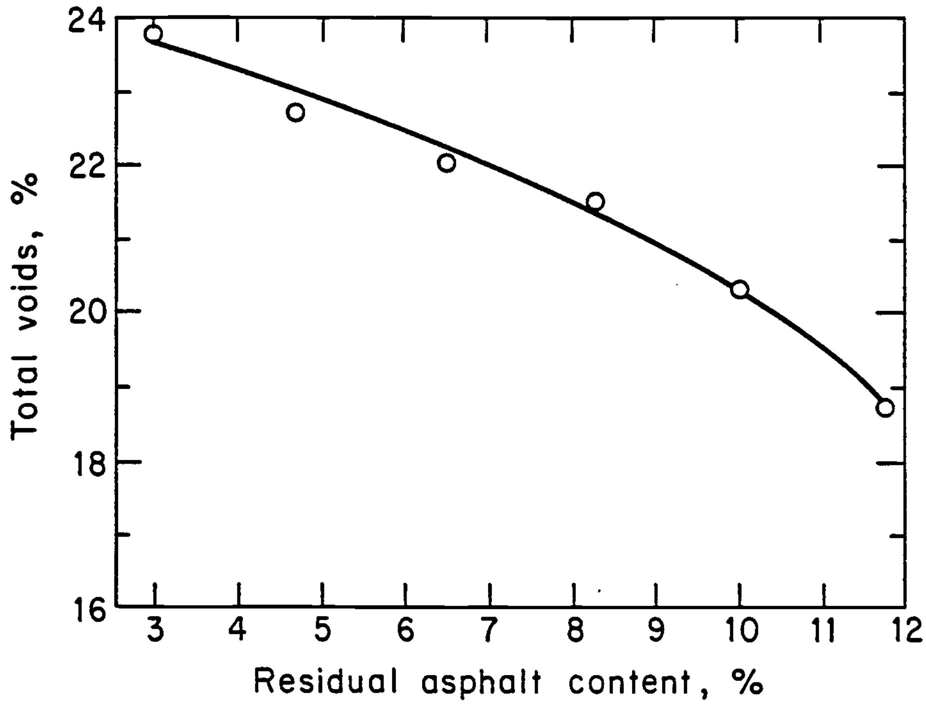


Figure 4.23. Effect of residual asphalt content on the total voids of marl emulsion mixture.

4) Figures 4.22, 4.23, 4.24 indicate that, as residual emulsified asphalt content increases, dry density decreases and total voids and absorption decrease.

The above results indicate the optimum emulsion content to be 14% (8.25 residue) with 4% water added at which stability is maximum, stability loss is minimum and water absorbed is minimum.

4.4 Summary

From the results of materials mix design, the values for emulsion and water contents shown in Table 4.8 are recommended for use with the aggregate for further testing. The six mixes will be evaluated using dynamic tests for modulus, fatigue and permanent deformation.

It should be mentioned that the optimum residual emulsified asphalt content for dune sand (6.5%) is lower than the optimum asphalt cement content required for dune sand asphalt mix (9%). Regular dense-graded limestone asphalt cement mix requires between 5% to 6.5% asphalt cement content, while for open-graded aggregate, the optimum emulsion content is 9% due to the absorption of aggregate (2.3%). The marl and dune sand mixes contain relatively high voids which means that the required asphalt content for marl should be relatively high

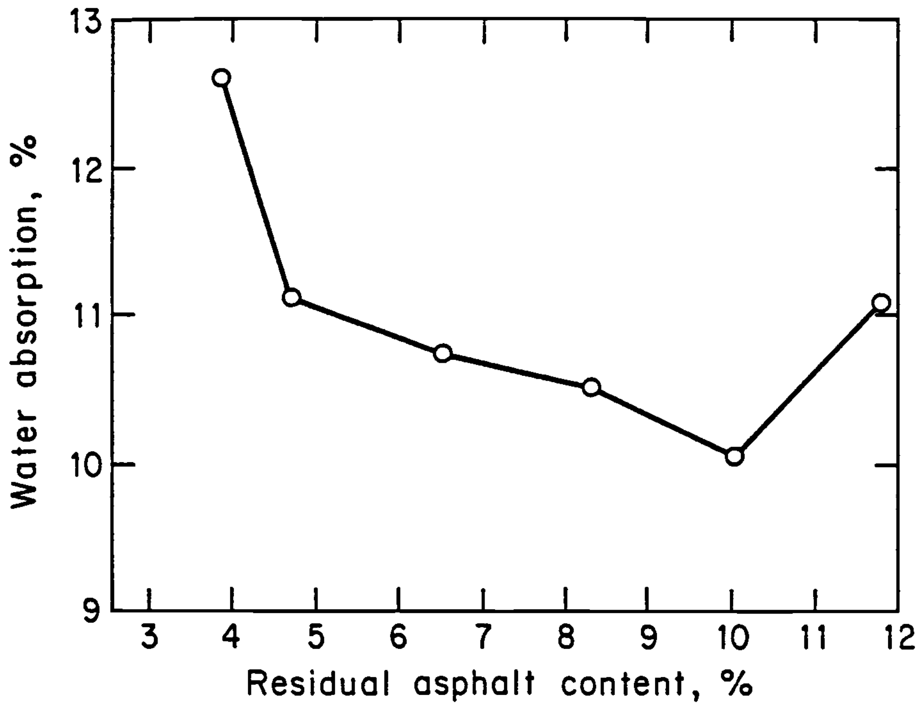


Figure 4.24. Effect of residual asphalt content on the absorption of marl emulsion mixture.

Table 4.8. Summary of Mix Design Results.

Material Type	Emulsion Type and Content %	Water Content %	Cement Content %	Mix Density lb/ft^3	Mix Voids %
Dune Sand	10% CMS-2h	2	2	123	18.5
	10% CMS-2h	2	5	128	17.7
Marl	14% CSS-1h	4	2	117.3	21.0
	14% CSS-1h]Saudi	4	5	120.4	20.0
	14% CSS-1h]Chevron USA	4	5	121.7	19.8
Limestone	9% CMS-2h	-	-	115.44	19.0

1 gm/cm^3 = 62.37 pcf

(8.5%), which is higher than that normally used for dense-graded mixes (5-6.5%).

5.0 DIAMETRAL TESTS ON STABILIZED MATERIALS

A series of dynamic tests was carried out to characterize the various mixes (shown in Table 4.8) and simulate their behavior under field conditions. The tests were carried out over a range of in-service temperatures and for different portland cement contents.

Tests included those to evaluate: 1) Poisson's ratio, 2) tensile strength, 3) dynamic modulus, 4) fatigue characteristics, and 5) permanent deformation characteristics. All tests were run using the diametral test method ASTM D-4123 [74]. The results of the tests are discussed in this chapter.

5.1 Poisson's Ratio Determination

Poisson's ratios for dune sand emulsion and marl emulsion mixes was determined using the equipment shown in Fig. 5.1. The INSTRON Machine (Model 1196), which has the capability of applying cyclic loading, was used to load specimens in a repeated split tensile test. The load is applied through a curved loading strip (1/2 in wide). Tests were conducted over a range of tensile strains at which it was possible to measure reasonable fatigue lives.

Both load and vertical resilient deformation were measured on the INSTRON graph recorder. Resilient

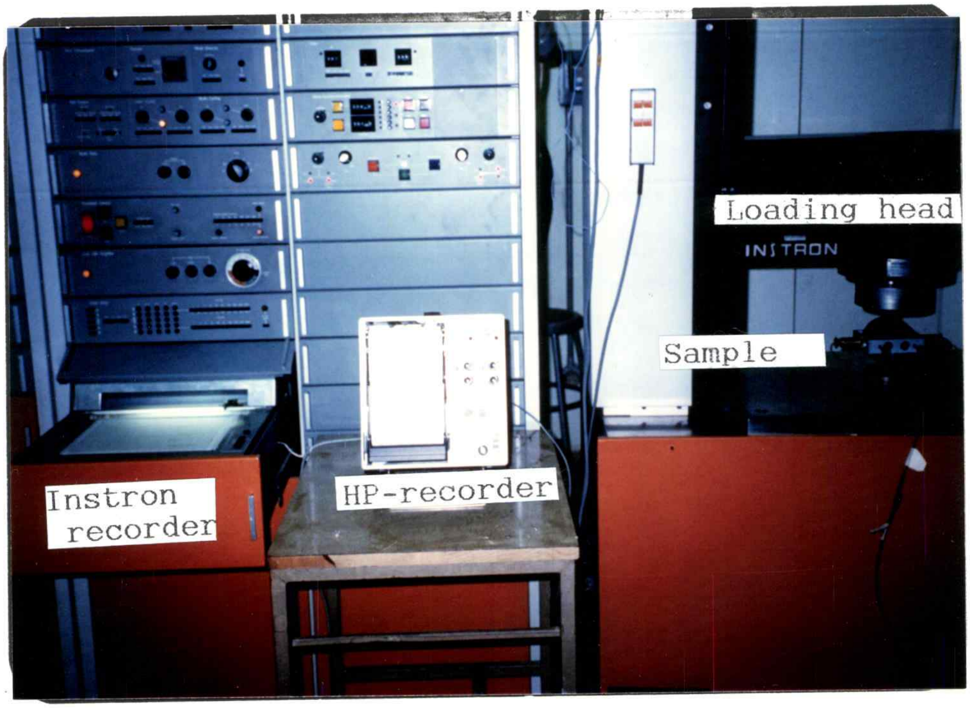


Figure 5.1. Procedure used to measure Poisson's ratio.

horizontal deformation was measured using two horizontal transducers attached to the specimen and was recorded using the HP Oscillographic Recorder (Model 7402A). Then an instantaneous resilient Poisson's ratio was calculated as follows [74]:

$$\mu = 3.59 \left(\frac{V_{RI}}{H_{RI}}\right) - 0.27 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5.1)$$

where, μ = Poisson's ratio

V_{RI} = Instantaneous resilient vertical deformation

H_{RI} = Instantaneous resilient horizontal deformation.

Results are given in Fig. 5.2 for dune sand emulsion and in Fig. 5.3 for marl emulsion. Poisson's ratio tends to increase with increasing tensile strains (or with increasing load). This finding is similar to that presented by Akili and Monismith [61], who found that Poisson's ratio for dune sand tends to vary between 0.25 and 0.37.

In addition, the amount of increase for dune sand (0.28 to 0.35) is lower than that for marl (0.24 to 0.38). Since specimens were tested at strain levels between 20 and 80 micro strains, Poisson's ratio at a tensile strain of 50 micro strains was selected for further calculations. Values of 0.33 and 0.34 were selected for dune sand emulsion and marl emulsion respectively.

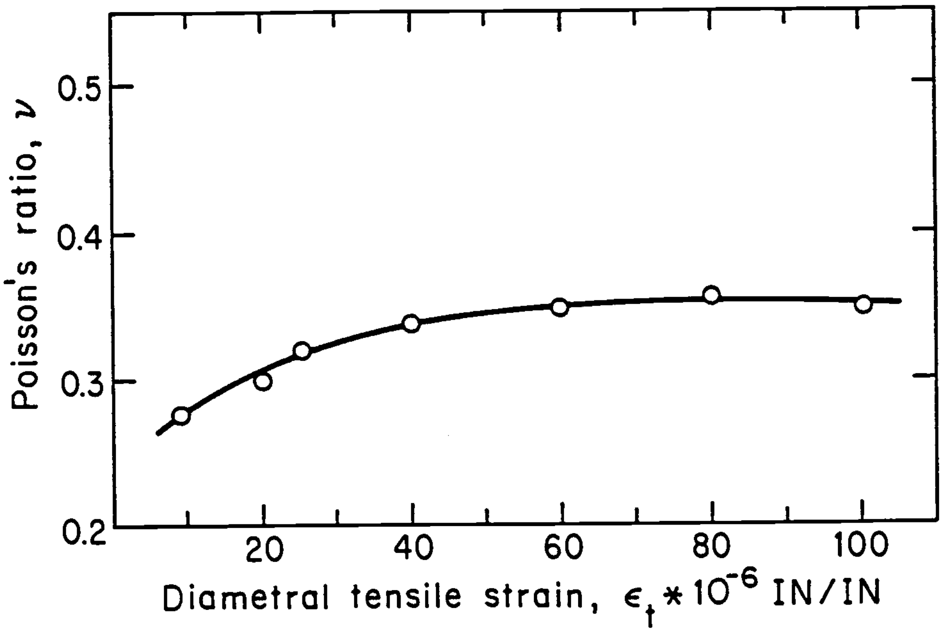


Figure 5.2. Relation between diametral tensile strain and Poisson's ratio for dune sand emulsion asphalt.

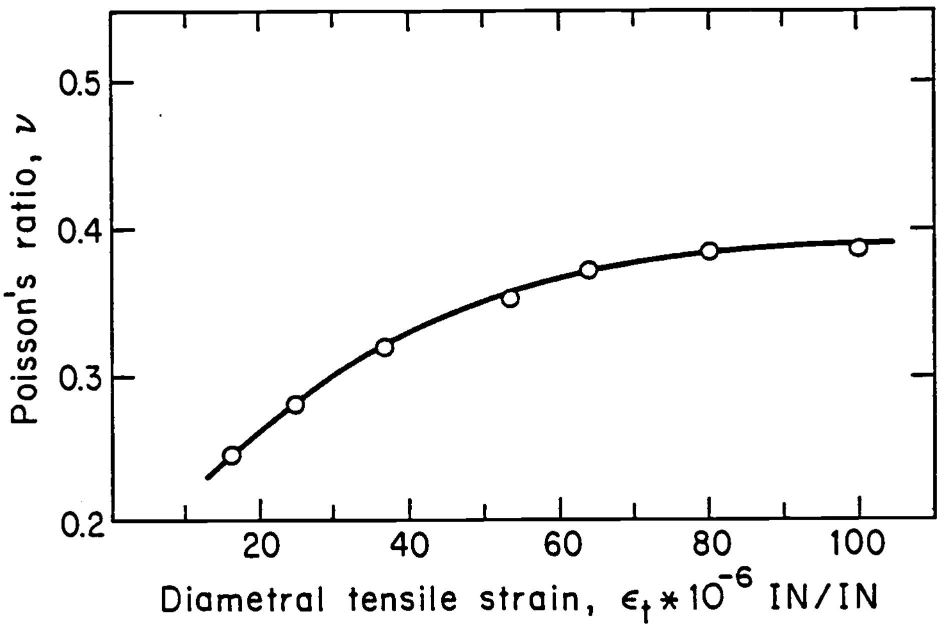


Figure 5.3. Relation between diametral tensile strain and Poisson's ratio for marl emulsion asphalt.

5.2 Tensile Strength

The indirect tensile test was used to measure tensile strength [74]. The load was applied through two curved loading strips across the vertical diameter of the specimen. The vertical load creates a tensile stress across the vertical diameter of the specimen. The load was applied at a constant deformation rate of 2 inches (51 mm) per minute using the INSTRON machine shown in Fig. 5.4. Continuous measurement of vertical load deformation was recorded with the x-y recorder on the INSTRON machine (Fig. 5.5). The indirect tensile strength was calculated from the following formula [60]:

$$S_T = \frac{2\ P_{max}}{\pi \times h \times D} \quad \ldots\ldots\ldots (5.2)$$

where:

S_T = Tensile strength, psi

P_{max} = Load at failure, lbs.

D = Diameter of sample (4 inches)

h = Sample height, inches.

All test specimens were prepared in the laboratory using the procedure discussed in Chapter 4. Samples were compacted using the Marshall compactor; 75 blows were applied to each side. Specimens were cured for 12 hours in the mold at 100°F (37.8°C), extracted and cured for

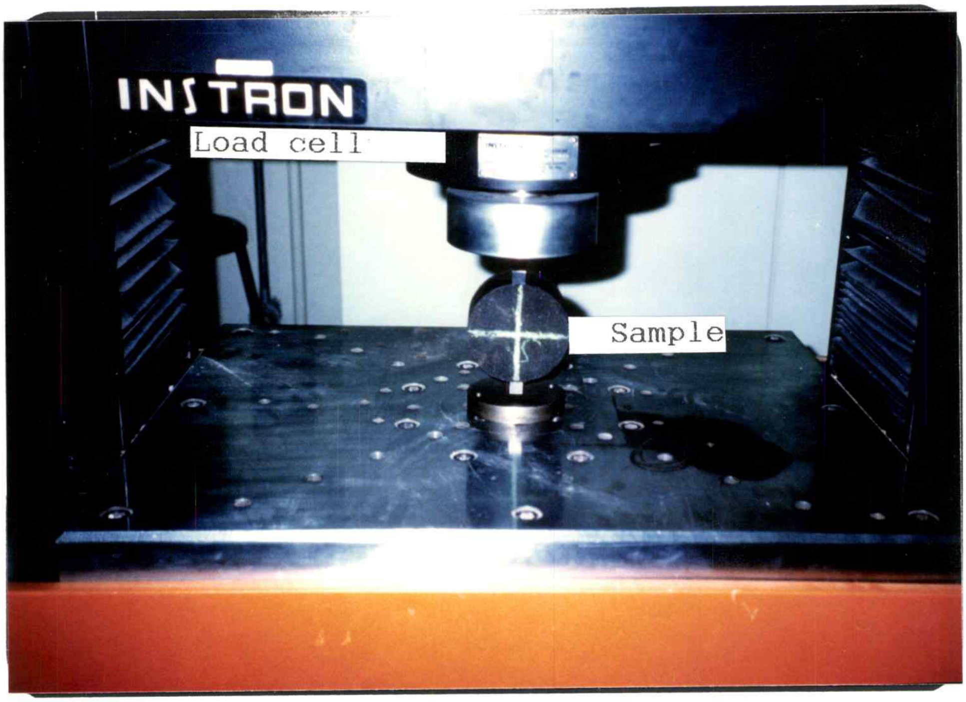


Figure 5.4. Test set up for determining tensile strength.

another 36 hours at 100°F (37.8°C) [56]. All specimens were cured for another 24 hours in vacuum desicator cabinet at 25 in Hg (63.5 cm) [77].

Split tensile strength was carried out over a range of temperatures to represent inservice temperatures at which it is possible to test materials successfuly, 10°, 25° and 40°C (50°, 77° and 104°F) for dune sand emulsion and 25°, 40° and 55°C (77°, 104° and 131°F) for marl emulsion. For each material, three specimens were tested at each temperature. Results of the tests shown in Fig. 5.6 indicated that dune sand emulsion tensile strength is highly susceptible to temperature variation while marl emulsion is not so susceptible to temperature changes. The figure also shows that increasing portland cement content from 2 to 5% considerably increases tensile strength.

5.3 Resilient Modulus Tests

Resilient modulus tests were used to test cured specimens at different temperatures and tensile strain levels. All specimens were prepared using the Marshall compactor. Seventy-five blows were applied to each side. A circular rubber sheet was used when compacting open-graded mixes to minimize degradation of limestone aggregate. All mixes were cured for 48 hours at 100°F (37.8°C) and 24 hours in the vacuum desicator cabinet at 25 in Hg (63.5 cm). Specimens were fabricated to have a

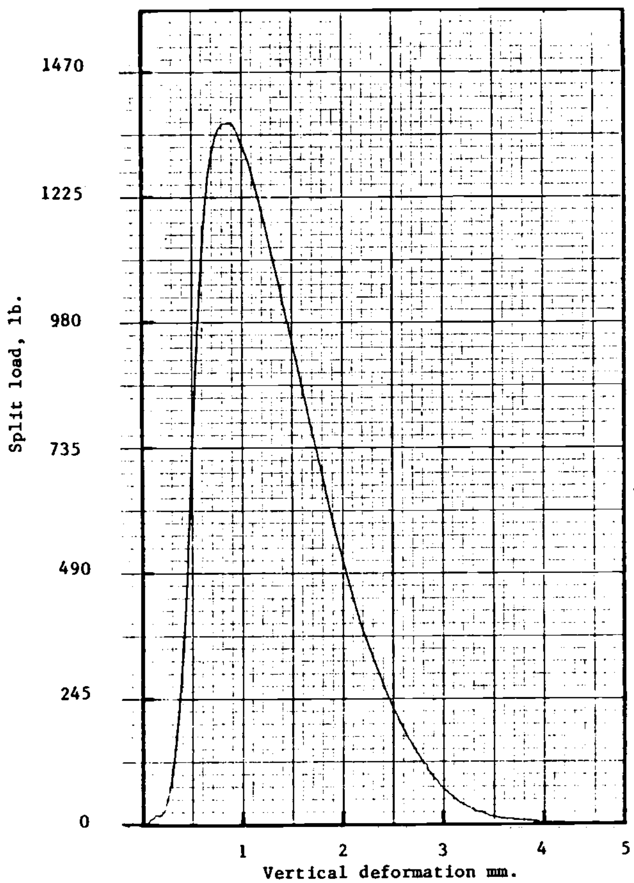


Figure 5.5. Example of split tensile test.

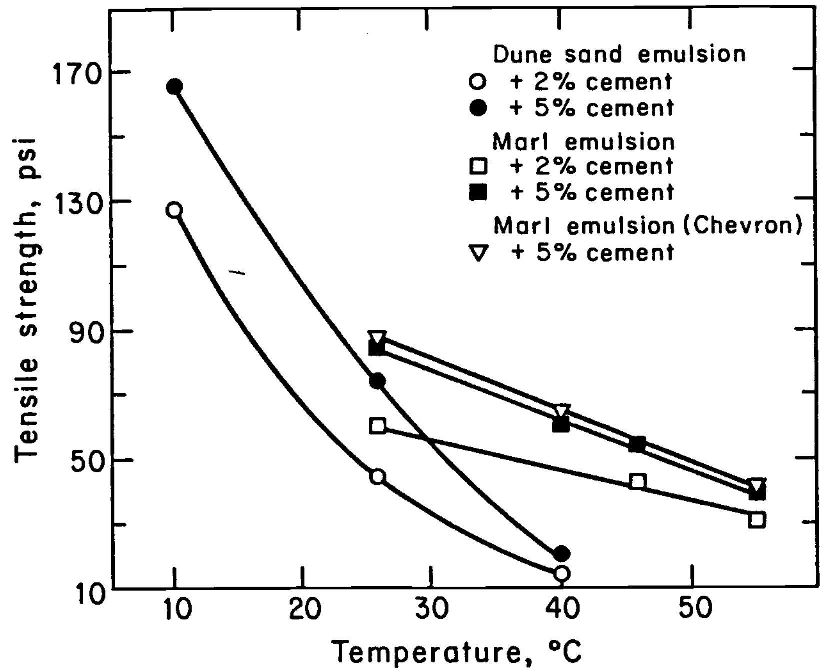


Figure 5.6. Effect of temperature on the tensile strength of emulsion treated materials.

diameter of 4 inches and a height of 2.5 inches. Three specimens were tested for each material at each temperature, portland cement content, and strain level (20, 40, 60, 80 and 100 microstrain).

The system used to test specimens was the repeated diametral test (ASTM D-4123). Horizontal deformation was measured with two transducers attached to the specimen (Fig. 5.7). Repeated loads were measured with a load cell below the specimen (Fig. 5.8). Loads and strains were recorded with a two channel oscillographic recorder (Fig. 5.9). A typical load/deformation trace is shown in Fig. 5.10.

The duration of pulse loading was 0.10 seconds which corresponds to a 30 mph actual tire speed. The load is applied at a frequency of 60 repetitions per minute. A seating load of about 10 lbs (4.55 kg) was used to hold the specimen in place. The resilient modulus was calculated using [66]:

$$M_R = \frac{P(\mu + 0.2734)}{t(\Delta h)} \quad \ldots\ldots\ldots (5.3)$$

where,

M_R = Resilient modulus, psi

P = Dynamic load, lb

μ = Poisson's ratio (0.33 for dune sand, 0.34 for marl emulsion, and 0.35 for open-graded emulsion mix)

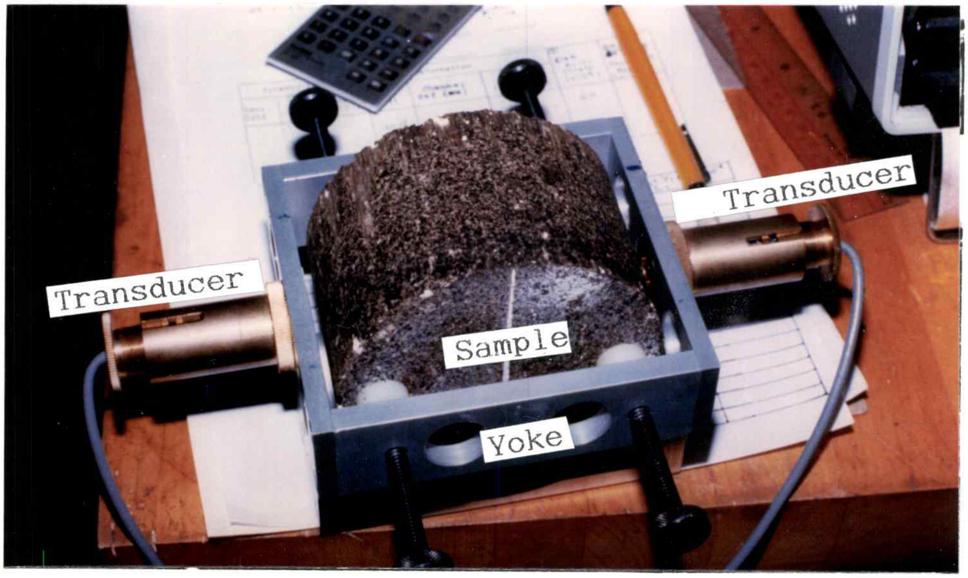


Figure 5.7. Diametral modulus yoke and holder

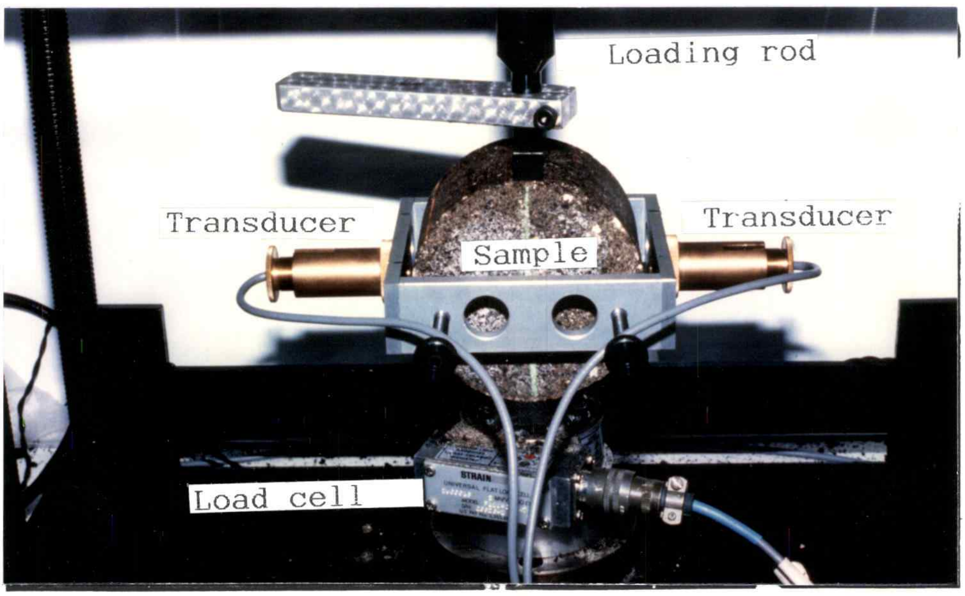


Figure 5.8. Set up for diametral modulus test (ASTM D4123).

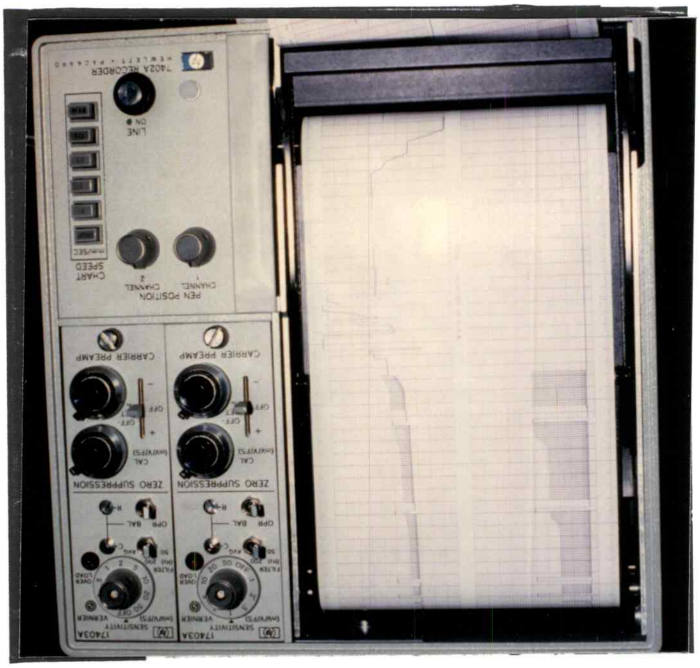
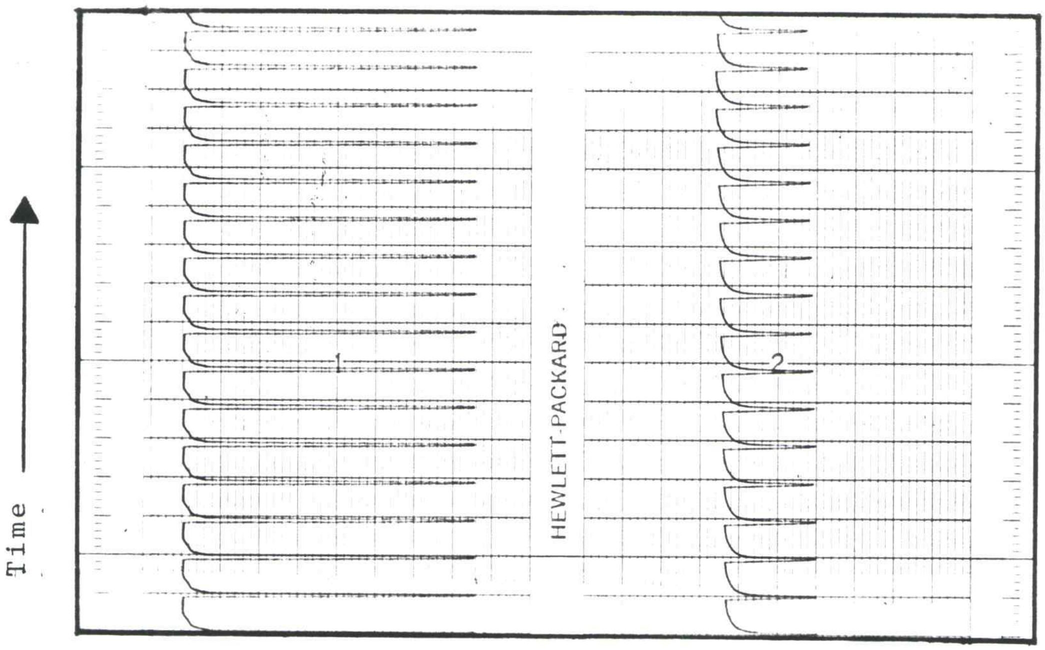


Figure 5.9. Two-channel Oscillographic recorder (Hewlett Packard model 7402A)



(a) Load (b) Deformation

Figure 5.10. Example of recorder output for diametral test.

t = Thickness of specimen, inches

Δh = Total elastic horizontal deformation, inches.

5.3.1 Testing Set-up

The system used to measure diametral modulus is shown in Fig. 5.11 [79]. The system consists of a control cabinet which regulates static and dynamic load magnitudes. Loading duration and frequency can also be controlled. A Shel-Lab low temperature incubator was used to control testing temperature. Specimen temperatures were measured using a thermister connected to a digital voltmeter. The thermister was attached to specimens with modeling clay (Fig. 5.12).

Specimens were subjected to a repeated load, and horizontal resilient deformations were measured as was described above. Deformations were measured after approximately 50-100 load applications where resilient deformation starts to stabilize.

5.3.2 Test Results

Modulus results are shown in Figs. 5.13 to 5.16. Sand and marl were tested at two portland cement levels (2 and 5%), three temperatures, 10°, 25° and 40°C (50°, 77° and 104°F) for open-graded emulsion and dune sand emulsion mixes and 25°, 40° and 55°C (77°, 104° and 131°F) for the marl emulsion mix.

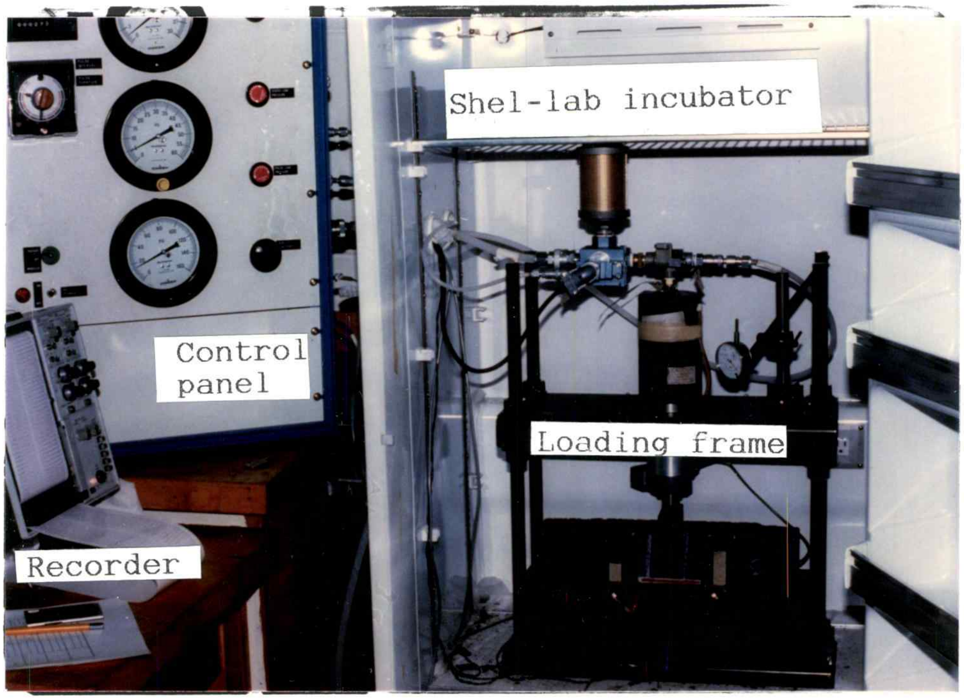


Figure 5.11. Testing apparatus and Shel-lab low temperature incubator.

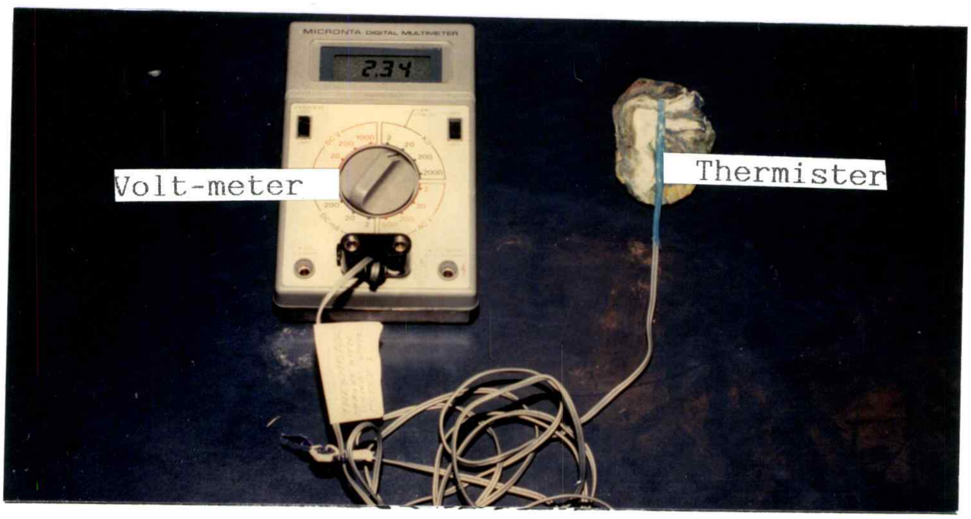


Figure 5.12. Digital volt-meter and thermister.

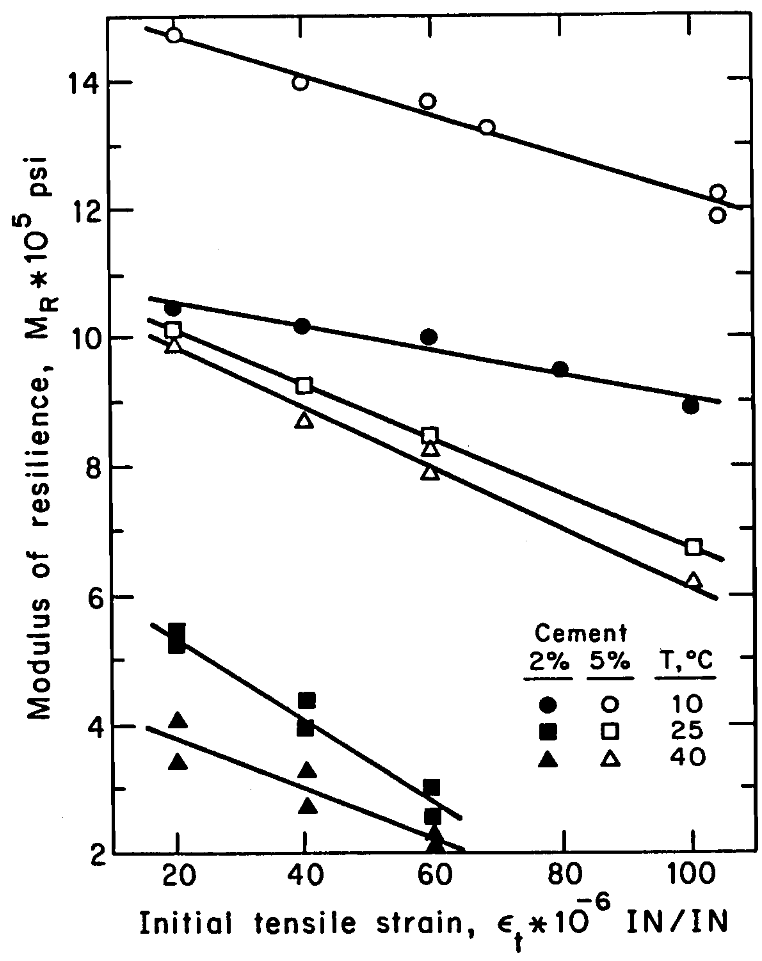


Figure 5.13. Relation between initial tensile strain and modulus of dune sand emulsion.

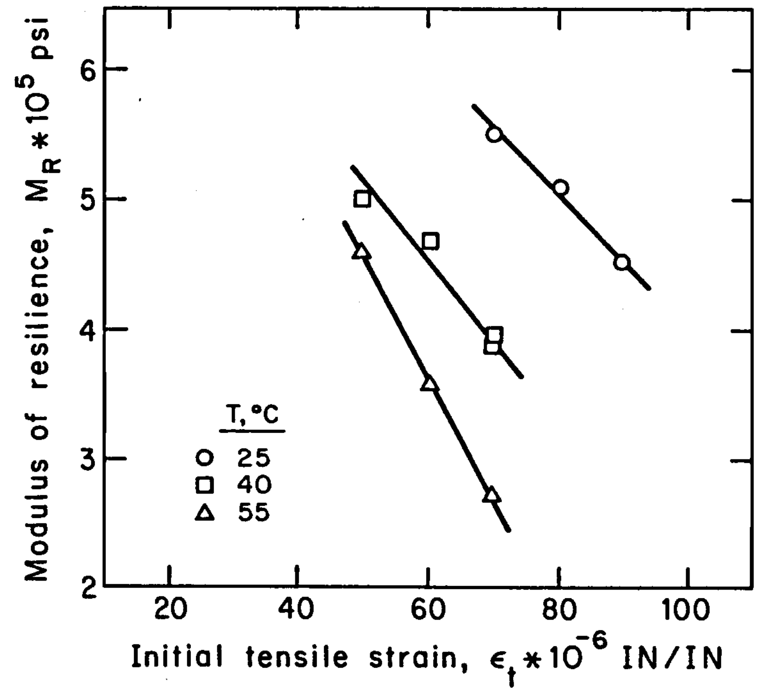


Figure 5.14. Effect of initial tensile strain on modulus of marl + 2% cement.

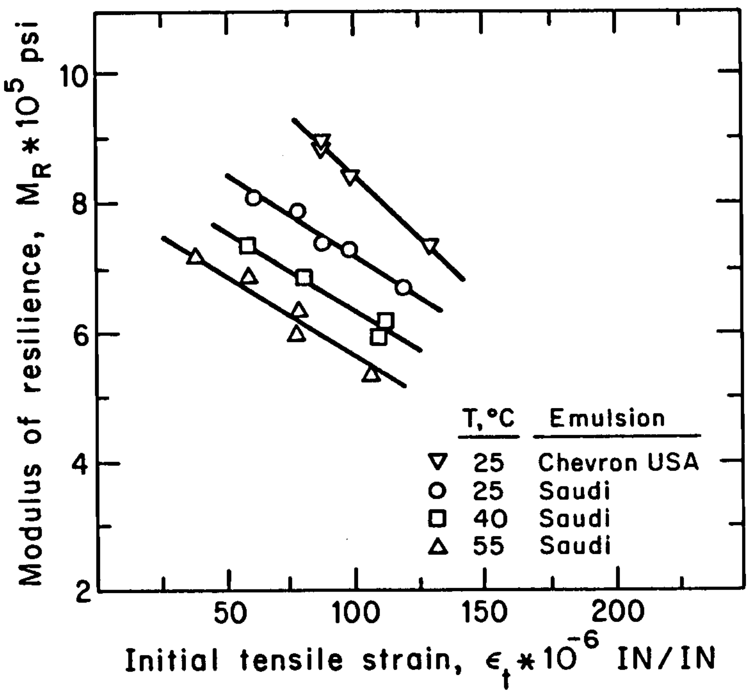


Figure 5.15. Relation between initial tensile strain and modulus of marl + 5% cement.

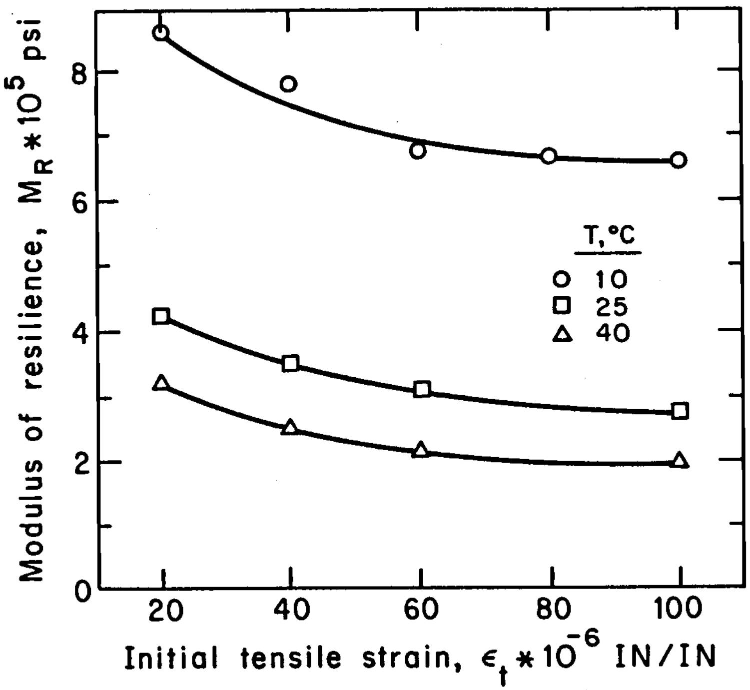


Figure 5.16. Relation between initial tensile strain and modulus for open graded asphalt emulsion @ 6 psi confining pressure.

As shown, an increase in cement content from 2% to 5% increased the modulus of dune sand emulsion more than 100%, especially at temperatures of 25°C and more. The same effect is observed when temperature is decreased to 10°C. The marl emulsion did not exhibit such a trend. Instead the variation in modulus due to temperature variation was less. The effect of cement content increase is almost the same as that for dune sand. A slight increase in the modulus was observed when the Chevron emulsion was used (in lieu of the Saudi emulsion), apparently due to better coating of the marl.

The modulus of the dune sand with 2% cement is comparable to the values reported by Santucci [67] for sand mixes with 1.3% cement after 50 days of curing time and by Kallas [62] for sand mixes with no cement after 12 weeks of curing time. This increase in modulus might be attributed to the increase in cement content (2%). Also, the curing procedure used in this research (48 hours at 100°F (37.8°C) followed by 24 hours in a vacuum cabinet) reduced the curing time considerably.

The open-graded emulsion mix was tested using a confining pressure of 6 psi in the confining equipment shown in Figs. 5.17 and 5.18. These results are shown in Fig. 5.16. As indicated, the modulus decreased by increasing tensile strain or temperature.

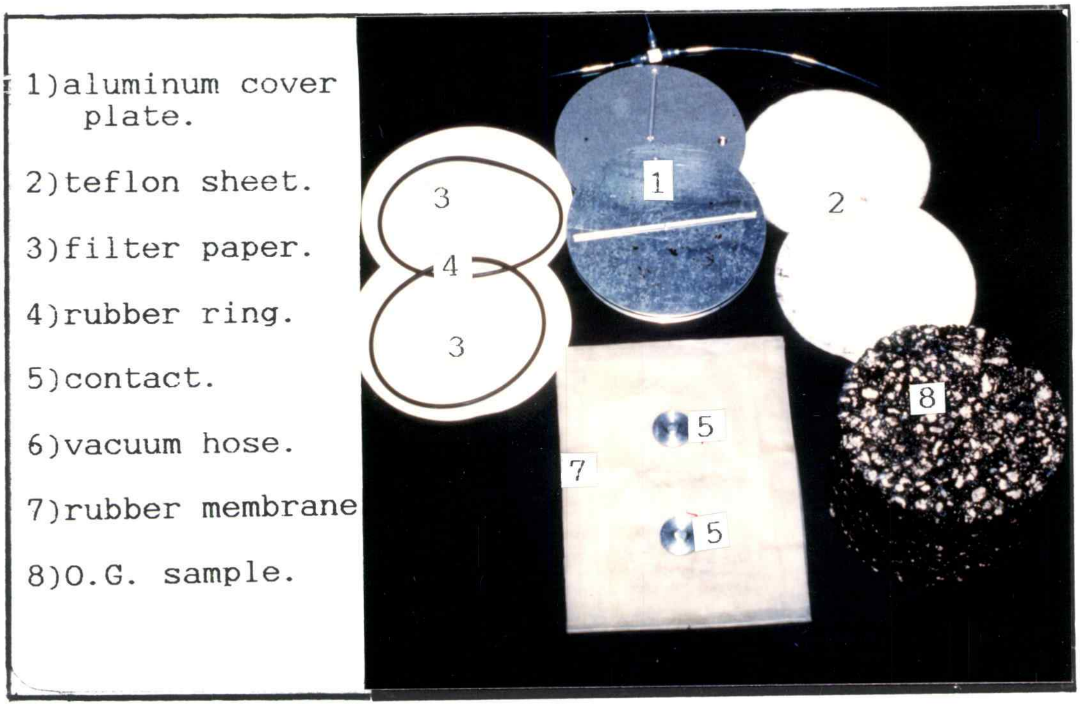


Figure 5.17. Diassembled confining pressure equipment.

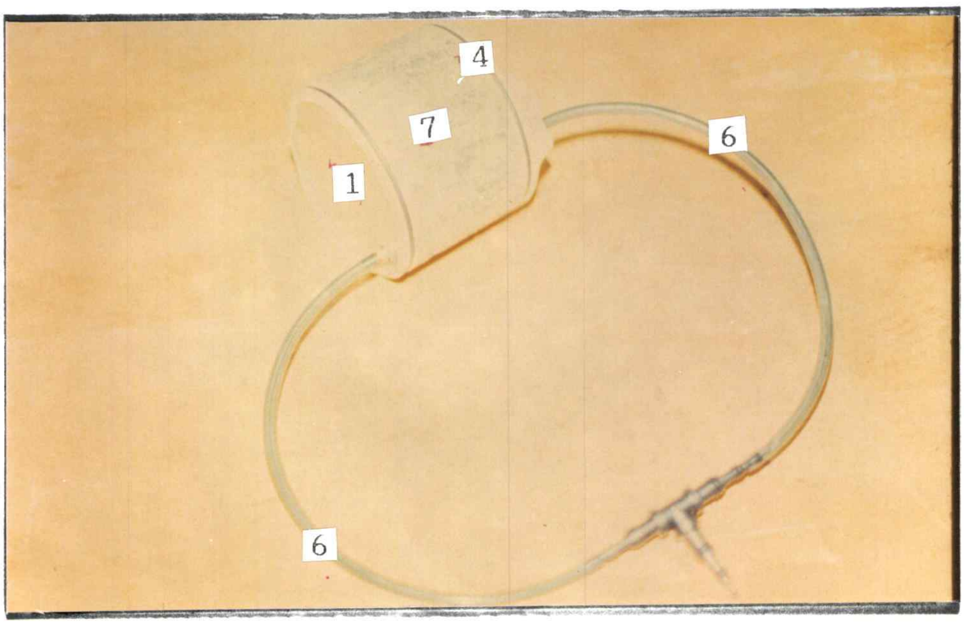


Figure 5.18. Confining pressure equipment, assembled.

5.4 Fatigue Properties

Several researchers have used the diametral test for evaluating fatigue of asphalt treated materials [57, 62, 63, 64]. Fatigue tests were conducted on the marl emulsion and dune sand emulsion mixes at three temperatures, 25°, 40° and 55°C (77°, 104° and 131°F) for marl and 10°, 25° and 40° (50°, 77° and 104°F) for dune sand and with two cement levels (2 and 5%). Tests on both mixes were conducted using at least three different tensile strain levels. Three specimens were tested for each material type at each temperature and strain level.

Each specimen was first tested for modulus and the tensile strain level at that loading was determined. The specimen was then prepared for the fatigue test by attaching foil tape to its surface. The specimen is then placed between two curved loading strips (Fig. 5.19). A seating load of 10 lb (4.55 kg) was applied to hold specimen in place and fatigue testing was then started. When the specimen fails, the foil tape breaks, causing the machine to stop (Fig. 5.20). The fatigue life is recorded on the machine counter.

5.4.1 Fatigue Results

The fatigue results are shown in Fig. 5.21 and Fig. 5.22 for dune sand emulsion with 2% and 5% cement, respectively. Figs. 5.23 and 5.24 show the fatigue results for marl emulsion with 2% and 5% cement.

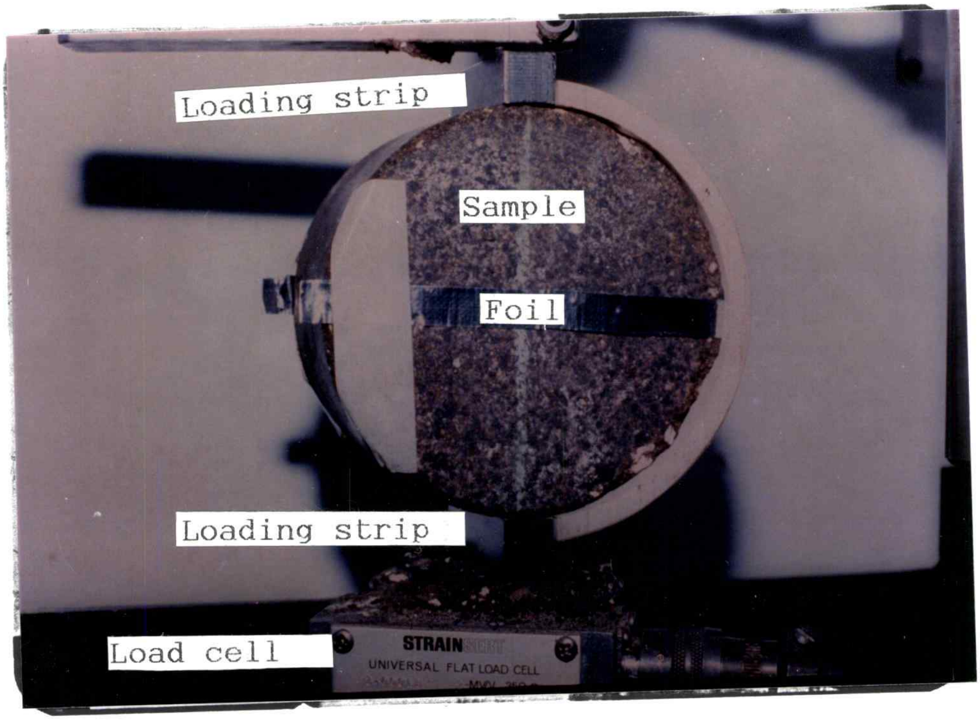


Figure 5.19. Specimen orientation for diametral fatigue.

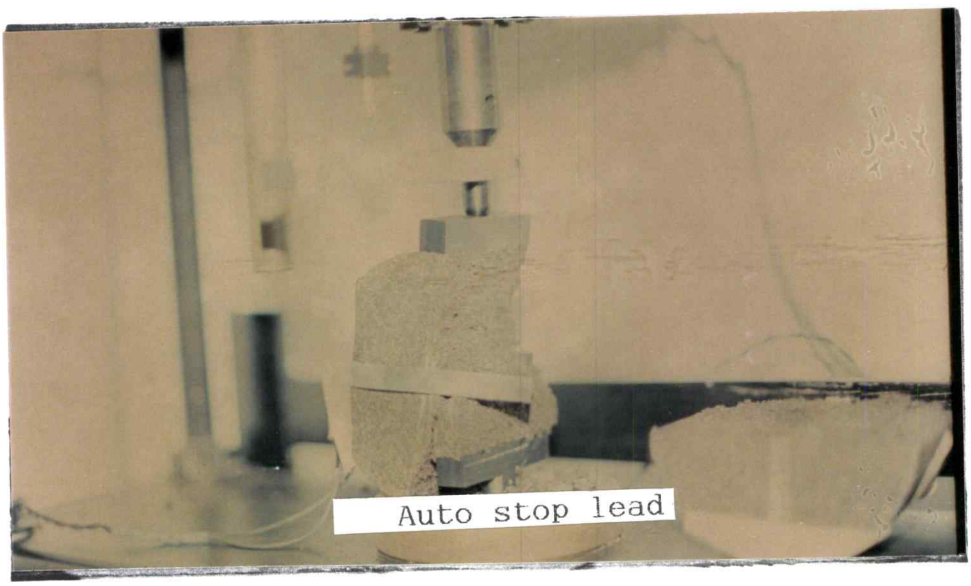


Figure 5.20. Failed specimen which results in breaking of foil tape and stopping the test.

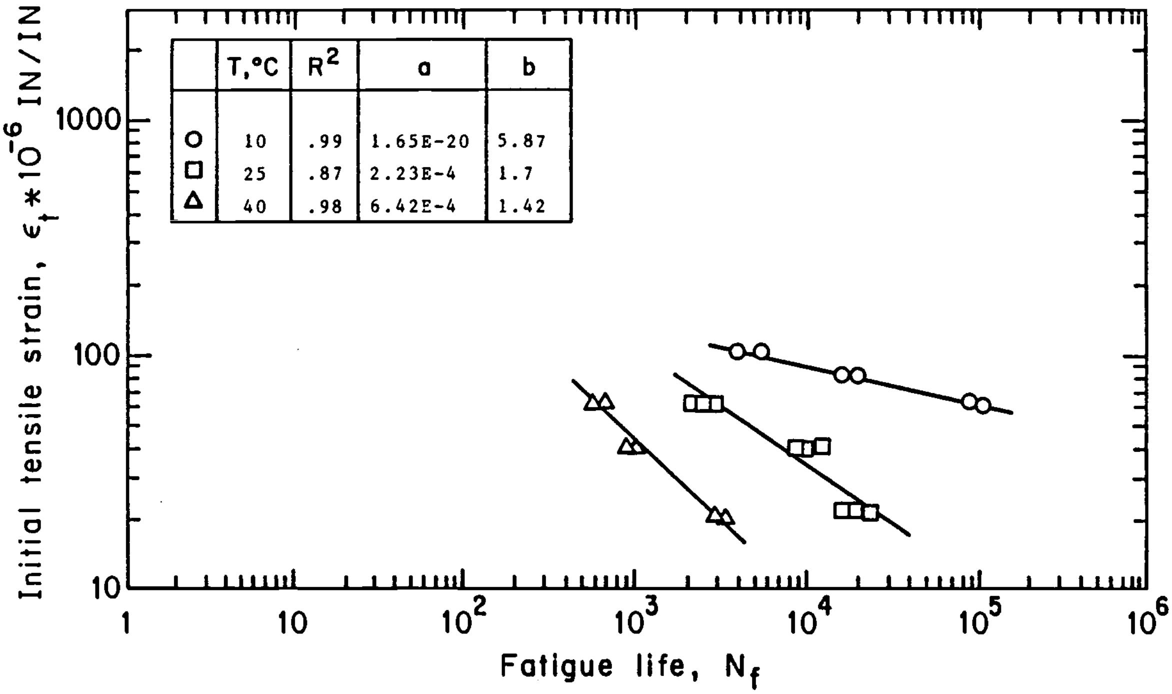


Figure 5.21. Relation between fatigue life and initial tensile strain for dune sand emulsion + 2%.

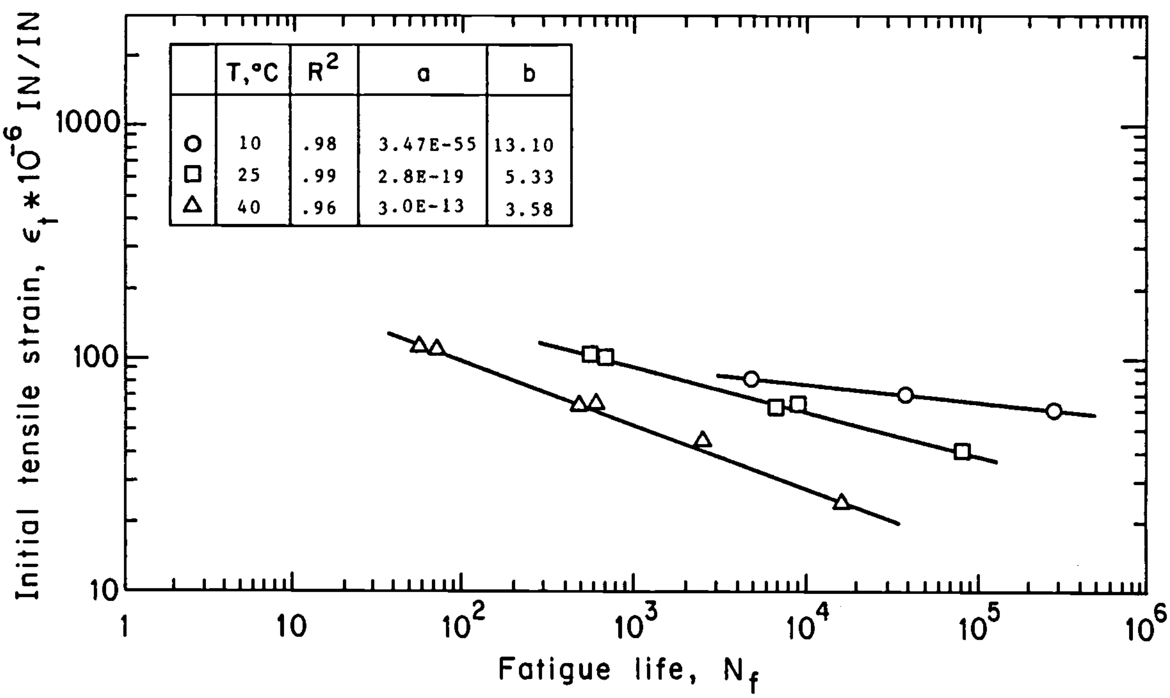


Figure 5.22. Relation between fatigue life and initial tensile strain for dune sand emulsion + 5% cement.

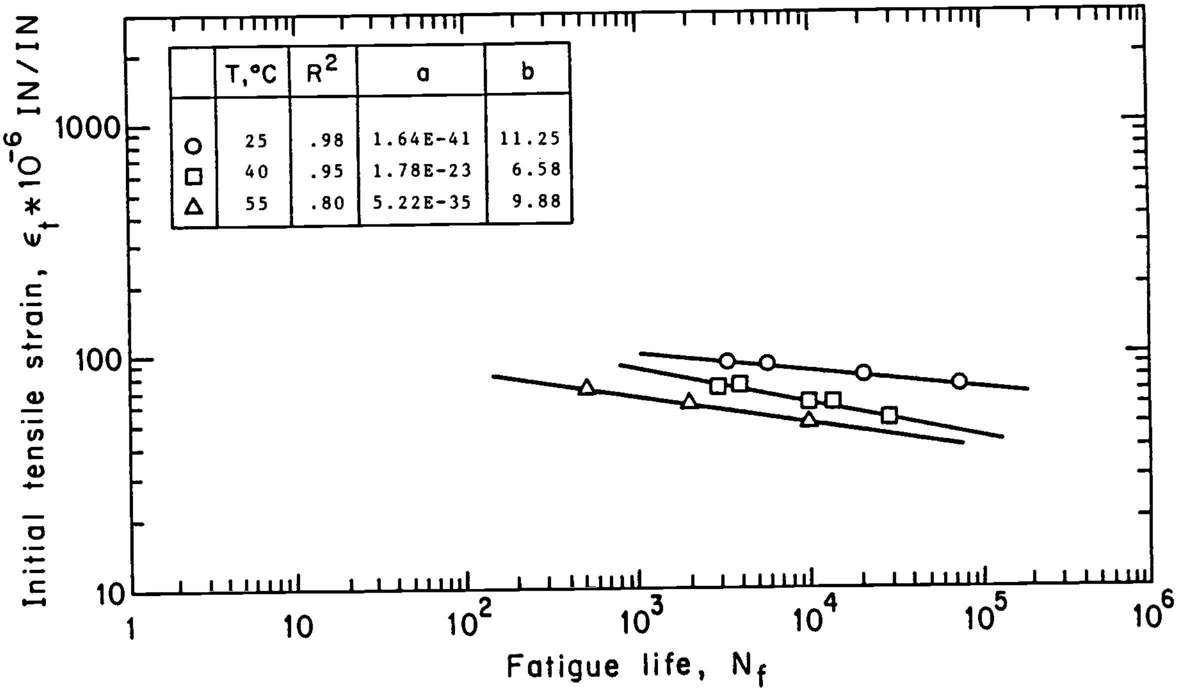


Figure 5.23. Relation between fatigue life and initial tensile strain for marl + 2% cement.

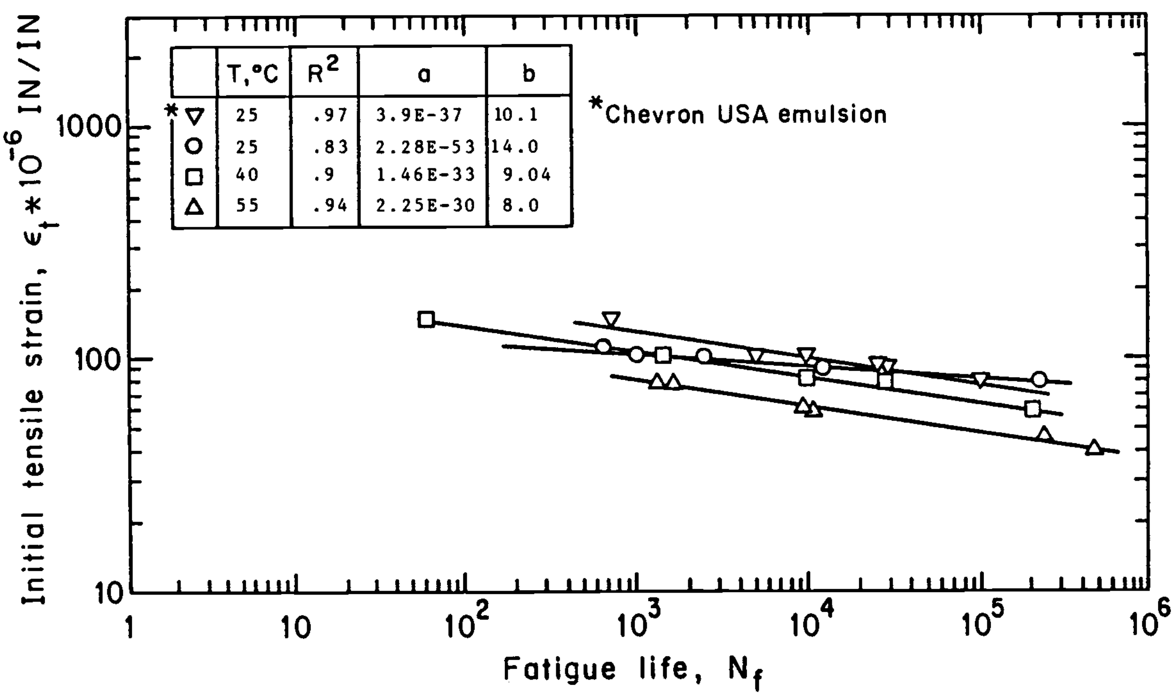


Figure 5.24. Relation between fatigue life and initial tensile strain for marl + 5% cement.

As indicated, the results followed the normal linear relationship between the logarithm of the applied tensile strain and the logarithm of fatigue life, given below [65]:

$$N_f = a\,(\varepsilon_t)^{-b} \quad \ldots\ldots\ldots\ldots \quad (5.4)$$

where,

ε_t = Initial tensile strain, inches

a = Antilog of the intercept of the logarithmic relationship

b = Slope of the logarithmic relationship between fatigue life and initial strain.

Values of a and b are affected by mix type, asphalt content, air voids and temperature [73]. A low value for constant "a" usually indicates a high fatigue life, while a low value of constant "b" indicates a steep slope of the fatigue line.

Two types of failures were observed when testing dune sand: 1) fatigue failure or brittle cracking, and 2) rutting failure or plastic flow. There is no clear borderline that can be drawn between the two failures, but it can be said that as the temperature increases and cement content decreases, the specimen tends to fail in rutting while if the temperature decreases or the cement content increases, the specimen tends to fail in brittle cracking. Marl specimens tended to always fail in brittle cracking even at higher temperatures and low cement level. This might be attributed to the effect of the fine silty particles on the viscosity of asphalt-marl mortar, which is not the case with the dune sand due to its low content of particles passing a no. 200 sieve.

In general, the test results indicate that the slope of the regression line increased with the increasing temperature due to the increased tendencty to plastic flow. The fatigue life tends to decrease with increasing temperature or decreasing cement content (lower stiffness). This trend is expected since the test is a controlled stress test [97]. The variation of "a" values is higher in the case of dune sand due to the temperature susceptibility of dune sand emulsion mix that influences the failure mode, as discussed above. The "b" values also tend to decrease by increasing temperature or decreasing cement content for the same reason. The rate of variation is higher for dune sand emulsion than marl emulsion.

It is also noted that at 5% cement content and low temperatures, fatigue curves tend to have flat slopes due to the effect of the cement, i.e. mixes behave as cement treated material.

Fatigue life equations are shown on each figure together with R^2 (coefficent of determination) which are given by:

$$R^2 = SSR/SSTO \qquad (5.5)$$

where,

SSR = regression sum of squares

SSTO = total sum of squares

R^2 values tend to be greater than 0.8, which is probably attributed to the uniformity of materials and the limited number of strain levels (usually three) at which each material was tested. Dune sand emulsion was tested at 10°, 25° and 40°C (50°, 77° and 104°F), due to its greater temperature susceptibility, while marl was tested at 25°, 40° and 55°C (77°, 104° and 131°F) because of its ability to withstand temperature variations.

Comparing the results with other researchers' results, Kennedy reported values of "a" ranged from $5.65 * 10^{-17}$ to $5.01 * 10^{-7}$ and "b" ranged from 2.66 to 5.19 for hot asphalt mixes. Johnson and Shahin [17] noticed that fatigue life of stress controlled beams, when plotted as a function of tensile strain, decreases with increasing temperature. Schmidt et al. [67] noted that the fatigue life of asphalt treated materials increases with increasing stiffness or modulus, which is similar to the trends observed in this research.

Fatigue test results are shown in Table 5.1 and are compared to other researchers' values shown in Table 5.2. A comparison indicates a close agreement with the results reported by Evans [63] and Kallas [62] at 70°F (21°C).

Table 5.1. Fatigue Equations as a Function of Tensile Strain, "Diametral Fatigue Test."

Material Type	Cement Content %	T °C	$N_f = a.(\varepsilon_t)^{-b}$ a	b
Marl (Chev.)	5	25	3.90E-37	10.10
Marl (Saudi)	5	25	2.28E-53	14.00
		40	1.46E-33	9.04
		55	2.25E-30	8.00
	2	25	1.64E-41	11.25
		40	1.78E-23	6.58
		55	5.22E-35	9.88
Dune Sand	5	10	3.47E-55	13.10
		25	2.80E-19	5.33
		40	3.00E-13	3.58
	2	10	1.65E-20	5.87
		25	2.23E-04	1.70
		40	6.42E-04	1.42

Table 5.2. Summary of Fatigue Data from Various Tests

Test Type	Investigator	Mixture Type	$N_f=a.(\varepsilon_t)^{-b}$ a	b
Repeated load indirect tension	Evans (63)	Dune sand, 10 lb seating load at 21°C (70°F)		
		•unconditioned	9.13E-11	3.2
		•conditioned	1.56E-26	7.09
	Aededimila (95)	Dense gravel mix, 4% AC-10 at 75°F	2.1E-9	3.06
Beam Flexure	Santucci (76)	Emulsified asphalt	1.81E-7	3.53
		cement modified	4.98E-16	5.8
	Kallas (62)	Dense graded crushed gravel emulsified asphalt, 15% voids, at 21°C (70°F)		
		• 5.5% SS-1h	2.52E-58	16.4
		• 7.5% SS-1h	4.3E-52	14.5
		• 5.5% CMS-2	5.01E-43	11.9

1 lb = 4.45 Kn; 1 psi = 6.894 Kn/m^2

Fatigue life can also be defined as a function of tensile stress (σ_t), where a linear relationship exists between the logarithm of the applied tensile stress and the logarithm of fatigue life, which can be expressed as,

$$N_f = K(1/ \sigma_t)^n \quad \text{. . . . . (5.6)}$$

where

N_f = fatigue life

σ_t = applied tensile stress, $(0.156 \frac{P}{h})$, psi

n = slope of the logarithmic relationship between fatigue life and tensile stress

K = antilog of intercept of the logarithmic relationship.

P = applied load, lb, and

h = specimen height, in

Fatigue test results (as a function of tensile stress) are shown in Figures 5.25 and 5.26 and Table 5.3. It is noted that (as expected) fatigue life increases by increasing cement (modulus), or by decreasing temperature or stress level. This result is similar to that observation reported by Shahin [17] and Schmidt [67]. These results are compared to those reported by other researchers (Table 5.4). The comparison indicates that dune sand produced fatigue equations close to those reported for other materials at 75°F (23.9°), while marl produced lower slopes (higher "n" values) and higher "K" values. This behavior increases by increasing cement or by

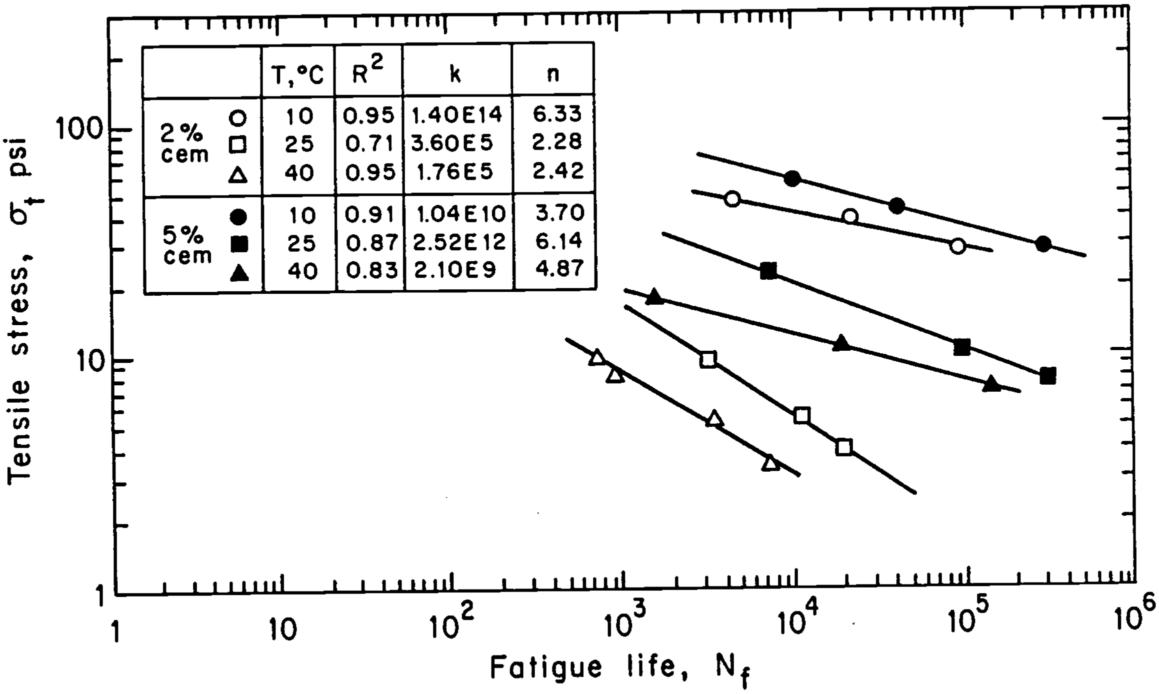


Figure 5.25. Relation between fatigue life and tensile stress for dune sand emulsion.

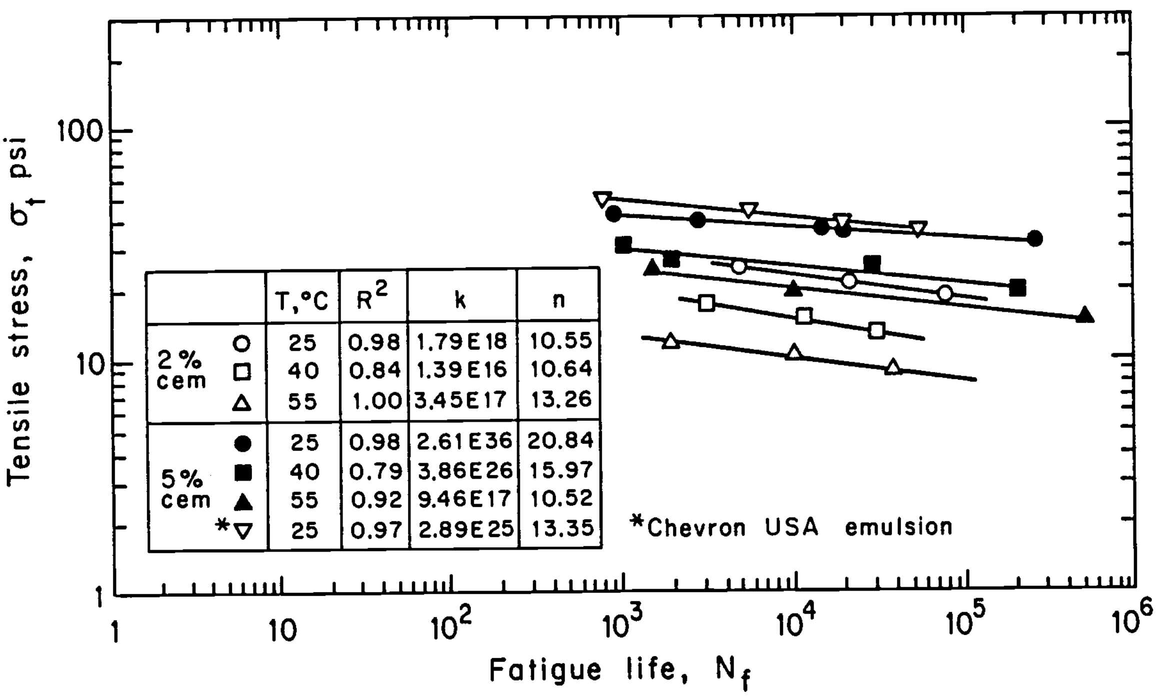


Figure 5.26. Relation between fatigue life and tensile stress for marl emulsion.

Table 5.3. Fatigue Equations as a Function of Tensile Stress, "Diametral Fatigue Test."

Material Type	Cement Content %	T °C	$N_f = k.(\sigma_t)^{-n}$	
			k	n
Marl (Chev.)	5	25	2.89E25	13.35
Marl (Saudi)	5	25	2.61E36	20.84
		40	3.86E26	15.97
		55	9.46E17	10.52
	2	25	1.79E18	10.55
		40	1.39E16	10.64
		55	3.45E17	13.26
Dune Sand	5	10	1.04E10	3.70
		25	2.54E12	6.14
		40	2.10E10	4.87
	2	10	1.40E14	6.33
		25	3.60E5	2.28
		40	1.76E5	2.42

Table 5.4. Summary of Fatigue Data from Various Tests (15).

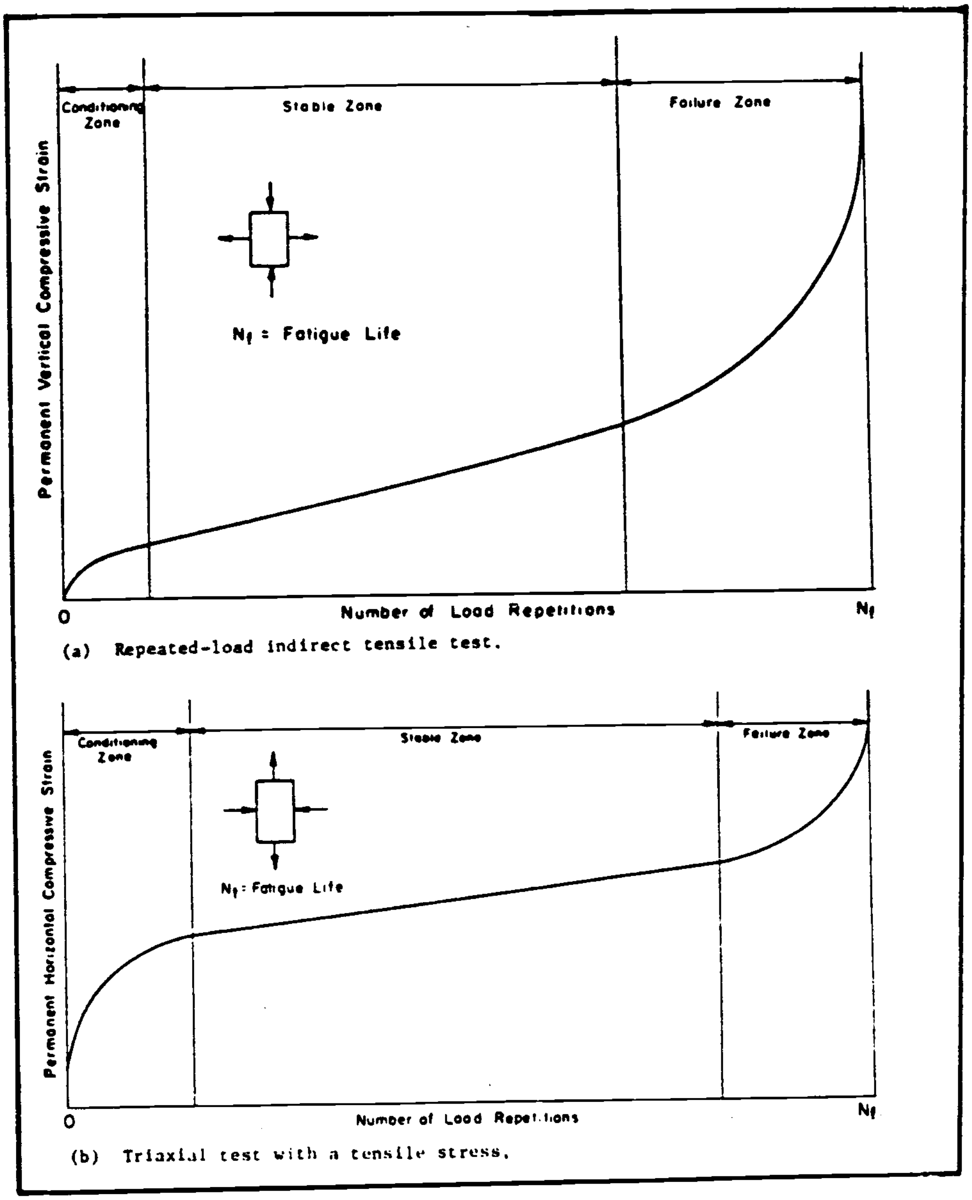
Test Type & Investigator	Mixture	Asphalt %	pen.	Temp. °F	$N_f=k.(\sigma_t)^{-n}$	
					k	n
Repeated load indirect tension; Kennedy (15)	Limestone	7.0	92	75	1.25E9	4.09
	Limestone	4.0	88	75	6.19E5	2.56
	Limestone	7.0	88	75	4.76E8	3.88
	Limestone	8.0	88	75	5.88E7	4.42
	Gravel	7.0	88	75	3.56E8	3.13
	Gravel	7.0	92	75	2.04E10	4.74
Axial load; Raithby & Sterling (94)	Pill's	6.5	38	50	2.24E21	5.97
	Mix G	6.5	38	77	3.65E11	3.87
Rotating cantilever; Pell & Cooper (92)	Wearing course	6.0	60-70	50	3.90E15	4.90
	Base course	6.0	40-60	50	7.50E19	6.40
Flexure; Monismith et al. (93)	British 594	7.9	40-50	68	1.36E11	2.87
	California	6.0	85-100	68	2.11E12	4.04
	California	6.0	60-70	68	7.29E12	4.21
	California	6.0	40-50	68	1.97E15	4.93

°F=32+1.8(°C)

decreasing temperature. Dune sand failure is affected by plastic flow at high temperature or low cement contents, as was discussed above. Marl emulsion is less affected by plastic flow and usually exhibits a brittle cracking failure. This behavior resulted in flat fatigue curves, which is similar to cement treated material behavior.

5.5 Permanent Deformation Properties

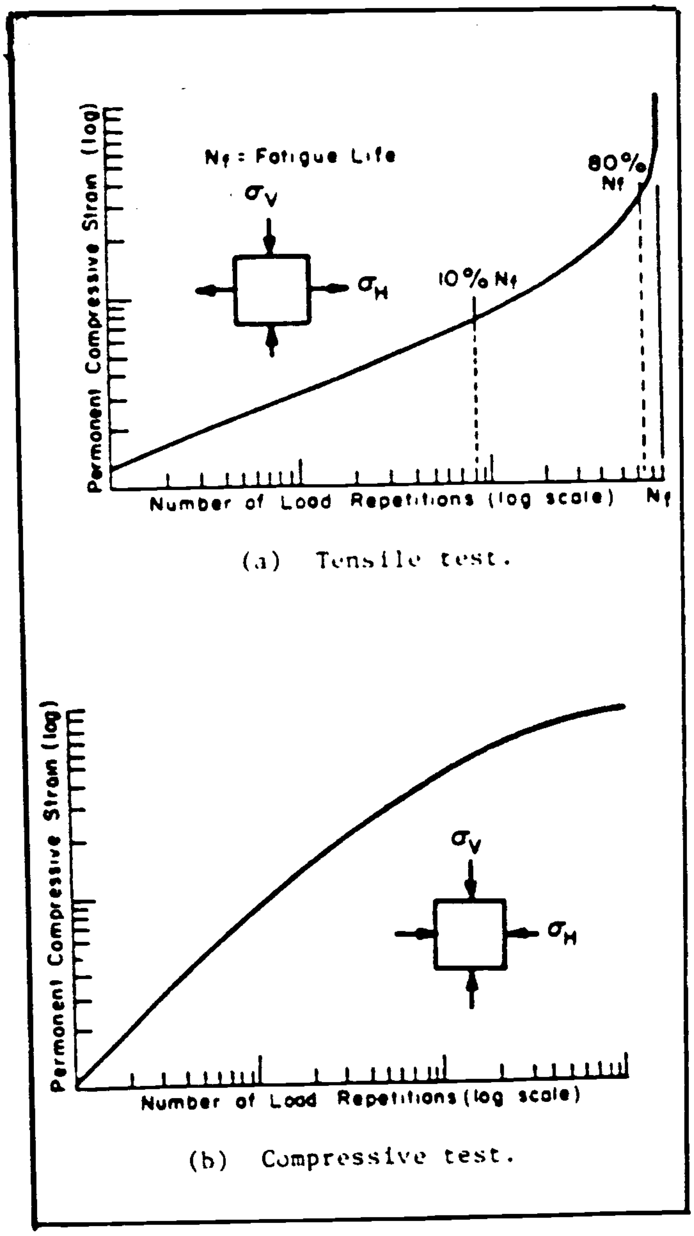
Repeated load tensile tests have been used to estimate the permanent deformation characteristics of asphalt materials [15, 58, 75]. The indirect tensile test simulates the state of stress in the lower position of the asphalt layer (tension zone). Indirect tensile tests and triaxial tensile tests (involving axial tensile stresses) produce rutting curves that are similar [58], but triaxial compressive tests yield rutting curves different from these tests as shown in Figs. 5.27 and 5.28. In the indirect and triaxial tensile tests, failure is caused by tensile stress while in the triaxial compressive test, the failure is caused by compressive stress. The relations between tensile strain and number of load repetitions to failure can be represented by a curve similar to that shown in Fig. 5.28. The first 10% of the rutting curve can be represented by a straight line. In the next 70%, slope begins increasing to 1.0 where failure starts. In general, the first 75% of permanent strain vs. number of load applications can be



(a) Repeated-load indirect tensile test.

(b) Triaxial test with a tensile stress.

Figure 5.27. Permanent strain relationships for tests involving tensile stresses . (58)



(a) Tensile test.

(b) Compressive test.

Figure 5.28. Typical permanent strain relationships for tensile & compressive tests.(58)

represented by a straight line when plotted on a log-log scale of the form [58, 61]:

$$\varepsilon_p = a\,N^b \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5.7)$$

where,

ε_p = Accumulated permanent strain

a = Intercept with ε_p axis

b = Slope of the straight line

N = Number of load repetitions.

Accumulated permanent strain can be calculated during testing using the following equation [57]:

$$\varepsilon_p = Y_T^{\frac{(-0.1185\ -\ \mu * 0.03896)}{(-0.8914\ +\ \mu * 0.0156)}} \; . \; . \; . \; . \; . \quad (5.8)$$

where,

ε_p = Cumulated strain, 10^{-4} inch

Y_T = Total vertical deformation, 10^{-4} inch

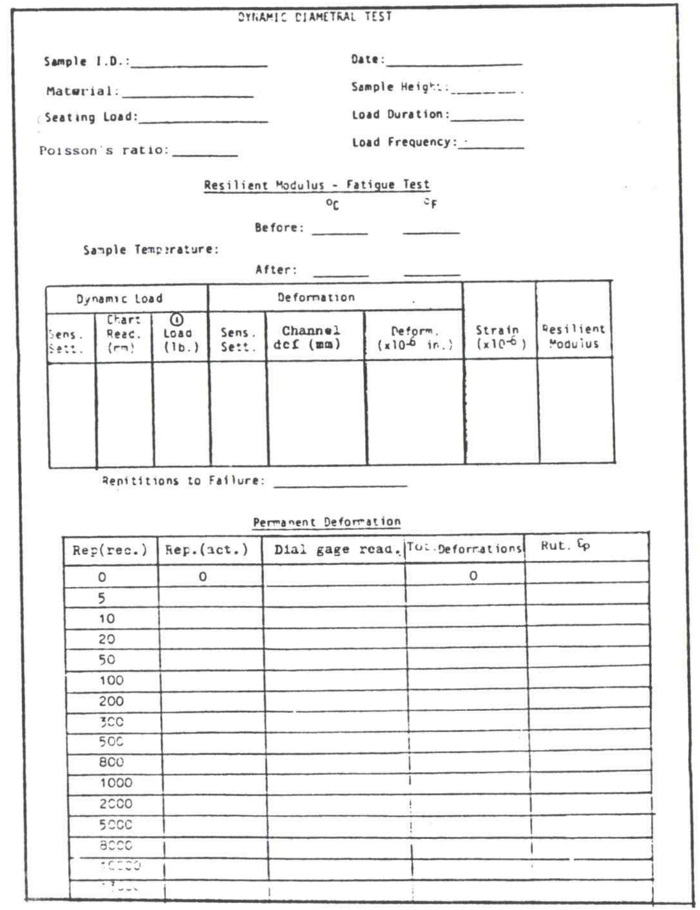
μ = Poisson's ratio (0.33 for dune sand and 0.34 for marl).

Specimens were tested at three temperatures at different stress levels. Total vertical deformation was measured using a dial gauge accurate to 10^{-4} inch as shown in Fig. 5.29. Measured values were recorded on a form similar to that shown in Fig. 5.30, where vertical strains were then calculated using Equation 5.8

5.5.1 Permanent Deformation Results

Both the dune sand and marl emulsion mixes were tested for permanent deformation. Two cement contents (2

Figure 5.29. Permanent deformation measurement.



DYNAMIC DIAMETRAL TEST

Sample I.D.: ____________ Date: ____________

Material: ____________ Sample Height: ____________

Seating Load: ____________ Load Duration: ____________

Poisson's ratio: ________ Load Frequency: ____________

Resilient Modulus - Fatigue Test

	°C	°F
Sample Temperature: Before:	______	______
Sample Temperature: After:	______	______

Dynamic Load			Deformation				
Sens. Sett.	Chart Read. (mm)	① Load (lb.)	Sens. Sett.	Channel def (mm)	Deform. (x10-6 in.)	Strain (x10-6)	Resilient Modulus

Repititions to Failure: ____________

Permanent Deformation

Rep(rec.)	Rep.(act.)	Dial gage read.	Tot. Deformations	Rut. ε_p
0	0		0	
5				
10				
20				
50				
100				
200				
300				
500				
800				
1000				
2000				
5000				
8000				
10000				
[illegible]				

Figure 5.30. Form used for dynamic diametral test, diametral fatigue, and rutting.

and 5%) were evaluated using the temperatures of 10°, 25° and 40°C (50°, 77° and 131°F) for dune sand emulsion and 25°, 40° and 55°C (77°, 104° and 131°F) for marl emulsion. These results are given in Figs. 5.31 to 5.42. Chevron emulsified asphalt was tested with marl + 5% cement at 25°C (Fig. 5.43).

Results indicated that a straight line relation exists between the logarithm of number of load applications and the logarithm of permanent strain, ε_p. Equation (5.7) was used to fit such a relation. Specimens were tested at different strain levels. Compressive stress at the center of the specimen was calculated by [58]:

$$\sigma_c = 0.468 \frac{P}{h} \quad . . . . (5.9)$$

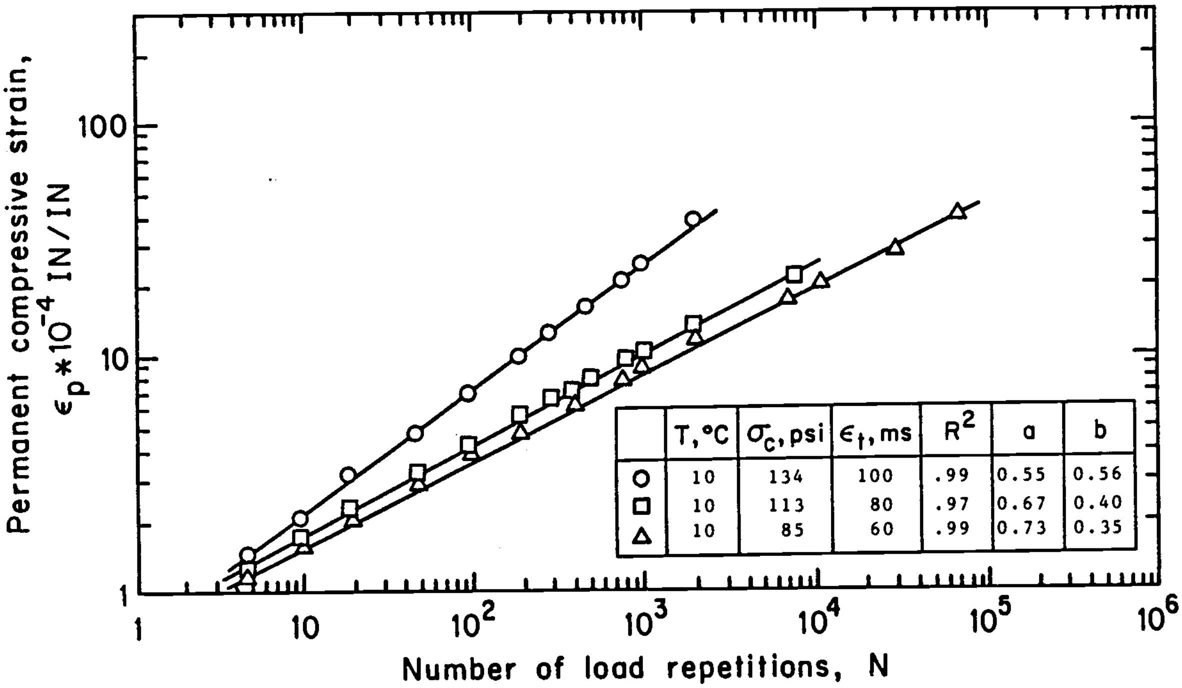
where

σ_c = indirect compressive stress (psi)

P = total vertical load applied to specimen, pounds

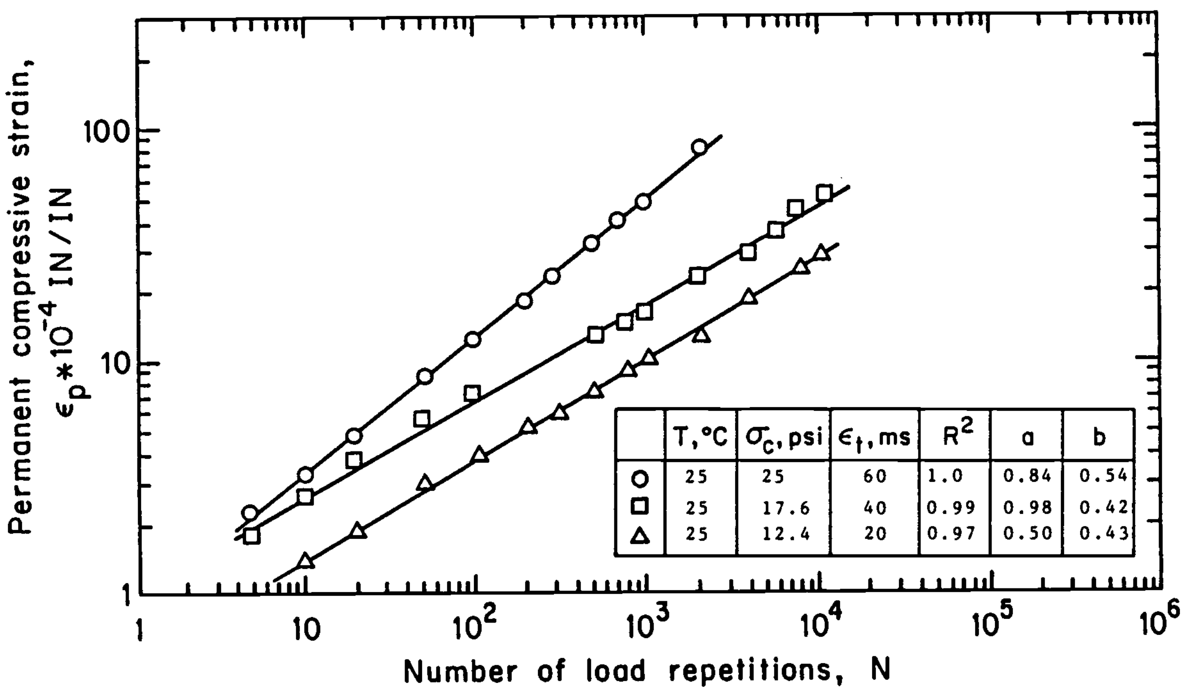
h = height of specimen at the beginning of test, inches

Tensile strain levels were selected based on the material's ability to withstand certain temperatures with a reasonable fatigue life (500 to 200,000). Results indicated that rutting tended to increase with increasing temperature, increasing stress (or tensile strain) level, or decreasing cement content. Increasing cement content from 2 to 5% resulted in reducing permanent deformation



	T, °C	σ_c, psi	ϵ_t, ms	R^2	a	b
○	10	134	100	.99	0.55	0.56
□	10	113	80	.97	0.67	0.40
△	10	85	60	.99	0.73	0.35

Figure 5.31. Relation between number of load repetitions and vertical strain for dune sand-emulsion + 2% cement.



	T, °C	σ_c, psi	ϵ_t, ms	R^2	a	b
○	25	25	60	1.0	0.84	0.54
□	25	17.6	40	0.99	0.98	0.42
△	25	12.4	20	0.97	0.50	0.43

Figure 5.32. Relation between number of load repetitions and vertical strain for dune sand emulsion + 2% cement.

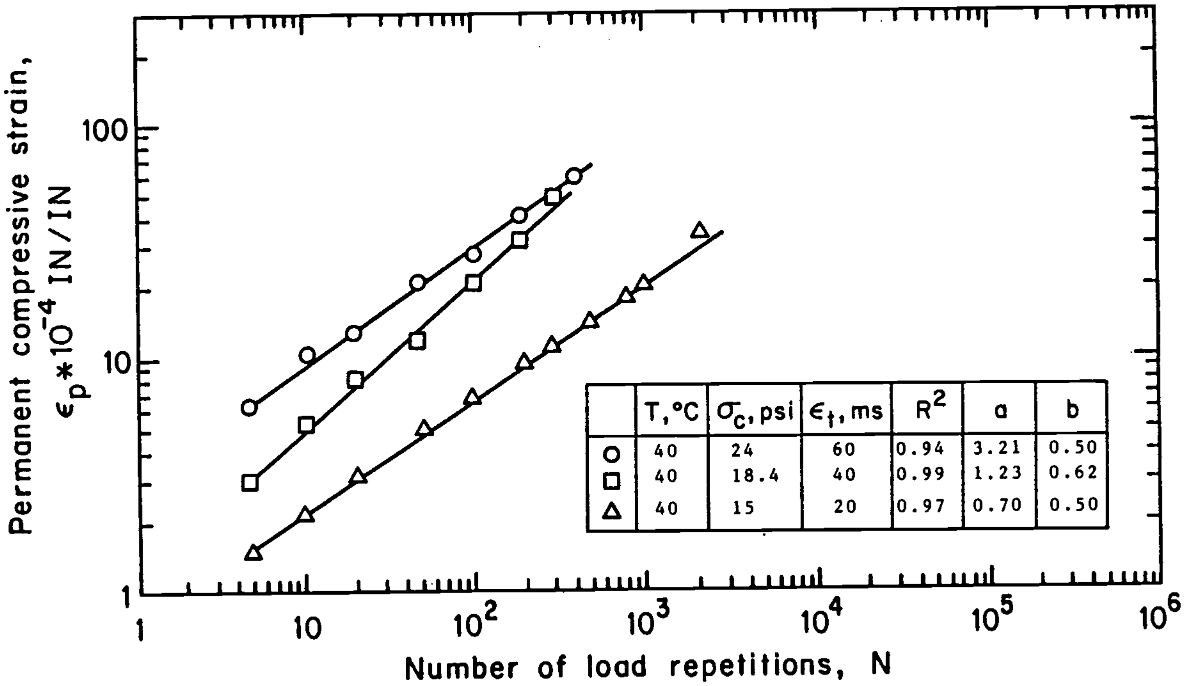


Figure 5.33. Relation between number of load repetitions and vertical strain for dune sand emulsion + 2% cement.

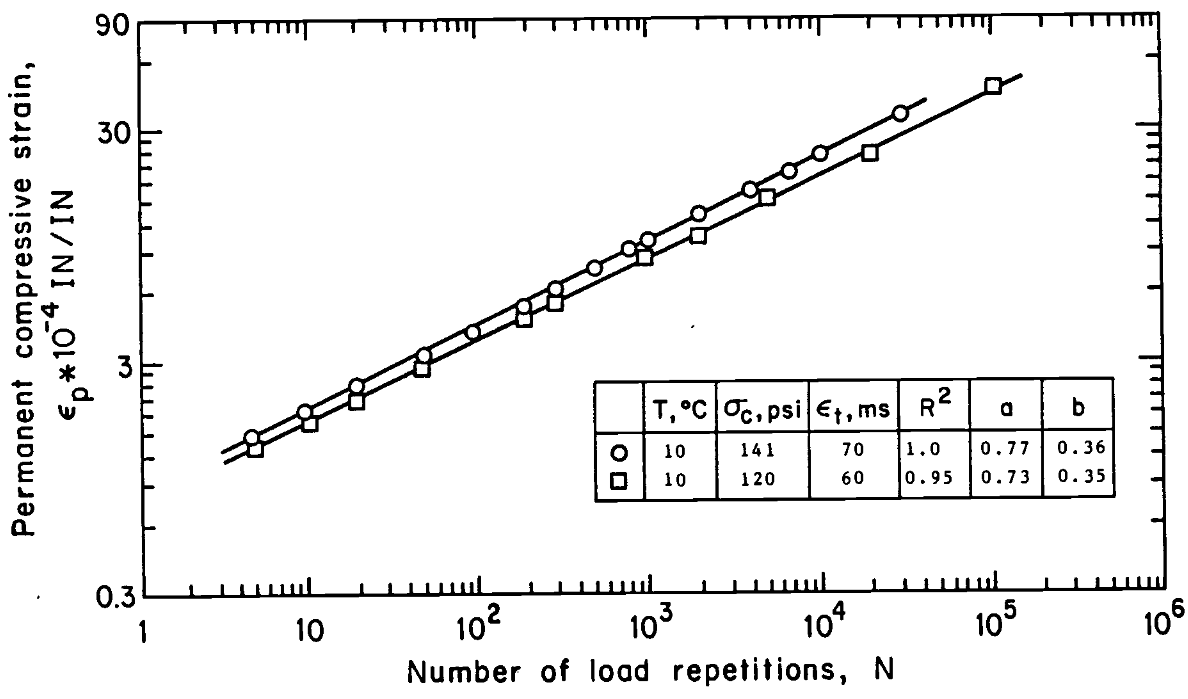


Figure 5.34. Relation between number of load repetitions and vertical strain for dune sand emulsion + 5% cement.

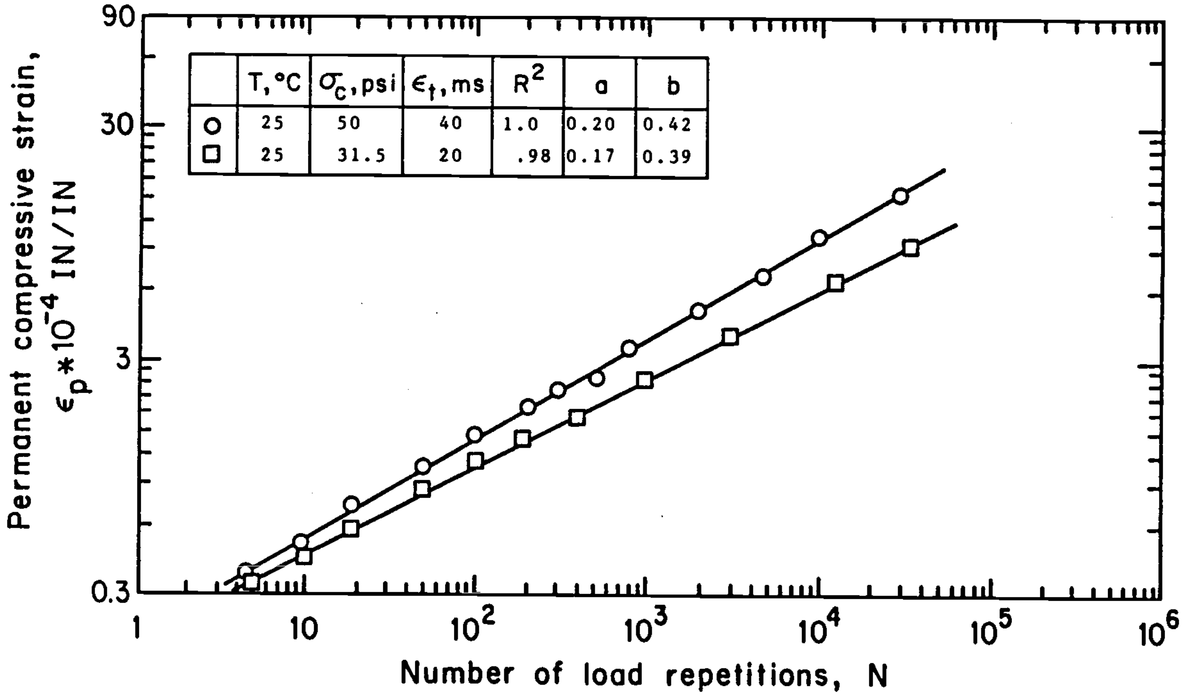


Figure 5.35. Relation between number of load repetitions and vertical strain for dune sand emulsion + 5% cement.

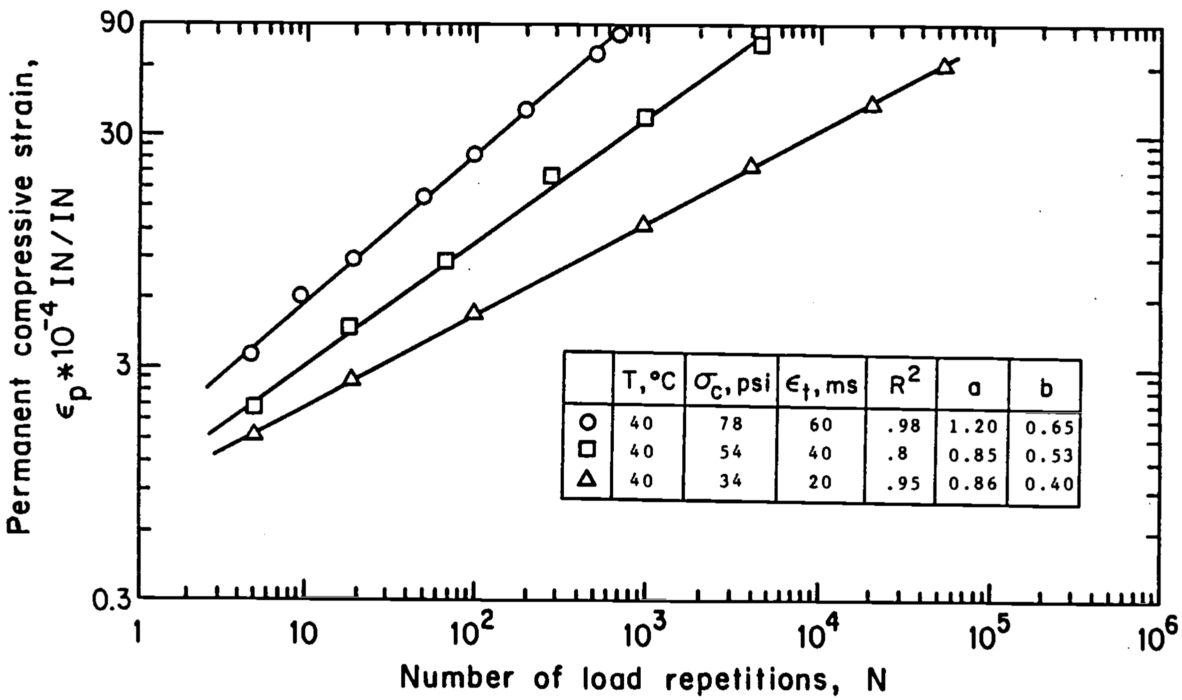


Figure. 5.36. Relation between number of load repetitions and vertical strain for dune sand + 5% cement.

of dune sand of about 60%. This is not the case with marl, which gave rutting values at 30% of dune sand rutting. Temperature variation did not affect marl rutting as significantly as it did dune sand, which indicated the ability of marl to withstand traffic loads at temperatures greater than $50^{o}C$ ($122^{o}F$).

Rutting equations were compared to values obtained by other researchers, such as Akili and Monismith [61] and Kennedy et al. [58], Table 5.5. It was difficult to make much comparison due to the difference in curing procedures, cement content, or material type. Dune sand emulsion with 2% cement gave rutting equations with "b" values similar to those reported by Akili (23 - curing days, 30-50 psi deviator stress) but with lower "a" values. All rutting equations for marl and dune sand gave regression constants ("a" and "b") within the range reported by Akili and Monismith. Marl at low stresses, produced a rutting equation close to that given by Kennedy [58] for hot asphalt cement, but lower than those of dune sand.

5.6 Summary

Comprehensive testing was conducted on marl and dune sand emulsion treated mixes. Tests were conducted at different temperature, strain and cement levels. The diametral test was used with loading duration of 0.1 sec and load frequency of 60 cycles per minute.

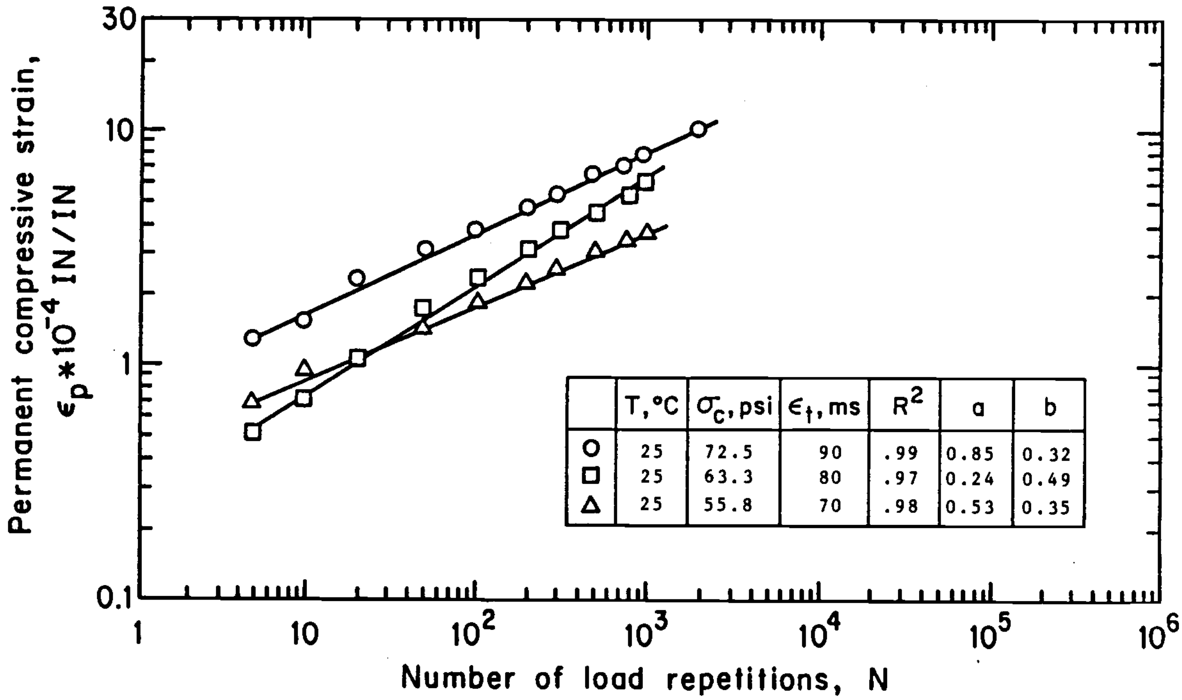


Figure 5.37. Relation between number of load repetition and vertical strain for marl + 2% cement.

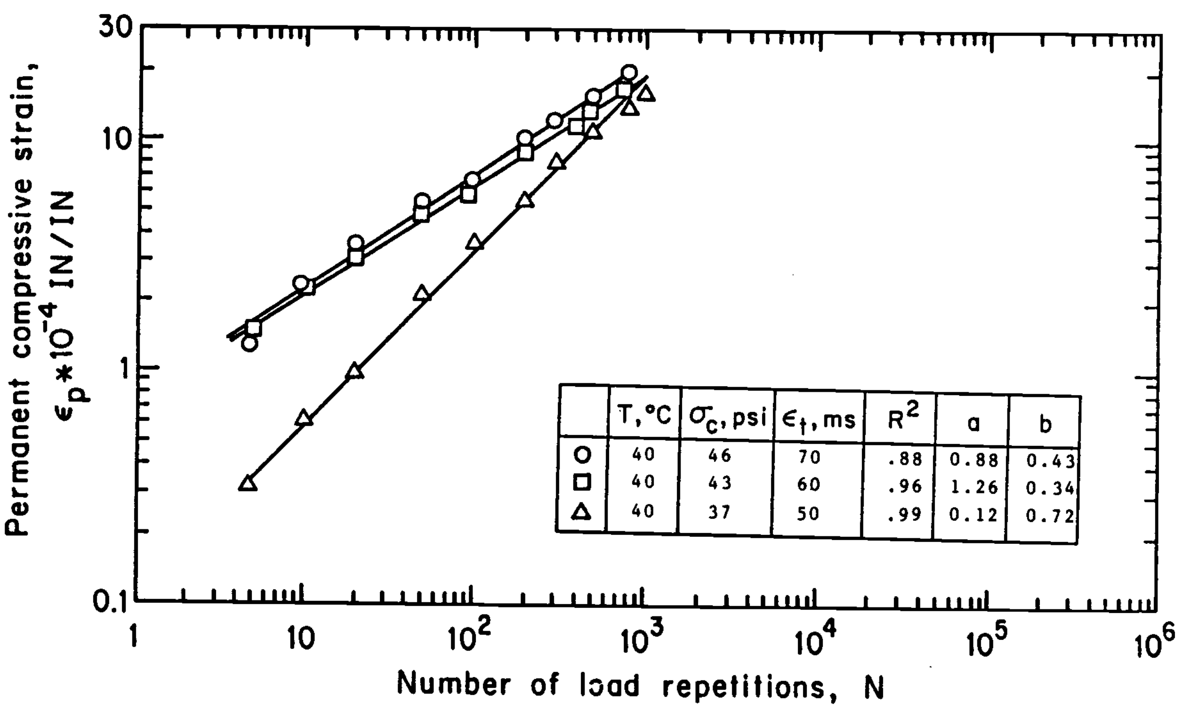


Figure 5.38. Relation between number of load repetitions and vertical strain for marl emulsion + 2% cement.

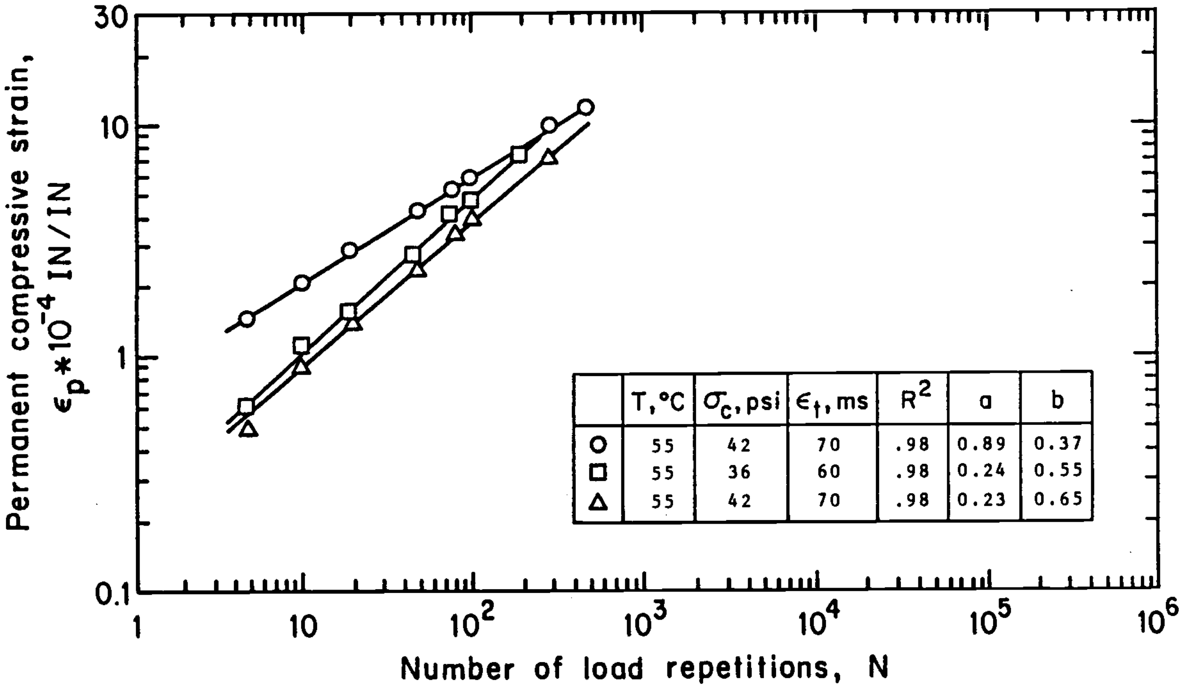


Figure 5.39. Relation between number of load repetitiona and vertical strain for marl + 2% cement.

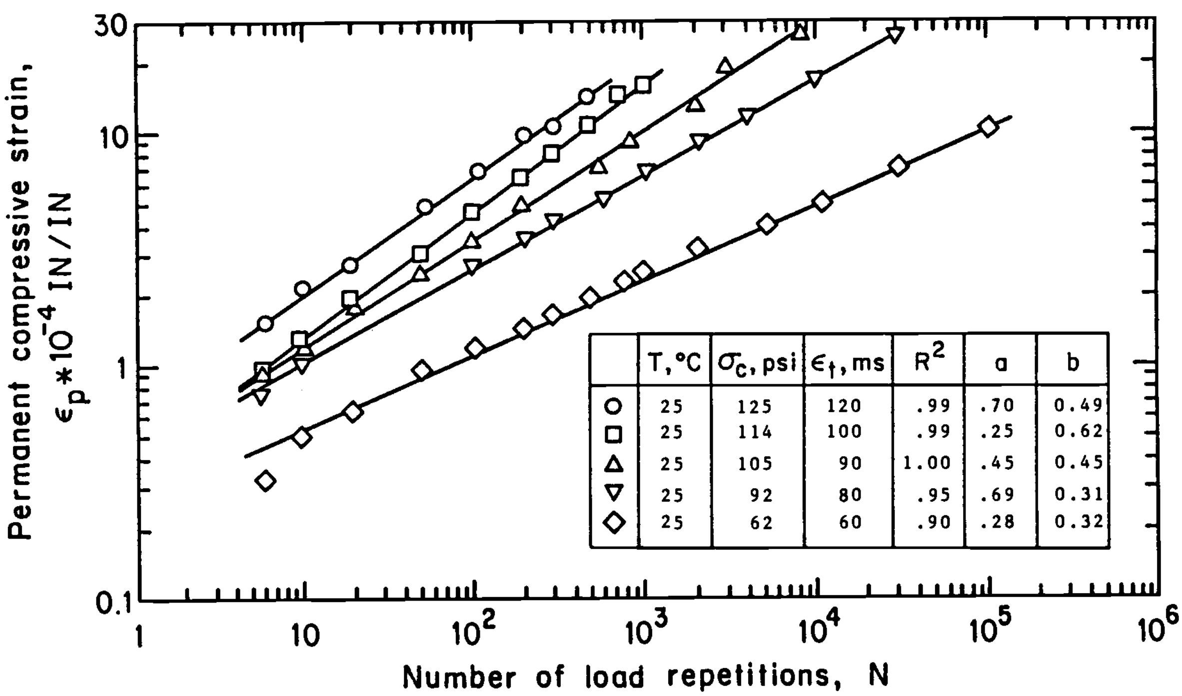


Figure 5.40. Relation between number of load repetitions and vertical strain for marl + 5% cement.

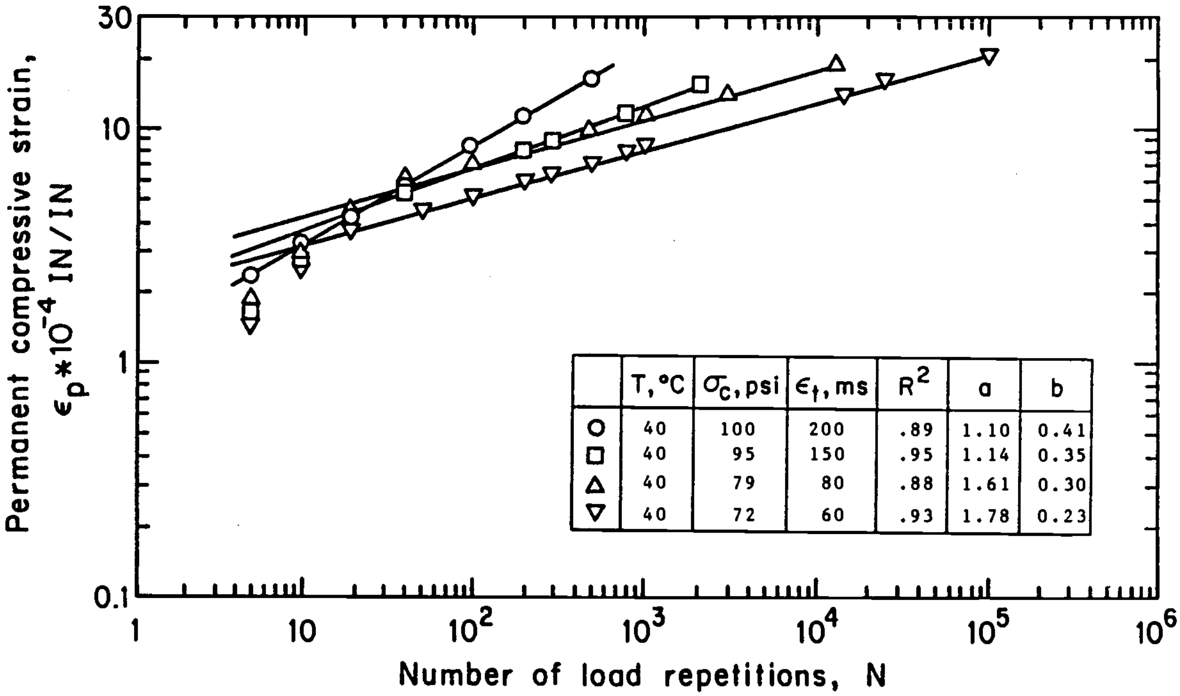


Figure 5.41. Relation between number of load repetitions and vertical strain for marl + 5%.

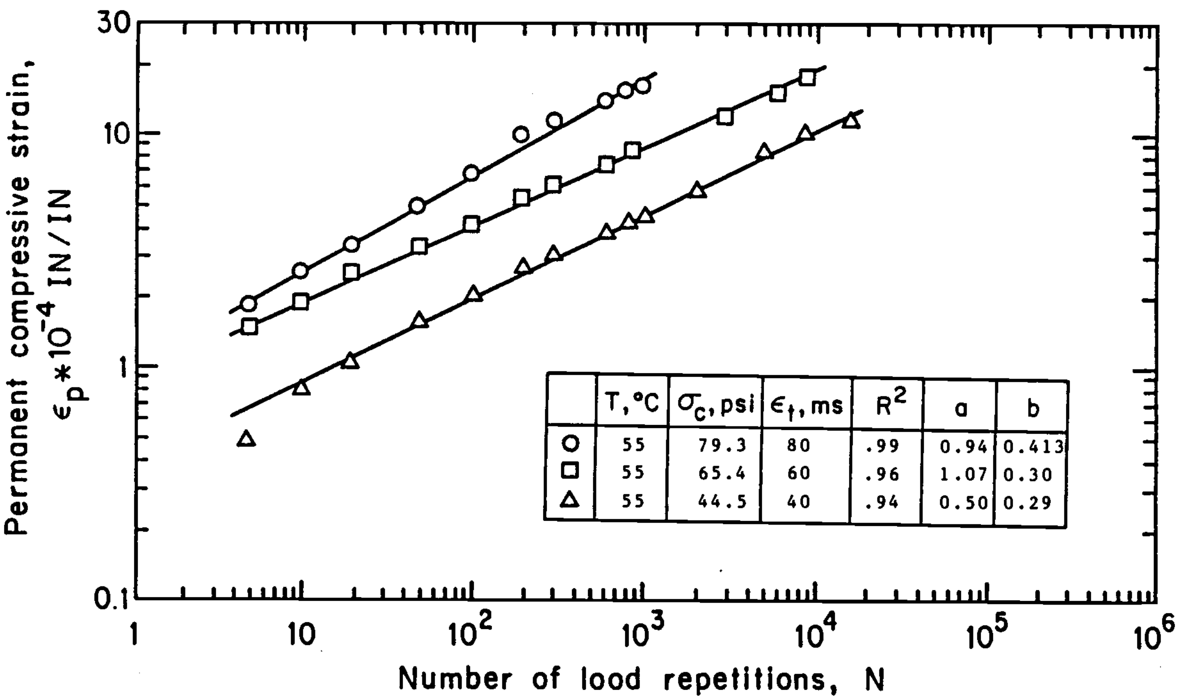


Figure 5.42. Relation between number of load repetitions and vertical strain for marl + 5% cement.

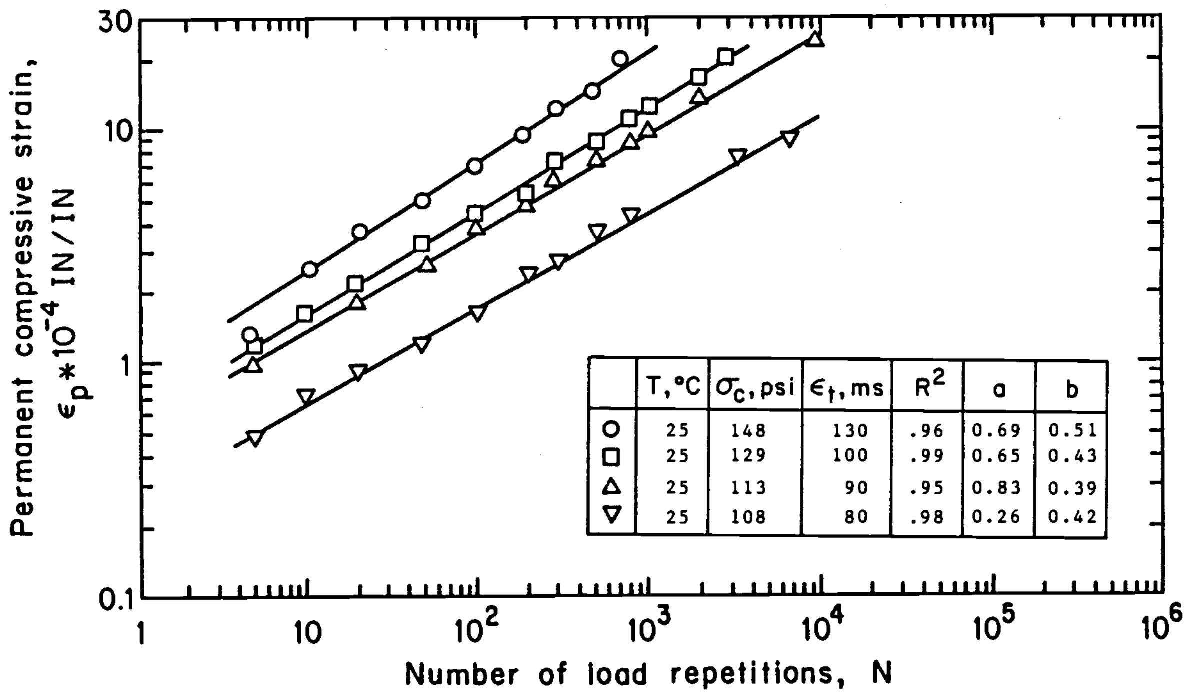


Figure 5.43. Relation between number of load repetitions and vertical strain for marl + 5%, using Chevron USA emulsion.

Table 5.5 Summary of Rutting Results From Various Triaxial Tests

Investigator	Mix Type		$\varepsilon_p = a \cdot (N)^b$	
			$a \cdot 10^4$	b
Akili and Monismith (61)	Dune sand emulsion, 1.5% cement, 7% CSS-1, 21°C (70°F), 5 psi confining pressure			
	Curing time, days	Deviator stress, psi		
	23	10	1.32	0.096
	23	20	2.2	0.228
	10	35	3.65	0.54
	23	35	1.79	0.451
	57	35	1.36	0.355
	116	35	0.42	0.359
	23	40	1.22	0.552
	23	50	2.66	0.78
Kennedy et al (58)	Dense-graded asphalt cement			
	Temperature = 65°F		0.54	0.16
	= 77.5°F		0.88	0.118
	= 90°F		0.61	0.39

PSI = 6.89KN/M^2

°F = 32 + 1.8 (°C)

Tested materials which are abundant locally can be used for road base construction (especially marl) to solve base rutting problems and to reduce the need for rare good quality aggregates. Test results indicated that such materials can perform satisfactorily in fatigue or rutting and therefore can be used successfuly for road base construction. The results indicated that marl is less affected by temperature and cement variations.

Fatigue equations were derived as a function of tensile strain and compressive stress. Rutting equations were also derived for every material at different temperature and stress levels. Fatigue life results can be used to give an estimate for material fatigue life in the field when used with appropriate shifting factor (e.g. 100). On the other hand, rutting results can be used to give indication about material susceptibility to rutting in the field. They can also be used to derive curves for predicting the amount of rutting in the pavement layer. Finally, results were compared with other researchers' results [15, 58, 61-63, 92-95], and were found to be similar to them.

6.0 BEAM DYNAMIC TESTING

The purpose of this chapter is to present results of tests conducted on emulsified asphalt treated materials using repeated beam flexure tests. Effect of temperature, load intensity and strain level on fatigue life are evaluated. Beam bending modulus is also calculated using two different methods. The results of these tests are also compared to diametral test results presented in Chapter 5.0.

6.1 Background

Several researchers have used beam tests for asphalt treated material characterization (Table 6.1). Tested beams have been supported either on an elastic foundation or unsupported. The unsupported beam tests have the disadvantage that tensile strains and creep movements can be induced in the specimen due to weight of the beam.

The beam test using an elastic foundation was selected to evaluate emulsion treated mixes in this research. This test is similar to that used by Barksdale [69] with some modifications (confining device) to enable the researcher to test open-graded mixes. The advantages of this method include:

1) Full support of beam
2) A stress state similar to that occuring in the field except that a uniaxial rather than

Table 6.1. Summary of Beam Tests Used by Selected Investigators.

Investigator	Support Type	Repeated Load Applied at	Sample Size in x in x in	Advantages	Disadvantages
Barksdale (69)	Elastic Foundation	Center of the Beam (top)	3 x 3 x 20	•Simple Test •Full Support	•Uniaxial Test •No Stress Reversal
Majidzadeh (102)	Elastic Foundation	Center of the Beam (top)	2 x 3 x 24		
(103)	Two Point Support	Center of the Beam (top)	1 x 1 x 12 2 x 3 x 16	•Simple Test	•Does not Simulate Field Support •Uniaxial Test •No Stress Reversal
Kallas & Puzinauskas (71)	Two Point Support	Two Points Equally Spaced (top)	3 x 3 x 15		
Monismith (70)	Two Point	Two Points Equally Spaced (below)	1.5x1.5x15		
Kallas (104)	Two Point Support	Center of the Beam (top)	4 x 4 x 15	•Stress Reversal •Unique Equations Apply	•No Full Support •Uniaxial Test •Relatively Complicated Testing Device
Kallas (62)	Two Point Support	Two Points Equally Spaced (below)	1.5x1.5x15		
Santucci & Schmidt (105) Deacon (59)	Two Point Support	Two Points Equally Spaced (below)	1.5x1.5x15		

1 in = 2.54 cm.

biaxial bending is developed. In a uniaxial test, only one axis of the specimen is subjected to bending, such as in beam bending test, while in a biaxial test, two axes of the specimen are subjected to bending, such as in a slab test

3) Simple test setup, and
4) Easily prepared specimens

The disadvantage of this test [69] is that a biaxial state of bending stress is not developed in the specimen. The specimen cannot be subjected to stress reversal (load is applied in one direction) as is the case in the real pavement condition.

6.2 Specimen Preparation

Beam specimens used in this research were 3 inch by 3 inch cross sections and 16 inches long (7.6 x 7.6 x 40.6 cm). All specimens were prepared and compacted using a kneading compactor to have properties (voids and density) similar to those prepared for split tensile tests as follows:

1) The beam mold (Fig. 6.1) was placed in the kneading compactor on a sliding rack (Fig. 6.2). The beam mold was moved manually in the sliding rack during compaction
2) The emulsified asphalt mixture was placed in the beam in three layers

Figure 6.1. Molds used to fabricate beam specimens.

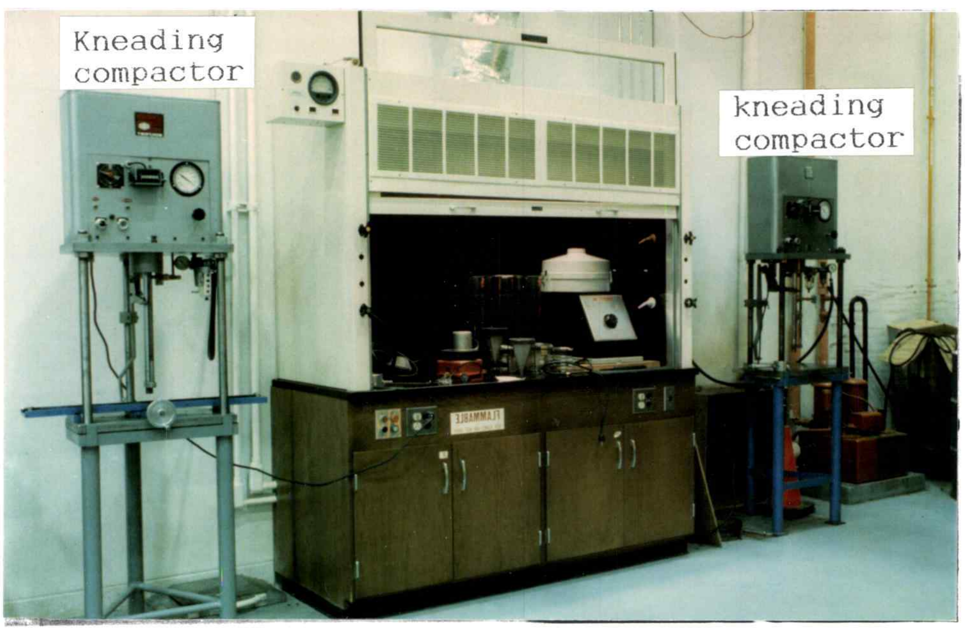


Figure 6.2. Compactors used to prepare beam samples.

3) Each layer was compacted with three passes where each pass consisted of ten tamps at 100 psi

4) Upon completion of compaction, a loading plate was positioned on top of the beam and a static load applied at a rate of 0.25 in/min (0.635 cm/min) until a height of 3 in (7.6 cm) was reached

5) The load head was then held in position for 2 minutes to prevent immediate material expansion

The above procedure was used to compact the dune sand, marl and open-graded emulsified asphalt mixes. However, the specimens prepared by this method required special handling. Mixes were cured for 48 hours in molds at 100°F (37.8°C) and 24 hours in a vacuum desicator cabinet at 25 Hg (63.4 cm Hg). The specimens were then extracted and stored on a horizontal surface to avoid inducing tensile strains in the beam before testing.

6.3 Test Procedure

The emulsified asphalt beam was placed on a rubber subgrade foundation to simulate field support conditions. The fatigue test equipment (Fig. 6.3 and 6.4) consists of a load frame, rubber pad 4 in (10 cm) thick, and pulsing

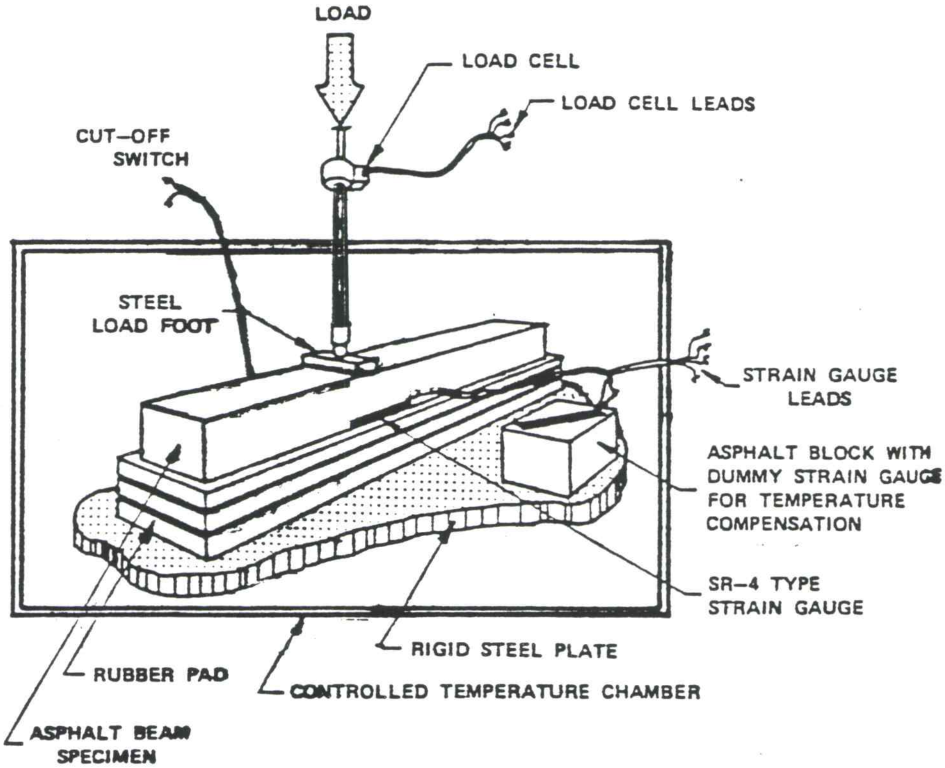


Figure 6.3. Schematic of beam fatigue test (69).

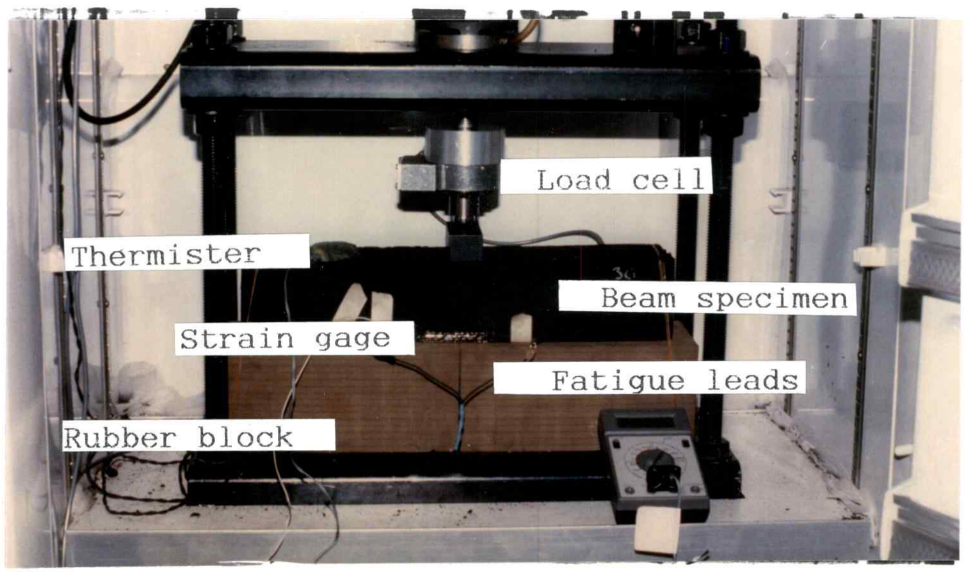


Figure 6.4. Photo of beam fatigue testing setup.

load system. The loading frame, rubber pad and fatigue beam were included within the environmental chamber to control testing temperatures over a range of in-service temperatures. The rubber pad has a subgrade reaction modulus of 112.7 pci (3280 gm/cc), as measured by static loading.

The load was applied to the center of the beam using a rigid steel plate which was 1.25 in wide, 3 in long and 1 in thick (3.2 x 7.6 x 2.54 cm). A SR-4 wire resistance strain gauge (BLH A 9-4) was glued at the center of the beam 0.1 in above the bottom of the beam to avoid leads cutting when the strain gauge was attached to the bottom. The strain gauge was oriented parallel to the neutral axis to measure the maximum bending tensile strain in the beam. Another SR-4 strain gauge was glued to an asphalt block inside the chamber for temperature compensation. Foil tape was then stretched and attached to the bottom of the beam similar to that shown in Fig. 6.5 The foil tape was used to stop the testing machine. When the specimen cracked the tape broke and the machine stopped (Fig. 6.6). The beam fatigue life was then recorded from the machine counter.

Before each test the rubber pad was cleaned, and the emulsified asphalt specimen was carefully centered on top of the rubber. The specimen was oriented so that loading was applied to the beam center. Strain gauge leads were

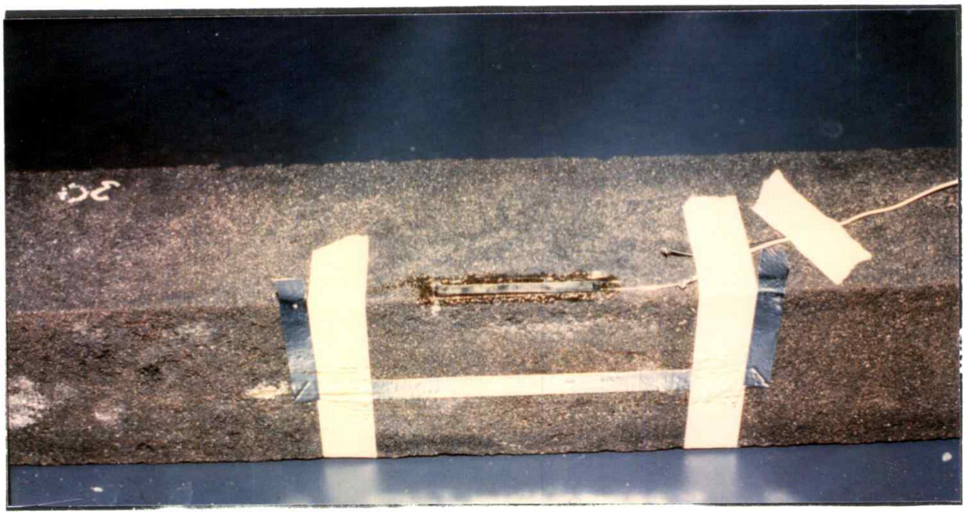


Figure 6.5. Beam ready for fatigue test with SR-4 strain gage attached to the side and foil tape attached to the bottom.

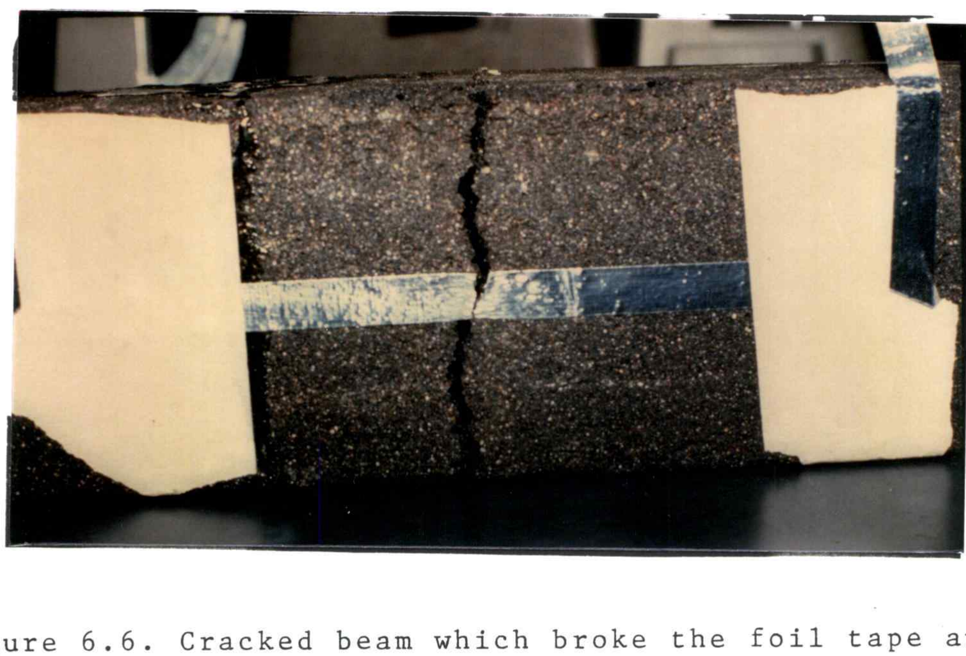


Figure 6.6. Cracked beam which broke the foil tape and stopped the test.

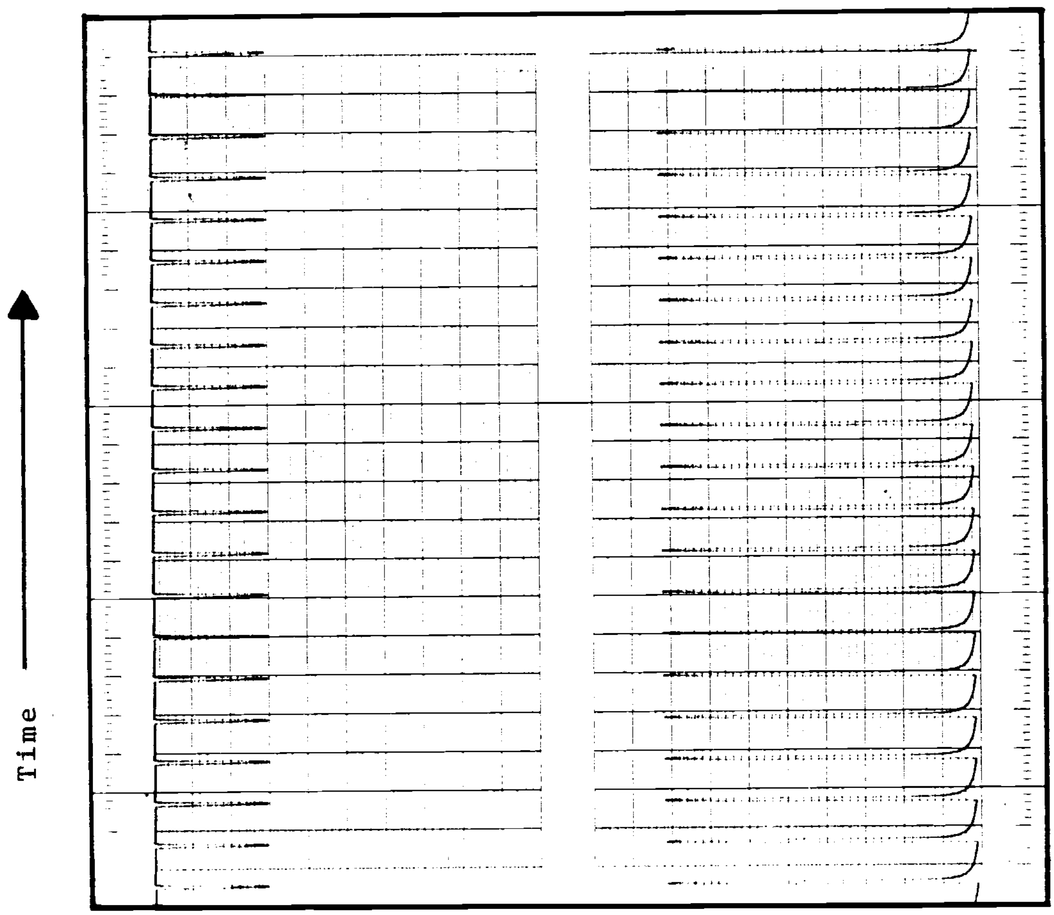
then connected and continuity was checked. A seating load of 12 lb (5.45 kg) was used to hold the loading strip in place. The beam ends were secured to the rubber block using a number of rubber bands to ensure continuous contact between the rubber block and the asphalt beam. Unsecured beams, especially dune sand emulsion and open-graded emulsion, tended to curve after loading and increased in curvature with load application. With increasing curvature, it was noted that the ends of the beam did not contact the rubber block upon load release, creating a gap different from initial testing and field conditions. This resulted in an increase in beam fatigue life, which was eliminated by securing the beam ends.

The strain gauge and load cell are then connected to HP oscillographic recorder (model 7402A). The load was applied to the specimen and both load and tensile strains recorded (Fig. 6.7), when the strain became stable (usually after about 300 repetitions). Test results were recorded on forms similar to those shown in Fig. 6.8.

Repeated loads were applied for 0.1 second at a frequency of 60 cycles/minute. This corresponds to a 30 mph tire speed for actual conditions [69].

6.4 <u>Open-graded Emulsion Beam Testing</u>

To the author's knowledge, this study was the first time open-graded emulsified asphalt mixes have been tested for flexural fatigue. The test procedure used was



(a) Load (b) Strain

Figure 6.7. Example of HP recorder output for the beam test.

BEAM FATIGUE TEST

Material:

Date:

Seating Load:

Sample temperature:

Load Duration:

Load Frequancy:

STRAIN LEVEL	SAMPLE NO.	LOAD(lb)	FAT.LIFE	Beam bending modulus, E_b

Figure 6.8. Form used for beam fatigue test.

similar to that described for the diametral modulus test where confinement was needed to keep the specimen intact.

The open-graded emulsion was confined using an 18 in long membrane having a diameter of 3.5 in. An SR-4 strain gauge was secured to the side at the lowest point in the center. Foil tape was stretched and attached to the bottom, as shown in Fig. 6.9. The rubber membrane was inflated using a 4.5 in tube (Fig. 6.10) and the beam (frozen) was inserted inside the membrane. The membrane ends were then secured using circular plates with foil tape ends attached to them (Fig. 6.11) (since they were attached to machine fatigue leads). After assembling, the membrane was then evacuated using 6 psi vacuum (Fig. 6.12).

Lastly, the strain gauge leads and fatigue wire leads which were attached to the testing machine to stop testing when failure occurred, were connected. The specimen was loaded at the center directly above the strain gauge (Fig. 6.13). During testing the vacuum was regulated using a vacuum regulator as shown in Fig. 6.14.

The membrane material was found to reinforce the beam specimen. This effect results in a slight increase in the beam modulus value, therefore in order to compensate for that, subgrade reaction modulus was increased to account for this effect. To calculate the effect of the membrane, the subgrade reaction modulus (k)

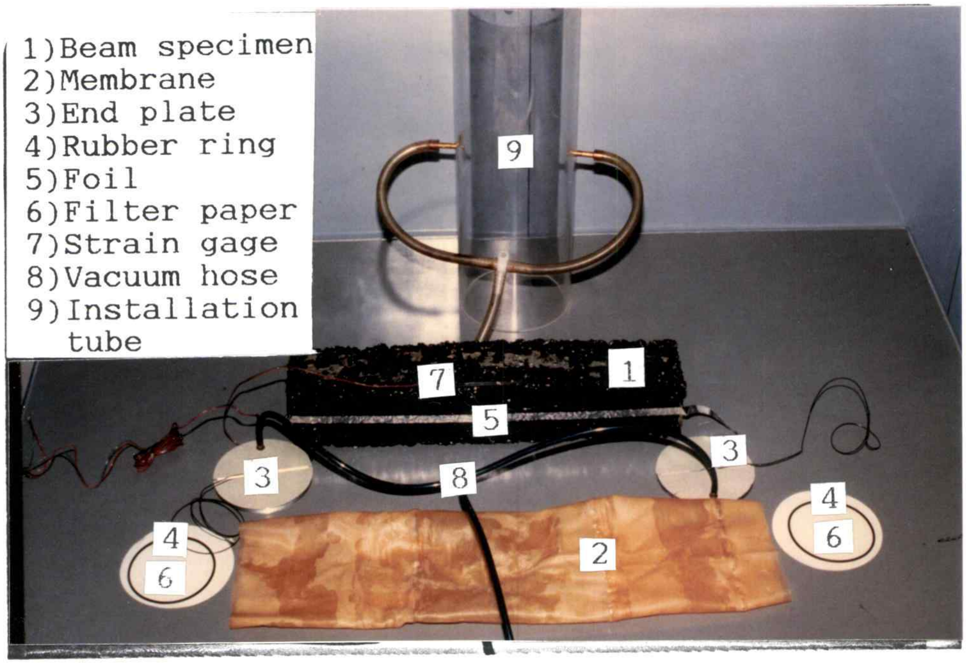


Figure 6.9. Disassembled confining pressure equipment for open graded mix with strain gage and foil tape attached to beam.

Figure 6.10. Installing the membrane on the open-graded beam.

Figure 6.11. Sealing the end of the membrane.

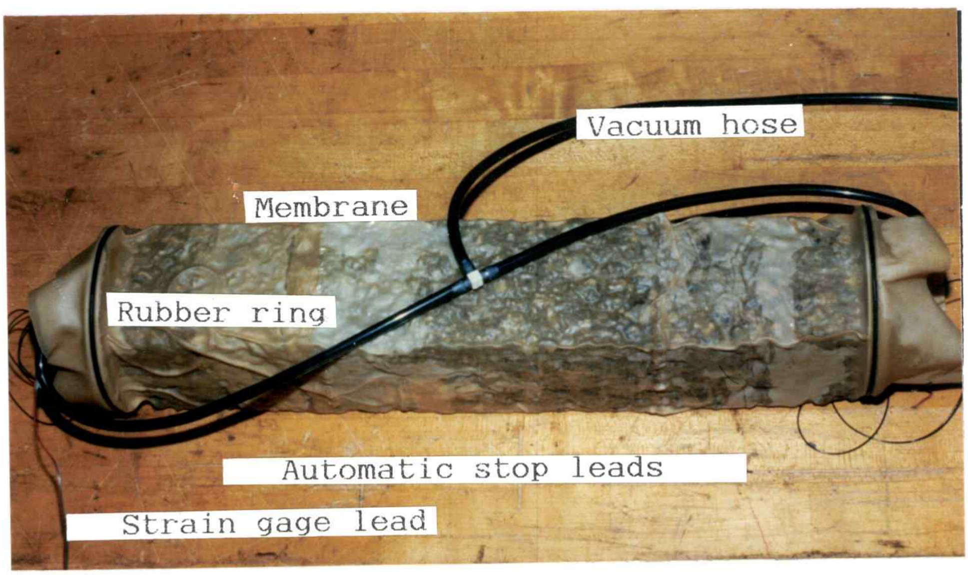


Figure 6.12. Assembled confining pressure equipment.

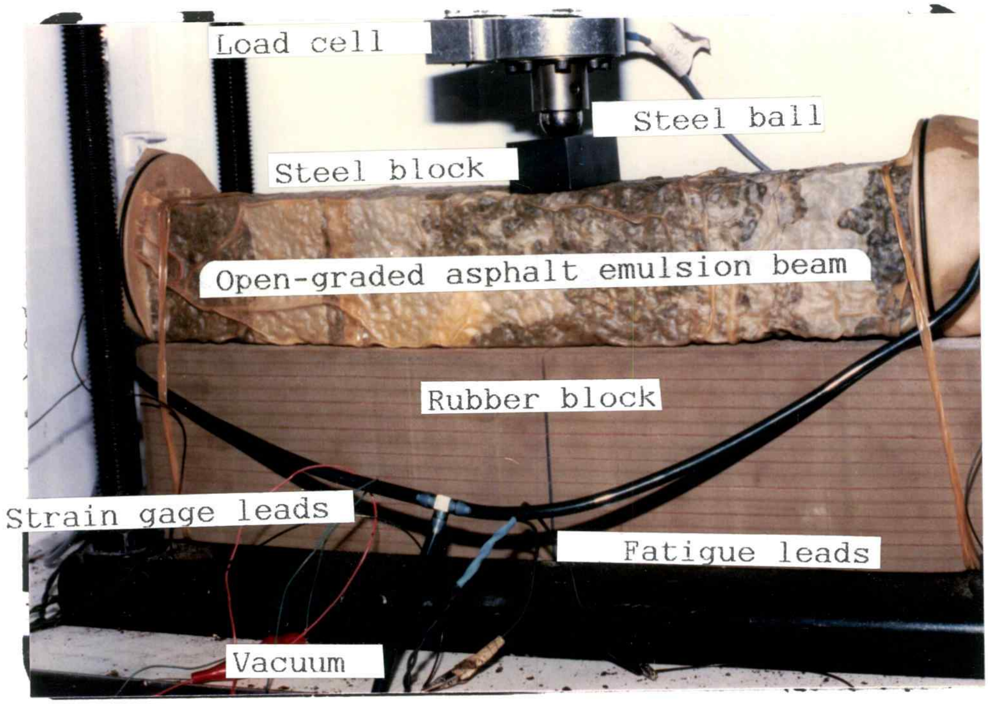


Figure 6.13. Open graded asphalt emulsion beam test setup.

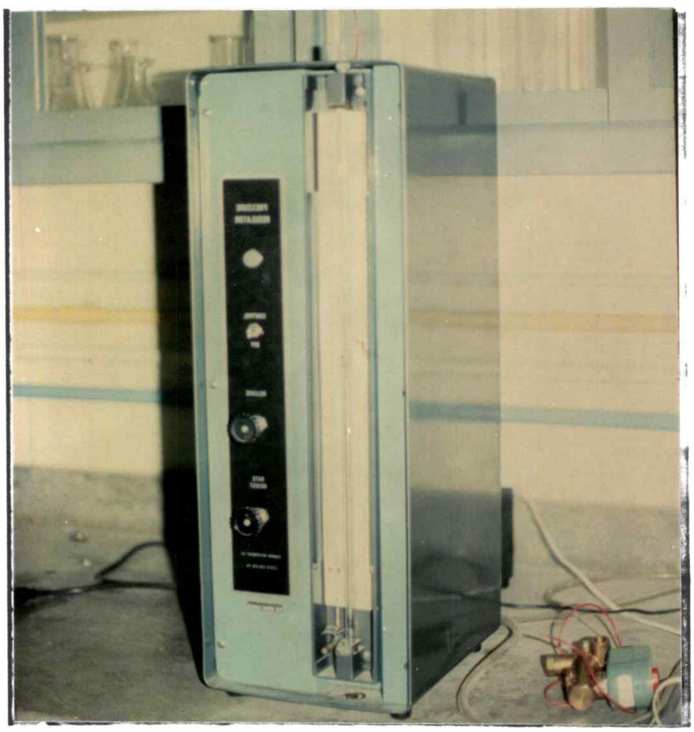


Figure 6.14. Vacuum regulator device.

for the rubber block was first evaluated using a 3 in (7.5 cm) square plate. Then an asphalt beam, 16 in (40 cm), sliced in 1 in (2.5 cm) thick slices, was inserted into the membrane and subjected to a 6 in (15 cm) vacuum. The membrane was then placed on top of the rubber block and loaded in the center using the same steel block. The increase in the (k) value is the effect of the membrane. The membrane was found to increase the subgrade reaction modulus by about 10 pci (291 gm/cc); therefore, the final subgrade reaction modulus was taken as 122.7 pci (3571 gm/cc).

6.5 Fatigue Life Test

The fatigue test results were plotted as a function of measured tensile strain in the beam and load applied to the beam. Such results are linear when drawn on a log-log scale [17, 67, 69, 97].

During testing, the tensile strain in the beam specimen was measured at 300-400 load repetitions. Although the strain gauges were placed at the center of the beam at the lowest point of the beam, they were not the maximum in the beam. The center of the gauge was usually located at a finite distance from the bottom of the beam. Therefore, maximum tensile strains (ε_t) were calculated as follows:

$$\varepsilon_t = \varepsilon_{tr} \quad \frac{H}{2L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.1)$$

where,

ε_{tr} = tensile strain measured by recorder, inch

H = beam thickness, inch

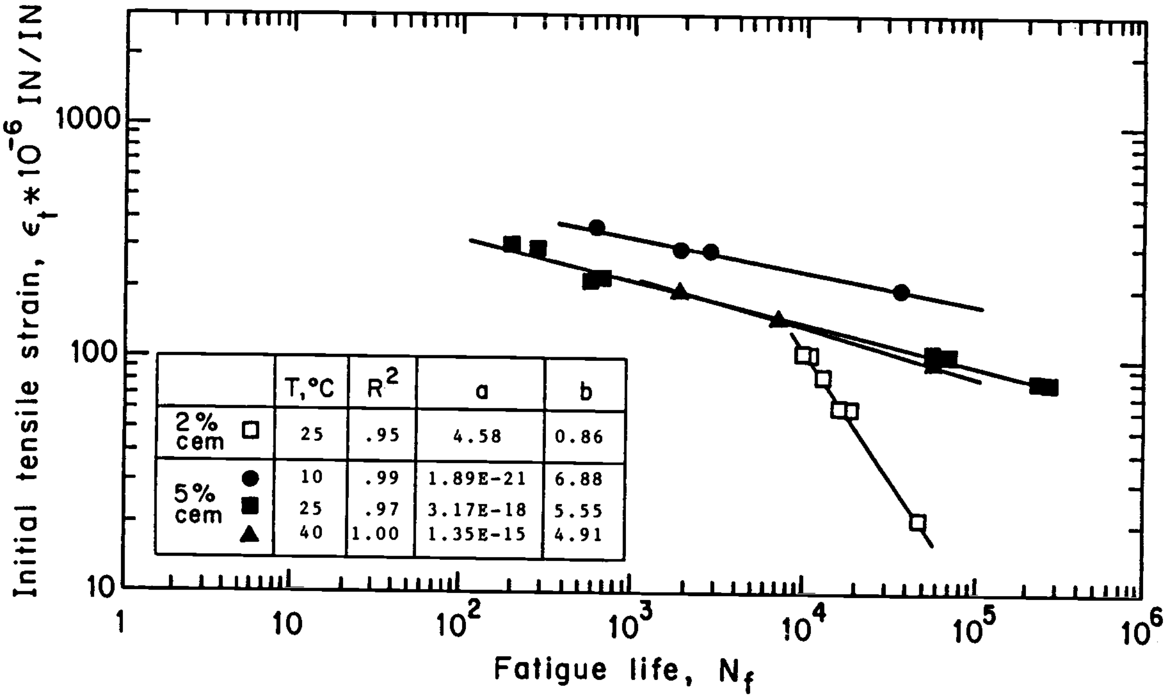
L = distance from neutral axis of the beam to the center of the strain gauge.

Specimens were tested using at least three strain levels to define the fatigue curve. Usually duplicate or triplicate specimens were tested at each strain level.

6.5.1 Fatigue Life Results

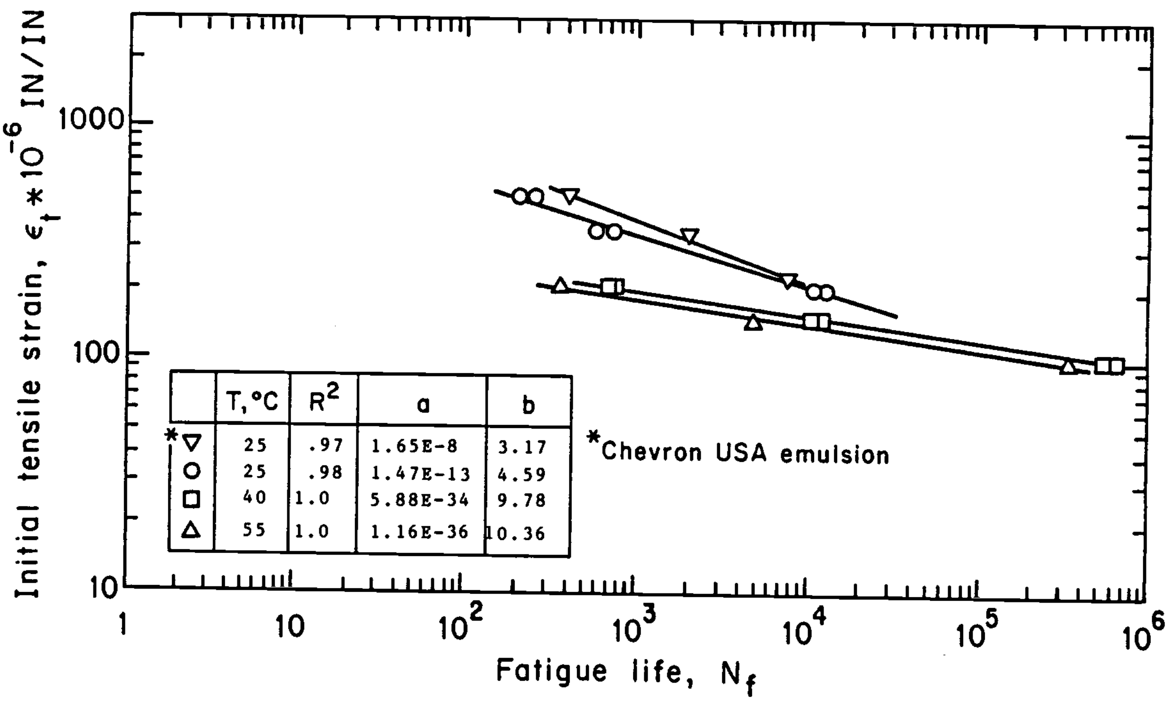
The beam fatigue test results are shown in Fig. 6.15 to 6.19. It is noted that dune sand mixes with 5% cement were tested at 10°, 25° and 40°C (50°, 77° and 104°F). Two cement levels were considered, 2 and 5% at 25°C (77°F). Marl emulsion mixes with 5% cement were tested at 25°, 40° and 55°C (77°, 104° and 131°F). The Chevron U.S.A. emulsion was tested with marl and 5% cement only at 25°C (77°F).

The results indicate that when the temperature increases, fatigue life tends to decrease, which is similar to the results presented by Shahin [17] and Pell [97]. Moreover, the curves for fatigue life at 25° and 40°C (77° and 104°F) for dune sand and 40° and 55°C (104° and 131°F) for marl were very close to each other. Only



	T,°C	R^2	a	b
2% cem □	25	.95	4.58	0.86
5% cem ●	10	.99	1.89E-21	6.88
5% cem ■	25	.97	3.17E-18	5.55
5% cem ▲	40	1.00	1.35E-15	4.91

Figure 6.15. Relation between fatigue life and initial tensile strain for dune sand emulsion beam.



	T,°C	R^2	a	b
*▽	25	.97	1.65E-8	3.17
○	25	.98	1.47E-13	4.59
□	40	1.0	5.88E-34	9.78
△	55	1.0	1.16E-36	10.36

Figure 6.16. Relation between fatigue life and initial tensile strain for marl + 5% cement beam.

a slight reduction of fatigue life was observed. Fatigue curves obtained from this test tend to have slopes close to those obtained from diametral tests. The dune sand emulsion fatigue curve slope tends to increase considerably (and therefore increase fatigue life) when portland cement content is increased from 2% to 5% (Fig. 6.15) where dune sand produced flat slopes as if it is cement stabilized material, due to the effect of Portland cement. The trend is the same when fatigue life is plotted as a function of load applied (Figs. 6.18 and 6.19). Fatigue life tends to increase with decreasing load or decreasing temperature as expected, since the test is a controlled stress test, due to the increased flexibility of the specimen. Further, the fatigue curves tend to be parallel for the same material. This result is similar to that presented by Schmidt and Santucci [67,76], Shahin [17], and Pell [97].

The fatigue life of marl and emulsion mix with 5% cement was found to have fatigue lives 16 times higher than diametral fatigue results at the same strain level, but with close slopes to the diametral. Dune sand emulsion mix with 5% cement shows the same thing but fatigue curves differed from diametral test fatigue curves in that they are parallel. Fatigue curves for dune sand emulsion mix obtained from diametral test, decrease in slope by increasing temperature due to the

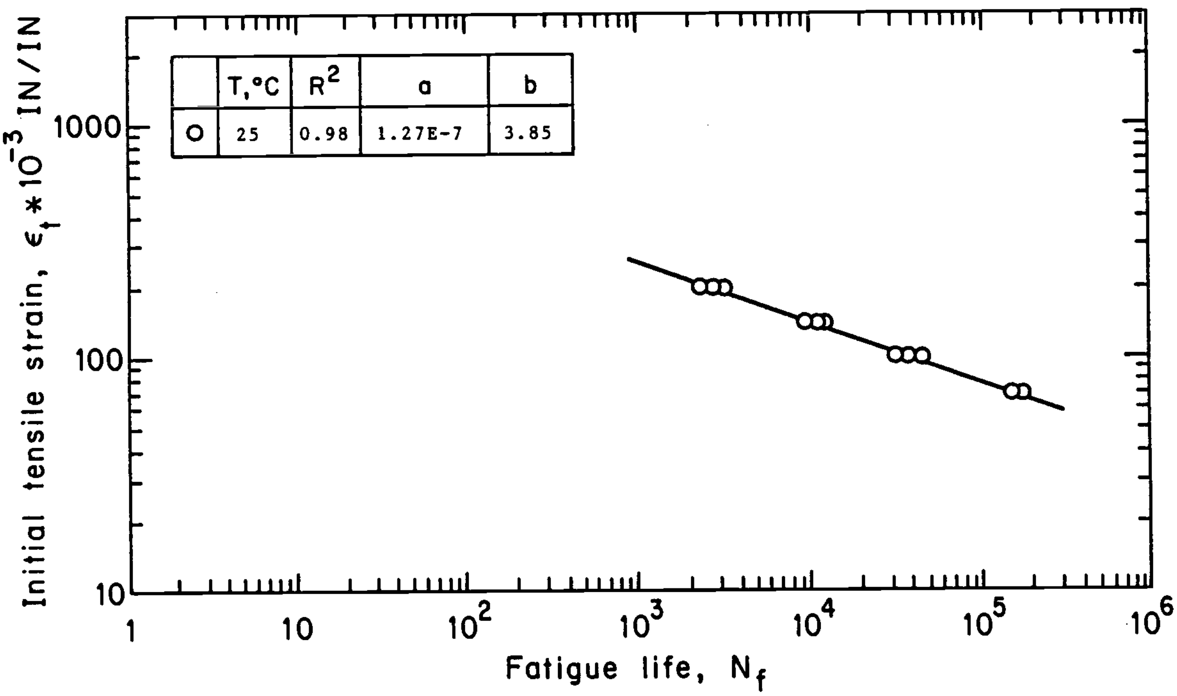


Figure 6.17. Relation between fatigue life and initial tensile strain of open-graded emulsion beam

Table 6.2. Fatigue Equations Developed From Beam Test

Material	% Cement	T°C	$N_f = a.(\varepsilon_t)^{-b}$	
			a	b
Marl (Chev)	5	25	1.65E-8	3.17
Marl (Sa)	5	25	1.46E-13	4.59
		40	5.88E-34	9.78
		55	1.16E-36	10.36
Dune Sand	5	10	1.89E-21	6.88
		25	3.17E-18	5.55
		40	1.35E-15	4.91
	2	25	4.58E0.0	0.86
Open-Graded Mix	0	25	1.27E-7	3.85

effect of plastic flow. This is not observed in the beam test, since all specimens failed with a brittle crack type of failure. Dune sand emulsion mix with 2% cement (Fig. 6.15) was found to have fatigue life 10 times higher than diametral fatigue results, with with close slopes. This might be attributed to the effect of plastic flow on diametral specimens at 2% cement content. The slope of dune sand emulsion mix with 2% cement gave a fatigue curve with "b" value lower than other curves on Fig. 6.15 due to the low cement content compared to that of other curves (5%).

Comparing the results of beam fatigue tests (Table 6.2) to other researchers' values (Table 5.2) indicated that fatigue curves of material tested at 25°C are close to those developed by Santucci [67,76] for cement modified emulsions, but are less than those for dense-graded emulsions [62,95].

The open-graded emulsion mix fatigue life results are shown in Fig. 6.17. This mix was very flexible and had a capability to withstand a high tensile strain. The test results were found to have low scatter and fitted the normal straight line relation. This indicates that fatigue life of open-graded mixes can be determined with the repeated flexural tests with little or no difficulty. Open-graded mix yielded fatigue lives 20-25 times higher than those of marl and dune sand. Marl at 25°C (77°F)

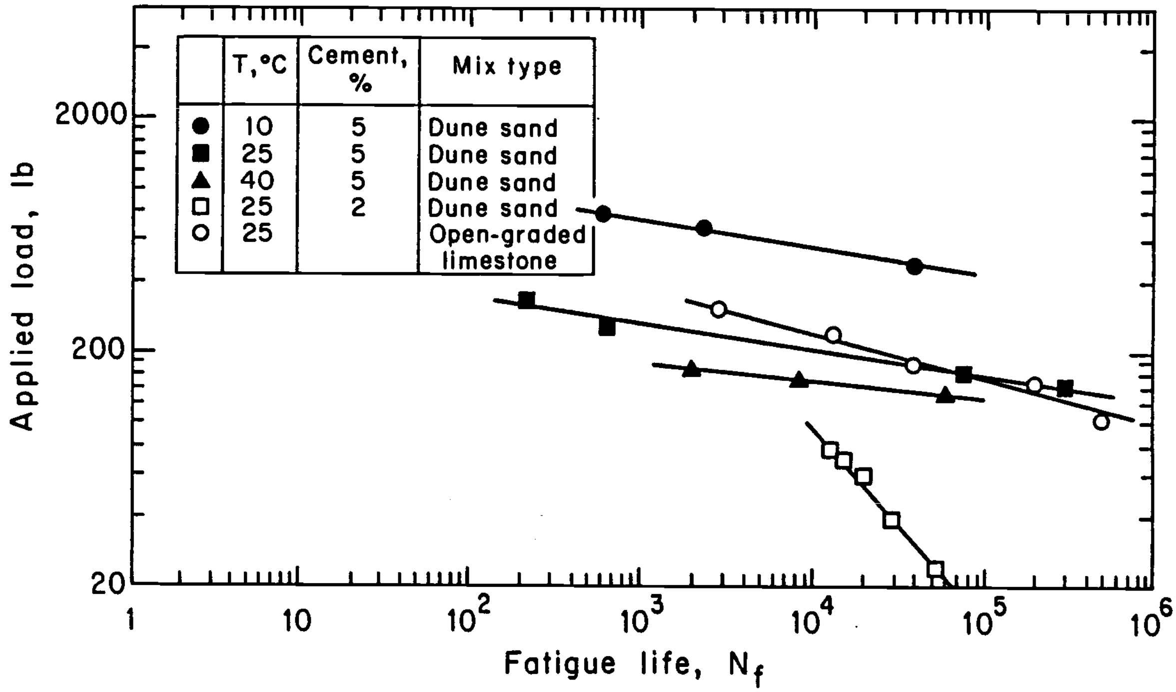


Figure 6.18. Relation between applied load and fatigue life for emulsion treated mixes.

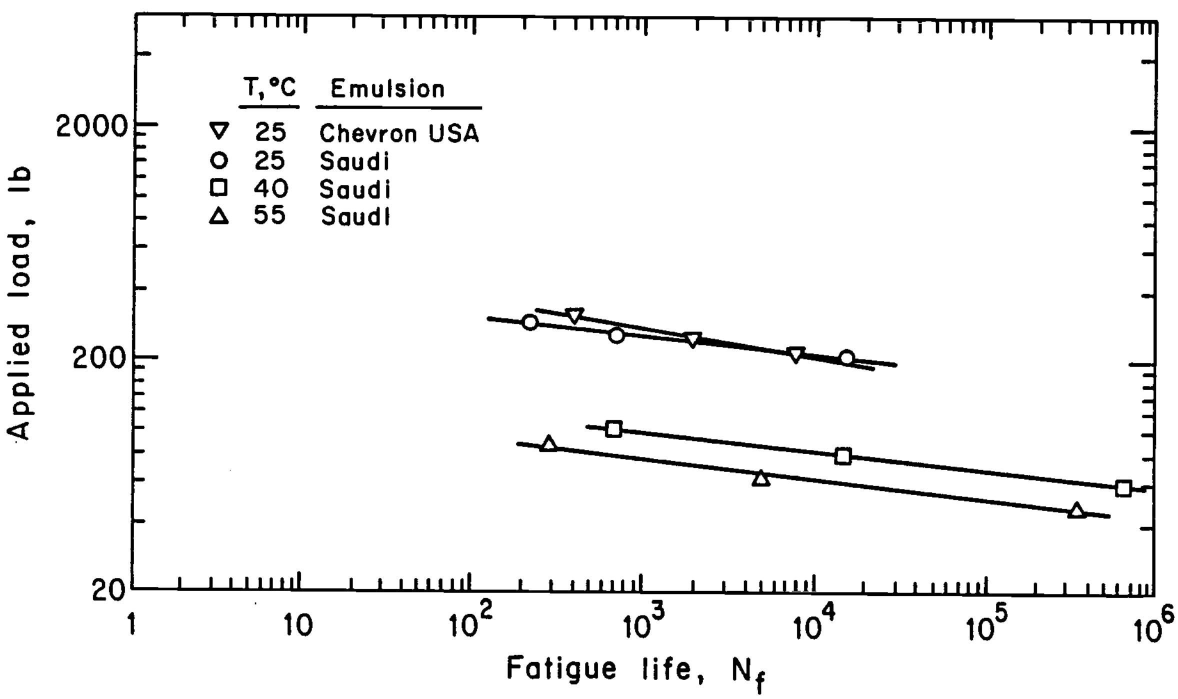


Figure 6.19. Relation between fatigue life and applied load for marl emulsion + 5% cement.

gave fatigue lives 8 times as high as dune sand, but only two times as high at 40°C. Moreover, both marl and dune sand emulsion tend to give similar fatigue-load curves at 25°C (77°F) (Figs. 6.18 and 6.19) which are close to that exhibited by open-graded mix. The dune sand emulsion mix with 2% cement gave a steep fatigue-load curve. This trend might be attributed to the effect of lower cement content.

6.6 Beam Bending Modulus

The bending modulus was calculated for the beams tested using two methods. The first method was with the use of the beam equation [69] While the second method was the use of a finite element technique [106,107].

6.6.1 Beam Equation

This equation is based on the Winkler theory (beam on elastic foundation theory) which assumes that the beam is elastic and is supported on a foundation consisting of a very large number of closely spaced linearly elastic springs [69].

The bending modulus can be evaluated based on the measured strain of the beam and loading. The bending modulus of the beam is calculated as follows [69]:

$$E_b = C \times \frac{(P\rho)^{4/3}}{4IK^{1/3}} \quad \text{............(6.2)}$$

where,

E_b = Beam bending modulus, psi.

P = Load applied to the beam, lb.

= Radius of curvature of the beam which is equal to the depth of the beam divided by two times the measured tensile strain (maximum) = $D/(2\ \varepsilon_t)$.

I = Moment of inertia of the beam, in^4 = $BD^3/12$, B is beam width, D is beam depth.

K = Modulus of subgrade reaction of the rubber pad, pci.

C = Correction factor obtained from Fig. 6.20 based on λ and L, where

$\lambda = (K/4EI)^{1/4}$,

L = beam length, 16 in.

E = modulus of elasticity of the beam

For each beam, a correction factor was determined, and the beam bending modulus calculated using the above equation.

6.6.2 Finite Element Method

The beam bending modulus (E_b) was also calculated using Finite Element techniques. An iterative procedure was used to generate E_b values which were then compared to the values obtained by the beam equation.

STRUDL (version 3) known as (IUG ICES - STRUDL II VMO) was used to analyze and solve the beam as a finite element problem [106, 107]. The beam was formulated as a plain strain problem* since it has a uniaxial stress state. No variations in strain or stresses were expected across the beam width.

The beam, steel strip, and rubber subgrade were divided into elements as shown in Fig. 6.21. Full friction was assumed between rubber subgrade and asphalt beam based on experimental observations. All edge nodes were assumed to be free except those on the bottom of the rubber subgrade. Those points were restricted in the vertical direction but released in the horizontal direction. Since this is a symmetrical problem, only half of the beam was used to run the program with half of the loading (P/2). Nodes along the vertical cutting line (line of symmetry) were then restricted in the horizontal direction.

The load, P_j and tensile strain ε_{tj} was measured for each beam. Then, the beam bending modulus was calculated using the procedure described in Fig. 6.22. In this procedure, an initial value of E_{bj} is assumed, for example, E. Using STRUDL, the tensile strain near the bottom at the center of the beam is calculated, for example, ε_{tij}. The calculated tensile strain is then compared to the measured one. If both are not equal,

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* A state of plane strain is said to occur when the strain components in the z direction are zero ($\varepsilon zz = 0$), while it is not the case for x and y directions [99].

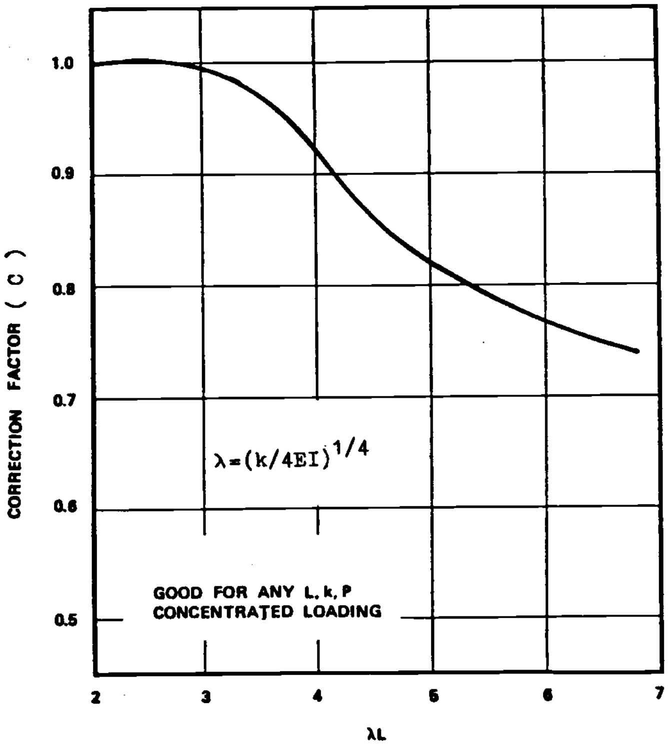


Figure 6.20. Chart for determining correction factor C for calculating bending modulus (69).

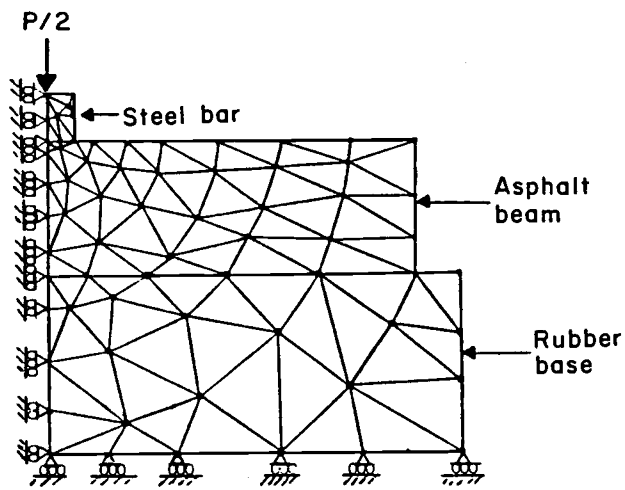


Figure 6.21. Beam test formulation for finite element analysis.

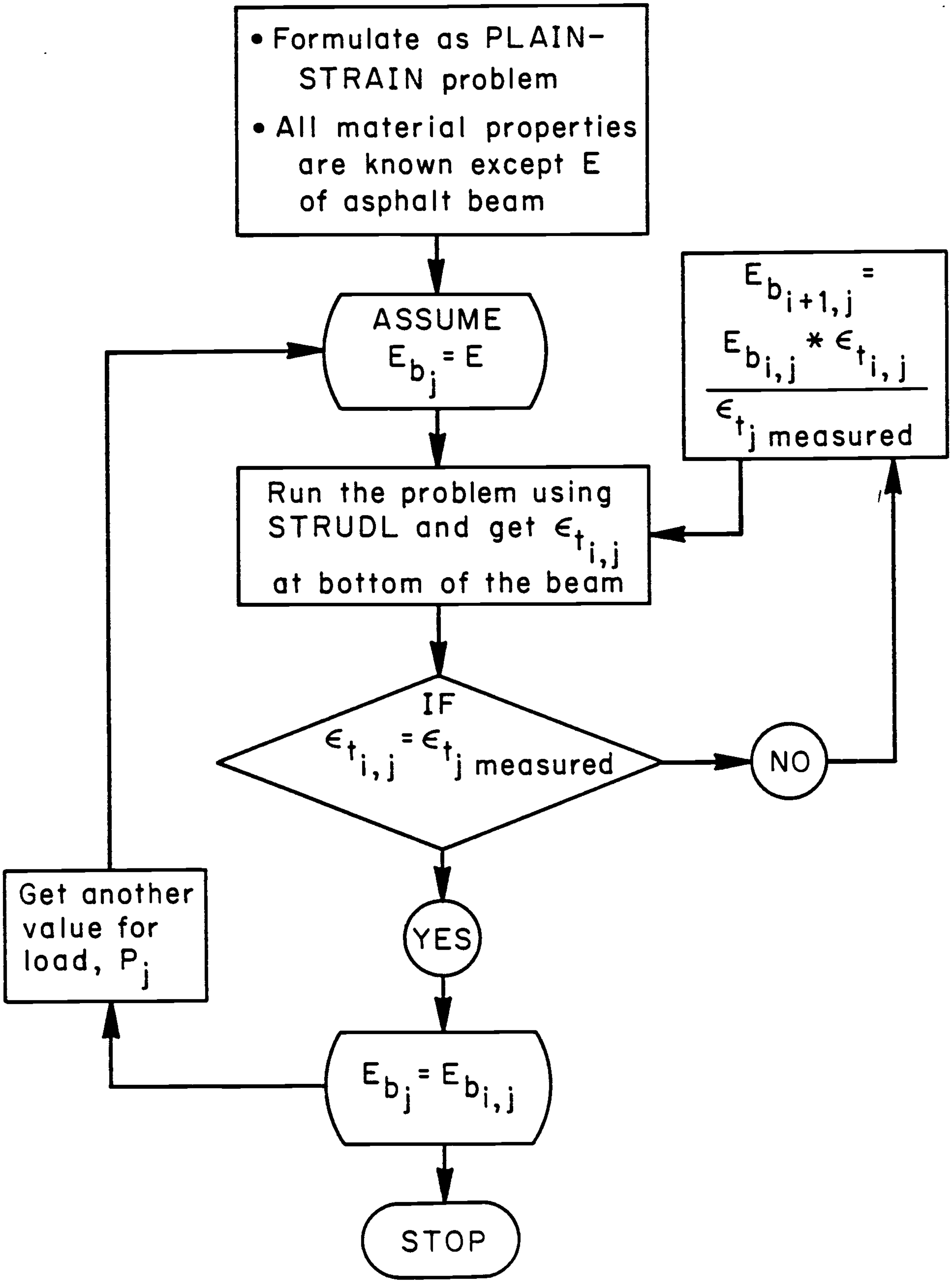


Figure 6.22. Beam analysis flow chart.

then the assumed E_b-value is corrected using the following equation:

$$E_{b\ i+1,\ j} = E_{b\ i,j} \times \left(\frac{\varepsilon_{ti,\ j}}{\varepsilon_{tj} \text{ measured}}\right) \quad .....(6.3)$$

where,

$E_{b\ i+1,\ j}$ = Bending modulus of beam j at iteration i+1.

$E_{b\ i,j}$ = Bending modulus of beam j at iteration i.

$\varepsilon_{t\ i,j}$ = Calculated maximum tensile strain at iteration i for beam j.

ε_{tj} measured = Actual tensile strain for beam j from experimental work.

This procedure was found to converge to the solution in no more than three iterations 92% of the times and in four iterations 97% of the times. When $\varepsilon_{ti,j} = \varepsilon_{tj}$ measured, then beam bending modulus is equal to $E_{bi,j}$. The procedure is repeated for other beams by selecting appropriate value of P_j and ε_{tj} measured.

The advantage of this procedure is that it considers materials properties such as Poisson's ratio which is not considered in the beam equation. Morover, it eliminates the use of a correction factor which influences equation 6.2. The finite element method can also be adjusted to consider different loading, or boundary conditions. The only disadvantage of the finite element method is its high cost when used on a mainframe.

6.6.3 Beam Modulus Results

The results of modulus calculations are shown in Figs. 6.23 to 6.27 for dune sand, marl and open-graded emulsion mixes. The results indicate that the bending modulus tends to decrease with increasing temperature and initial tensile strain or with decreasing cement content. Values obtained by both methods have the same trend. Furthermore, values obtained using the finite element method are closer to those obtained by the diametral test (Chapter 5) than those values obtained by beam equation. Values calculated using the finite element method are similar to the values of the diametral test for all materials except at 25°C (77°F), where values calculated are higher than those produced by the diametral test.

Values calculated with the beam equation seem to underestimate the bending modulus of open-graded and marl mix when compared to the diametral test. Use of this equation also tends to overestimate modulus values of dune sand emulsion.

6.6.4 Saudi vs. Chevron, U.S.A. CSS-1h Emulsions.

Two types of emulsified asphalts were used with marl + 5% cement. The first was a CSS-1h emulsion produced by Sand Still Company, and the second a CSS-1h produced by Chevron, U.S.A. Company. The Chevron emulsions were

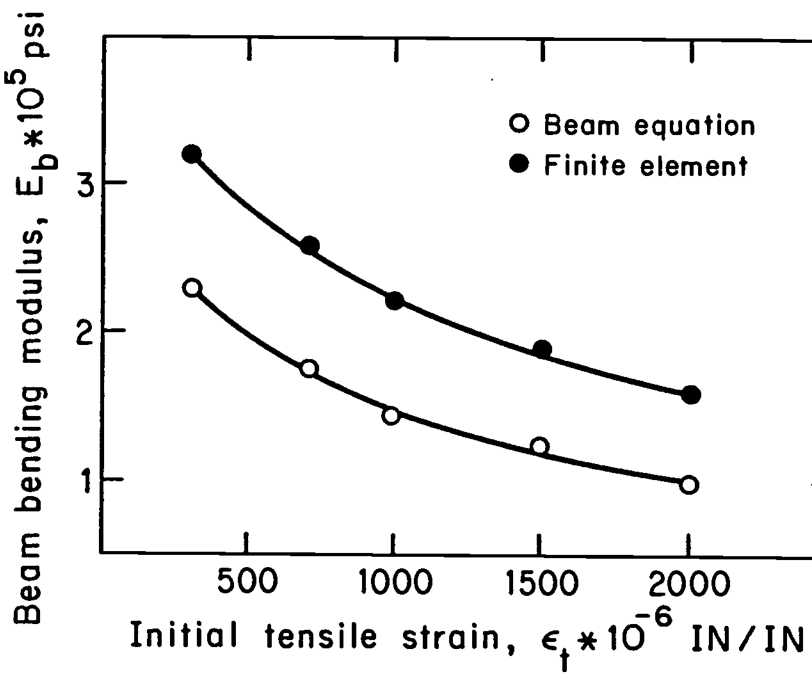


Figure 6.23. Effect of initial tensile strain on bending modulus of open-graded asphalt emulsion at 25°C.

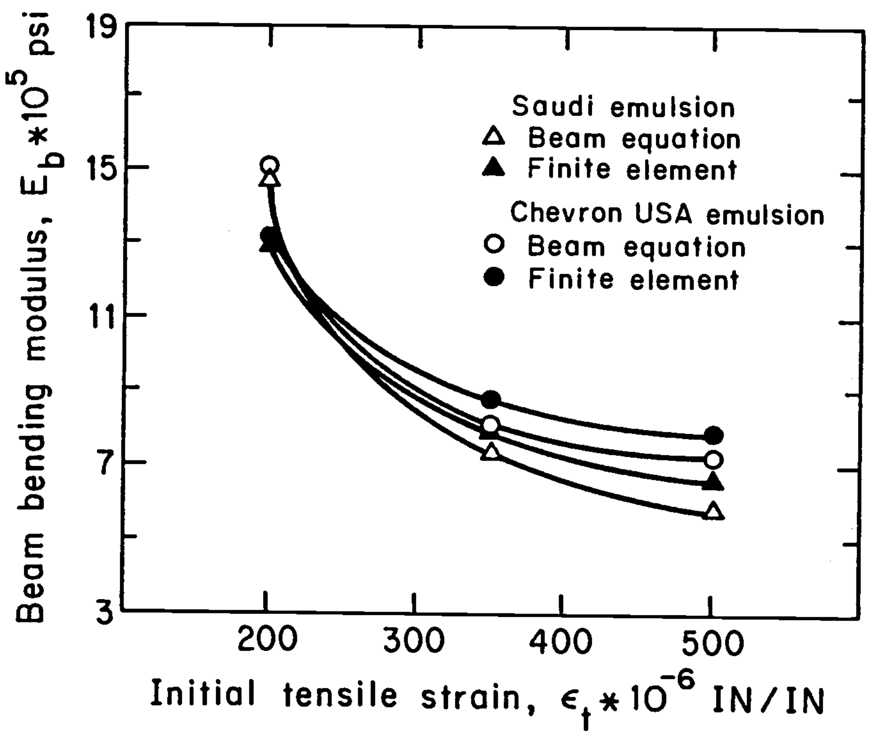


Figure 6.24. Effect of initial tensile strain on bending modulus of marl emulsion + 5% cement at 25°C.

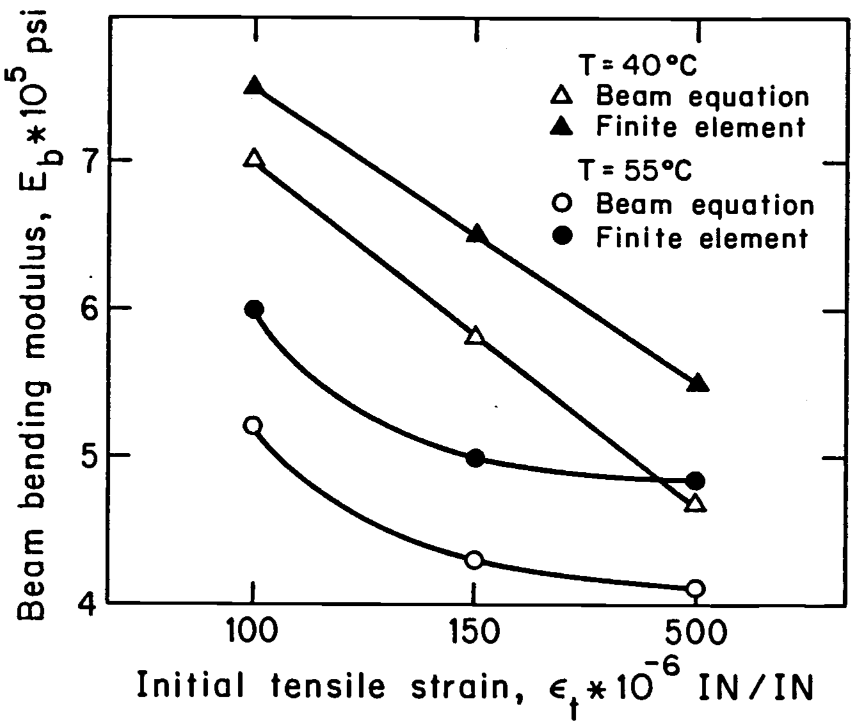


Figure. 6.25. Effect of initial tensile strain on beam bending modulus of marl mix + 5% cement.

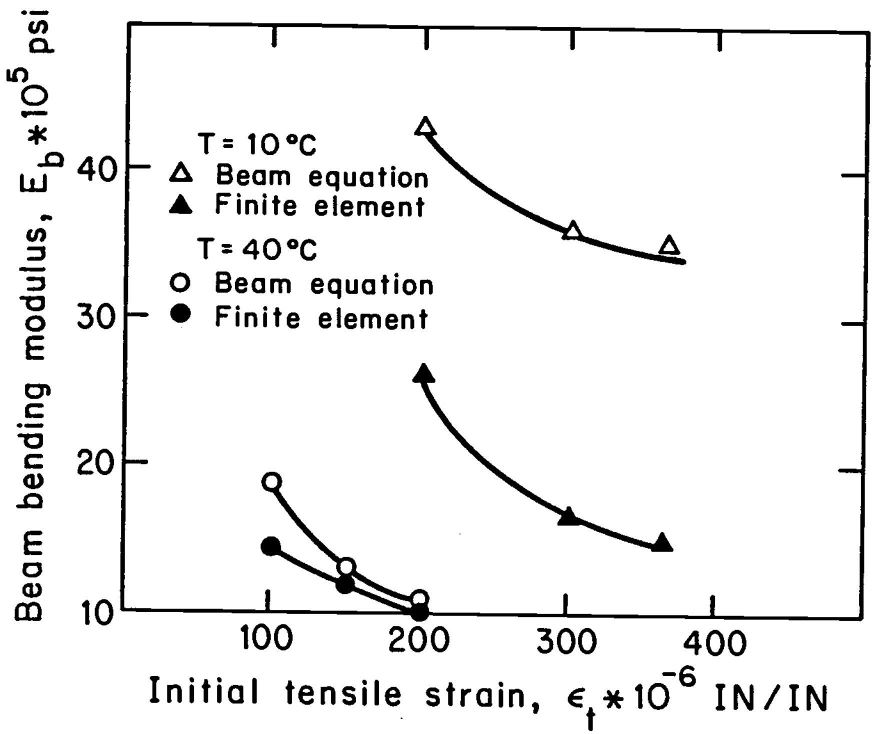


Figure 6.26. Effect of initial tensile strain on beam bending modulus of dune sand emulsion mix + 5% cement.

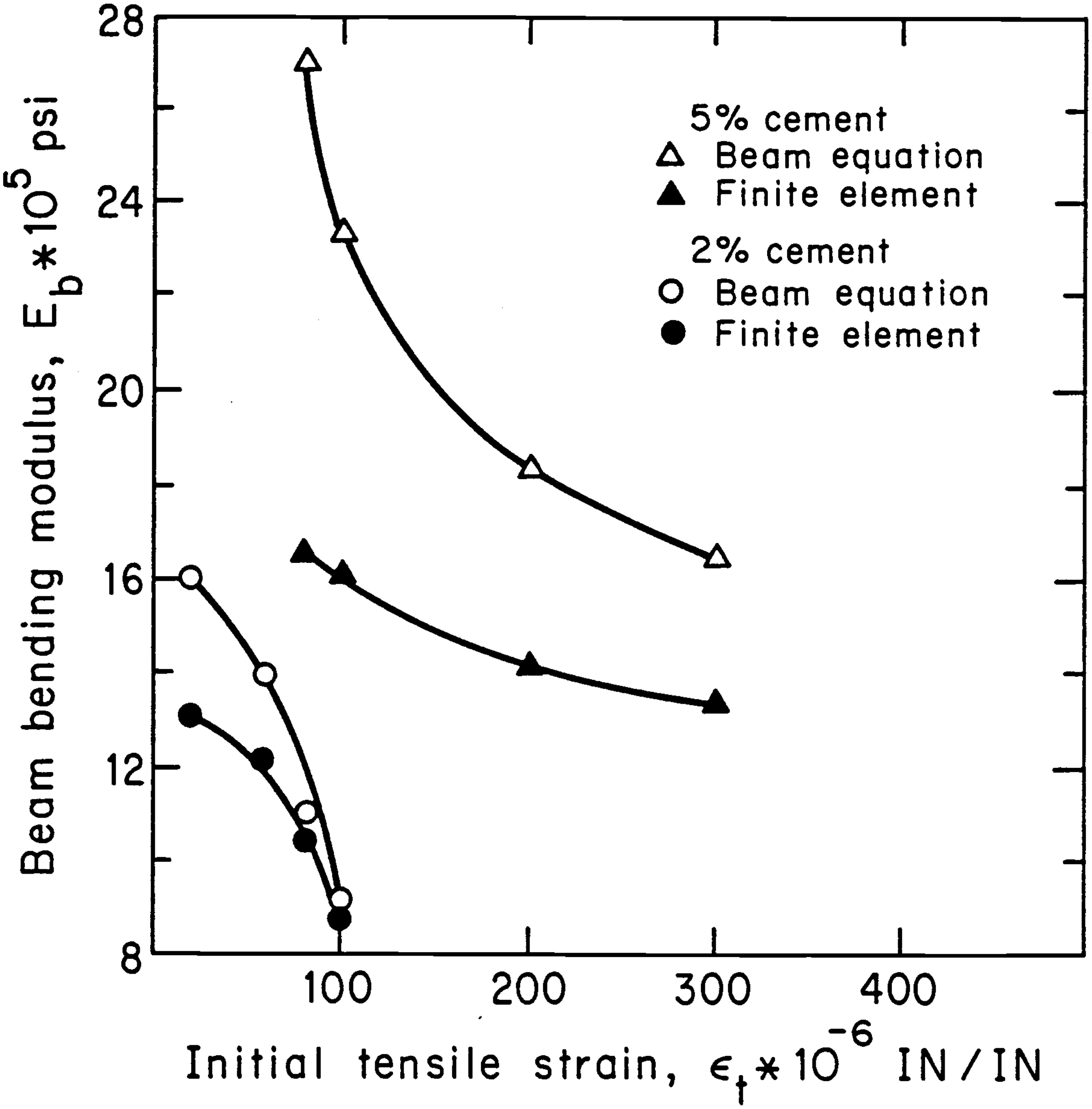


Figure 6.27. Effect of initial tensile strain on bending modulus of dune sand mix at 25°C.

tested at only one temperature (25°C) due to the limited amount received. The properties of both emulsions are shown in Table 4.2.

A statistical F-test was used to test for the difference between the effects of the two treatments. Tests were conducted at α = .1 (90% confidence). As shown in Table 6.3, the hypothesis that both tests are similar (have the same effect) could not be rejected at α=0.1 for split tensile strength, and fatigue life for diametral and flexural test. The hypothesis was rejected for modulus of resilience and beam bending modulus. The two way analysis of variance (Table 6.3) was used to test the effect of the two treatments. F-test was calculated for each test as follows:

F = M.S. among/M.S. error

where,

M.S. among = Mean Square among treatments

M.S. error = Mean Square error.

The calculated F-test was then compared to Table (F) value at 90% confidence and 1 and 8 degrees of freedom.

$$F_{(0.9,1,8)} = 3.05$$

Since F values are smaller than F table, for fatigue life and split tensile strength, then the hypothesis (H_o) that both treatments have the same effect cannot be rejected (i.e. treatments have the same effect). For modulus, since F values is greater than F-table, the

Table 6.3. Statistical Test Results.

Test Type:*	Diametral Test						Beam Flexure			
	S_t Psi		M_R Psi		N_f		N_f		E_b Psi	
Emulsion Type:*	Sa	Ch	Sa	Ch	Sa	Ch	Sa	Ch	Sa	Ch
Observation #										
1	83	86	750000	890000	250000	100000	14000	7800	1200000	1200000
2	85	84	790000	840000	20000	30000	13500	12500	800000	880000
3	80	82	770000	892000	18000	29000	600	800	650000	790000
4	64	62	764000	820000	13000	15000	210	190	580000	560000
5	60	65	720000	830000	10500	12000	250	230	730000	800000
6	59	61	700000	730000	3700	5400	750	820	1370000	1400000
7	43	41	660000	690000	2200	7000	230	400	120000	117000
8	40	40	500000	520000	700	1200	650	2000	700000	720000
9	39	41	800000	950000	500	750	1500	1700	590000	630000
M.S. Among	4.500		.2785E11		.7768E9		.1531E7		.7081E10	
M.S. Error	2.875		.1327E10		.1325E10		.2395E7		.1253E10	
F Ratio	1.565		20.99		0.5863		0.6394		5.651	
F(0.9,1,8)	3.46		3.46		3.46		3.46		3.46	
Reject Ho, M1=M2	No		Yes		No		No		Yes	

* S_t = tensile strength

M_R = modulus

N_f = fatigue life

E_b = beam bending modulus

Sa = Saudi emulsified asphalt (CSS-1h)

Ch = Chevron USA emulsified asphalt (CSS-1h) hypothesis is rejected. Therefore, it can be said that Chevron USA emulsified asphalt produced higher modulus values (stiffer mixes), otherwise both emulsions have similar effects at 25°C (77°F).

6.7 Summary

The beam test was used to evaluate sand and marl emulsion treated mixes as well as open-graded emulsified asphalt. The results indicated a considerable increase in fatigue life over that measured with the diametral test; however, the slopes of the curves are close to those produced with the diametral test, as was discussed earlier. Dune sand curves were found to be parallel to each other at different temperatures due to the elimination of the plastic flow effect which was observed in the diametral test. Fatigue life was found to increase by 16 times over diametral values for 5% cement mixes and 10 times for mixes with 2% cement due to the effect of the cement and diametral failure mode.

Two methods were used to calculate beam bending modulus: a finite element method and the beam equation. The finite element method was found to give close or similar values to those measured with the diametral test. Use of finite element technique provides a fundamental solution for the beam test. Moreover, it provides the chance of evaluating different material properties and loading conditions.

Open-graded emulsified asphalt was evaluated for the first time in this experiment using repeated flexure tests. The fatigue curves obtained for all mixes had little scatter (Table 7.2).

7.0 DEVELOPMENT OF PAVEMENT THICKNESS DESIGN CHARTS FOR USE IN SAUDI ARABIA

Design charts for thickness design are developed in this chapter based on modulus results and fatigue life curves obtained from the beam test as it is closer to field conditions than the diametral test. A suitable shift factor was applied to shift beam fatigue results to represent field conditions based on what other researchers had used. Only dune sand and marl emulsion mixes with 5% cement were considered, since this gave a better fatigue and rutting resistance performance than with 2% cement, and open-graded emulsion mix.

7.1 Design System

The analytical procedure followed to produce design charts includes:

1) Selection of model
2) Evaluating material properties and environmental factors
3) Selection of design criteria (appropriate failure criteria)
4) Analysis of pavement structure for different thicknesses
5) Determination of equivalent 18 kips axle load allowable

6) Developing design charts

This procedure is summarized in Fig. 7.1. A more comprehensive procedure is given in Reference [22]. Each of these steps is discussed in more detail in the following sections.

7.2 Model Selection

Many researchers have attempted to develop a comprehensive and realistic model. Their efforts resulted in a realistic, simple and physically sound solution. The solution of these models is available in the form of tabular or graphical data such as that provided by Santucci [76], or as computer programs such as SHELL BISAR.

Since the computer programs have a greater capability and versatility, SHELL BISAR was selected for use in this research.

7.3 Material Characteristics

Emulsified asphalt mixes properties were obtained from results of this research. Other construction materials (such as asphalt cement, marl subbases) information was obtained mainly from local specifications [52,54] and from available field data.

Subgrade materials in Saudi Arabia's specifications are characterized using CBR, therefore CBR was used to characterize these materials. Depending on the road type and intended use, CBR was varied between 5 and 40. Since

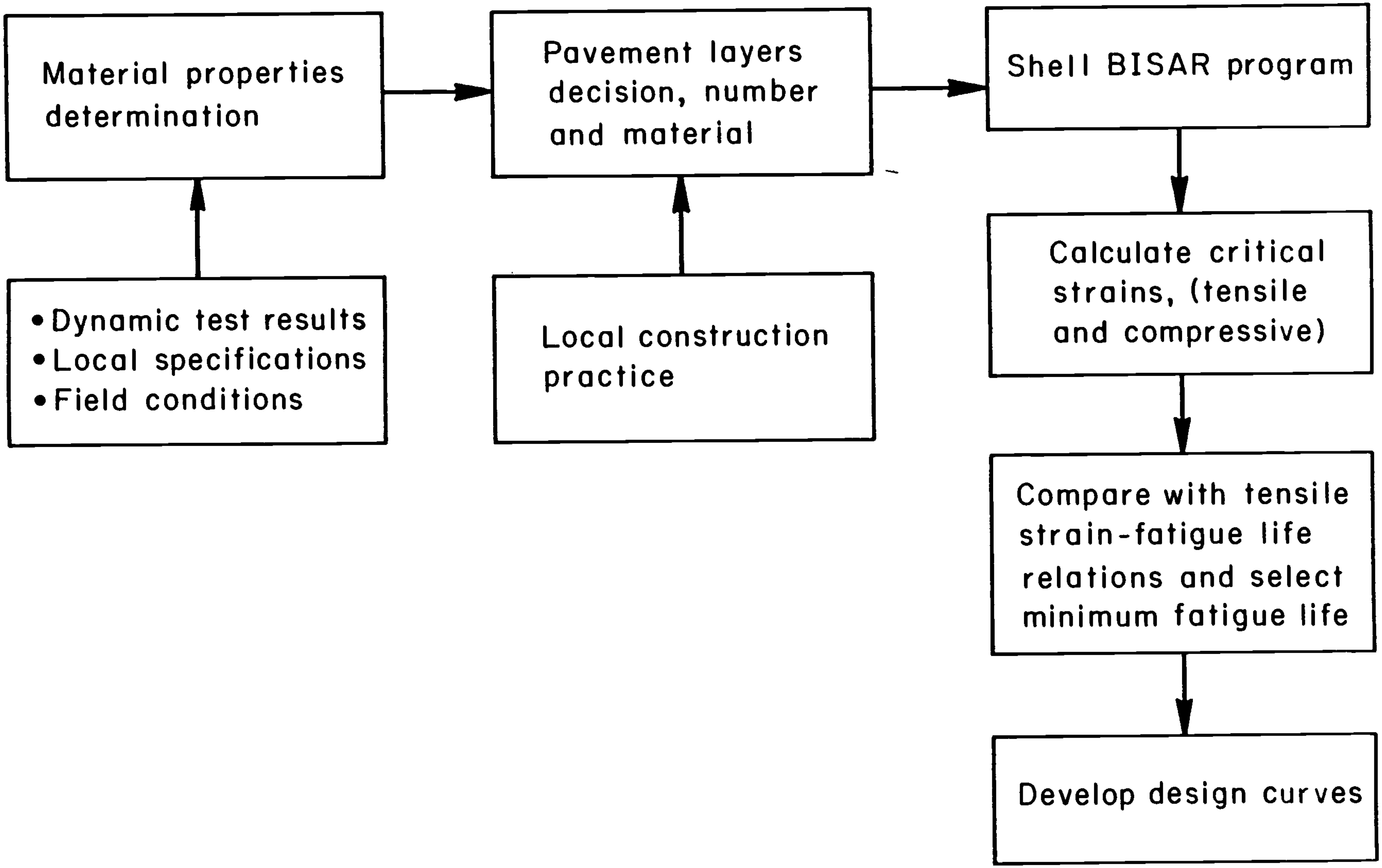


Figure 7.1. Procedure used to develop design charts.

most of the roads are constructed using marl, the modulus of subgrade was obtained using the formula [76, 100],

$$E_s(psi) = 1500(CBR) \quad \ldots\ldots\ldots\ldots \quad (7.1)$$

The stiffness of emulsified asphalt treated materials was determined from the test results reported in Chapter 5 and air cured specimens. Since the modulus of resilience of emulsion treated materials is affected by temperatures and curing time, modulus values cured at field conditions (40°C, 104°F) were found to vary with the log of curing time with the highest increase in modular value obtained after one day. Modulus values tend to continue increasing for five to six months [84]. Therefore design modulus values were determined from specimens cured in field conditions (40°C, 104°F) after four days. These values are expected to be representative of field conditions since they are 70% of ultimate cure values. After air curing, the materials were found to have the following modulus values, $5*10^5$ psi for dune sand emulsion mix, $4*10^5$ psi for marl emulsion mix, and $1.5*10^5$ for open-graded emulsion mix. The stiffness used for conventional asphalt concrete was $7*10^5$ psi [75].

7.4 Design Criteria

Design procedures based on multilayer elastic theory limit distresses caused by fatigue cracking at the bottom of asphalt concrete layer and rutting at the surface of subgrade [64, 100, 76]. Maximum tensile strain has been proven to be a good fatigue indicator and was used in this study. Because of the observed faiure mode (brittle cracking), the fatigue relationships developed from beam fatigue tests (Chapter 6) were used to develop the design charts.

These fatigue curves were shifted to represent field conditions. Different researchers have used a number of shift factors to shift their lab fatigue results to represent field conditions as shown in Table 7.1. It is noted that values of 3 to 13.4 have been used to shift the beam flexure test [10, 11, 20, 36, 65]. Shift factors of 100.0 have been used to shift diametral fatigue results [23]. Therefore, a decision was made to use a shift factor of 5 to shift beam fatigue results to field conditions. Since beam fatigue life results are 16 times as high as diametral fatigue results, this is equivalent to a shift of 80 (16*5) to diametral fatigue results obtained in Chapter 5. The shift factor was applied to the "a" value of the fatigue equation as recommended by Rauhut [65]. Shifted curves are shown in Fig. 7.2 together with emulsion treated materials properties. Fatigue curves developed at 40°C (104°F) were used in this section since the mean annual air temperature in Saudi Arabia is about 40°C (104°F). The highest temperature reached in bases during the hot summer are 43°-46°C (110°-115°F).

Table 7.1. Summary of Shift Factors from Different Studies.

Author	Laboratory Test	Mix Type	Temp- erature	Shift Factor	Field Standard
F. Finn, C. Saraf R. Kulkarni, K. Nair, W. Smith, and A. Abdullah (11)	Beam flexure	D.G.A.C.	40-100°F	13.4	AASHTO Road Test
W. Vandijk (10)	Three point bending test	D.G.A.C.	20°C	4-8	Wheel tracking machine
J. Brent Rauhut and Thomas W. Kennedy (65)	Beam flexure	Dense Emulsified	70°F	3-4	--
J. Craus, R. Yuce, and C.L. Monismith (36)	Beam flexure	A.C.	--	11.24	AASHTO Road test
F. Giannini and G. Camomilla (21)	Beam flexure	D.G.A.C. Soil A.C.	-20-30°C	10	Road monitoring Italy
P. Bazin and J. Saunier (43)	Cantilever test	D.G.A.C.	--	2-4	Rotating traffic simulator
S.F. Brown, P.S. Pell and A.F. Stock (20)	Rotating bending test	Rolled A.C. Hot A.C.	33-61°C	100.0	British conditions
A.I.M. Classen, J.M. Edwards, P. Sommer, and P. Vge' (19)	"Push Pull" triaxial	D.G.A.C. sand A.C. bitumen macadem	-10-35°C	A*B*C A=2.5 B=2.-10 C=1.-0.5	"BISAR" layered elastic program
Anderson, et al. (23)	Indirect tenile test	A.C.	--	100.0	Road monitoring, Utah

* A = traffic distribution shift factor
B = healing and intermittent loading shift factor
C = temperature gradient shift factor

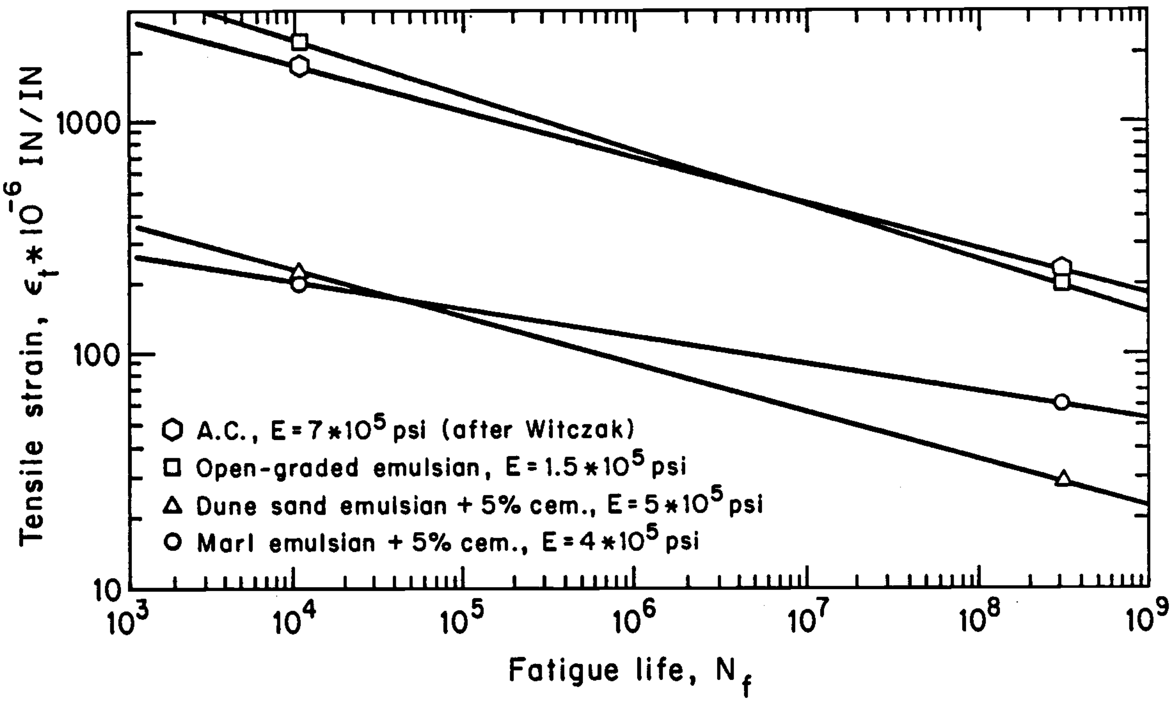


Figure 7.2. Relation between fatigue life and tensile strain at 40°C.

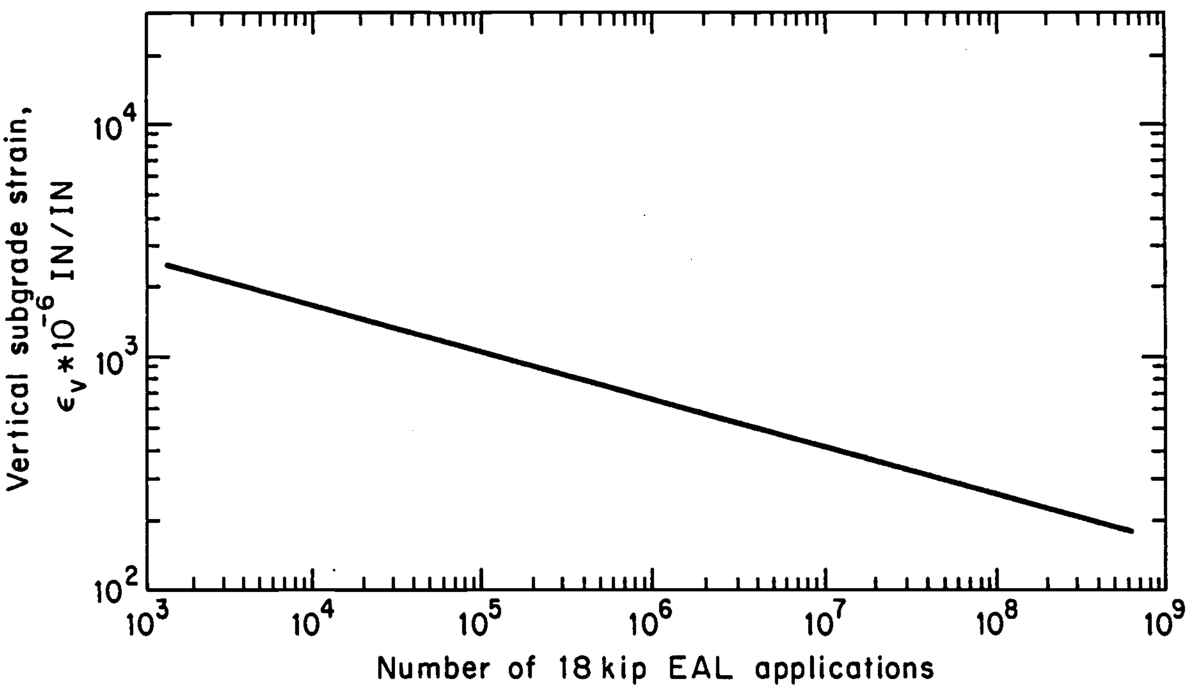


Figure 7.3. Subgrade strain criteria (65, 76, 100).

Compressive vertical strain at the top of the subgrade is a good indicator for permanent deformation [76, 100]. The relation between allowable vertical compressive subgrade strain as a function of the number of 18 kip (80 kn) equivalent axle load repetitions developed by Monismith and used by Santucci [76] was used in this research (Fig. 7.3) as the second failure criteria.

Since limiting stress and strain does not consider the deformation of stabilized layers, rutting curves (Figure 7.4) were developed to predict rutting in the stabilized layers, when average vertical stress is known for that layer. These curves were developed by extrapolating diametral rutting results, shown in Fig. 5.36. Use of Figure 7.4 enables one to predict cumulative rutting in the dune sand emulsion mix with 5% portland cement if the number of load repetitions and average vertical stress in that layer are known. This will enable the designer to minimize rutting in the stabilized layer (by limiting total pavement deformation to 1.0 in). The rutting curves were developed for dune sand mix only since rutting is not critical for marl or open-graded emulsion mixes. Marl emulsion produced rutting values 30% of those for dune sand.

7.5 Cases Analyzed

Three different cases were analyzed as shown in Fig. 7.5. The first is a full depth pavement for low volume

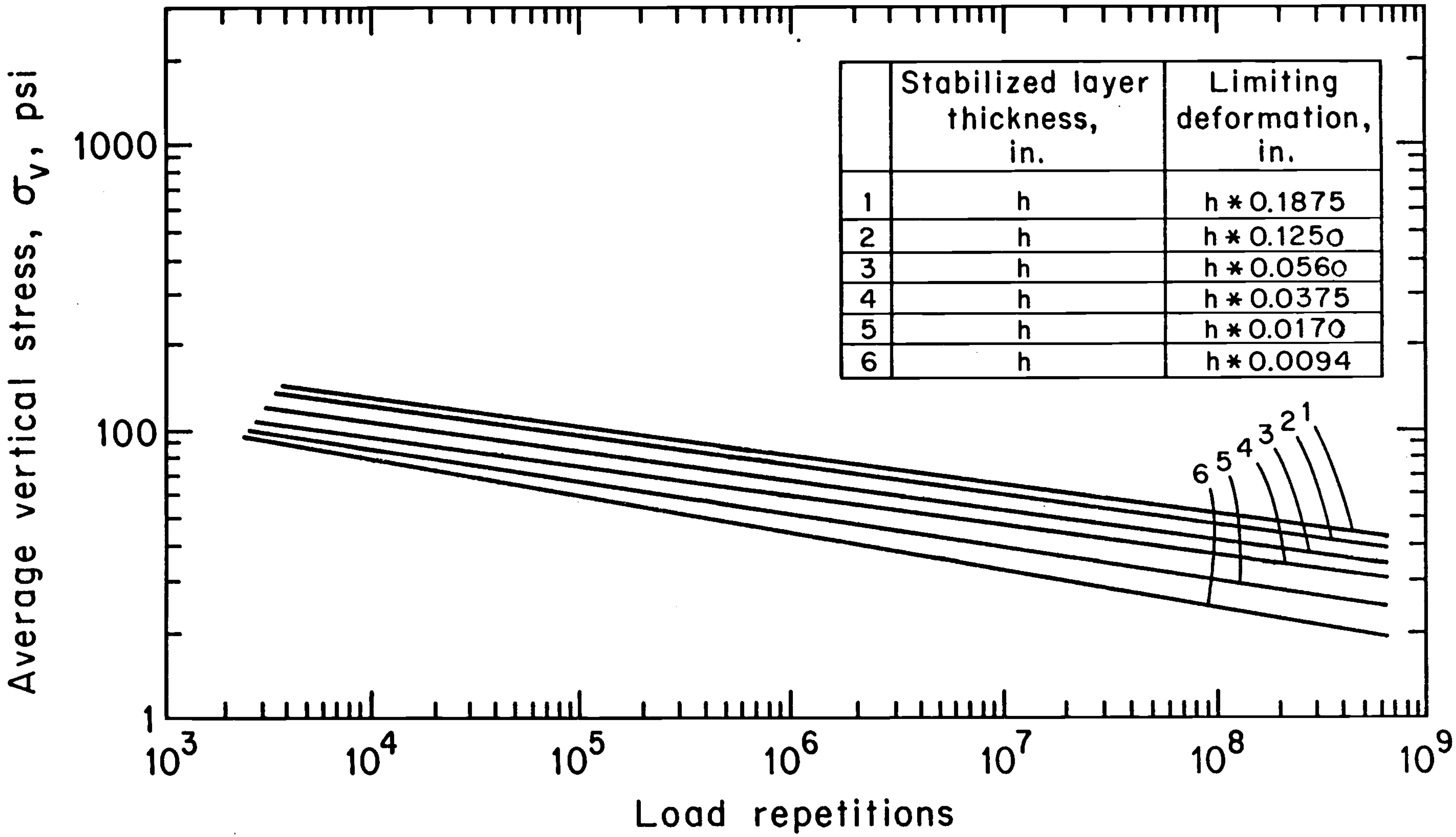


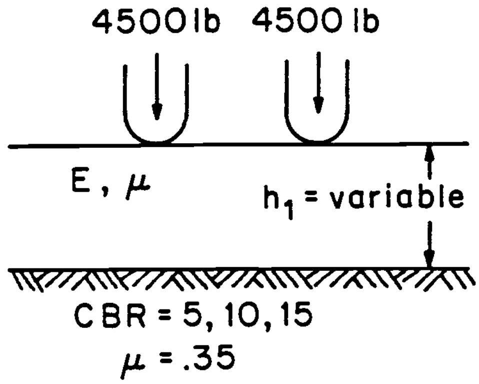
Figure 7.4. Cumulative strain failure criteria for dune sand emulsion mix with 5% cement layer.

and temporary pavements with marl subbase having a CBR of 10 (minimum specifications). The second is a two layer system having 2 inches (5 cm) of hot asphalt mix for local streets with marl subbase having a CBR of 20 (minimum specifications). The third is a two layer system with improved subgrade and 4 inches (10 cm) hot asphalt mix for highways having a marl subbase with CBR of 30 (minimum specifications). Material modulus values were obtained from specimens air cured for 4 days as discussed earlier. Materials Poisson's ratio calculated in Chapter 5 were used.

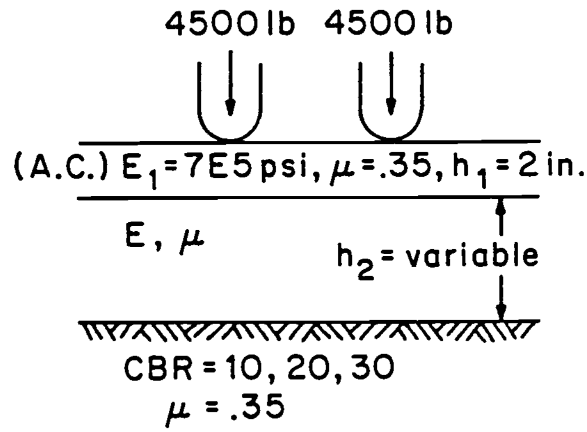
7.6 Structural Design

As discussed in the previous section, the designed pavement must satisfy the two strain criteria shown in Fig. 7.6 They are vertical compressive strain (ε_v) at the surface of the subgrade and the horizontal tensile strain (ε_t) at the bottom of the treated layer. The SHELL BISAR computer program was used to analyze the considered cases [101].

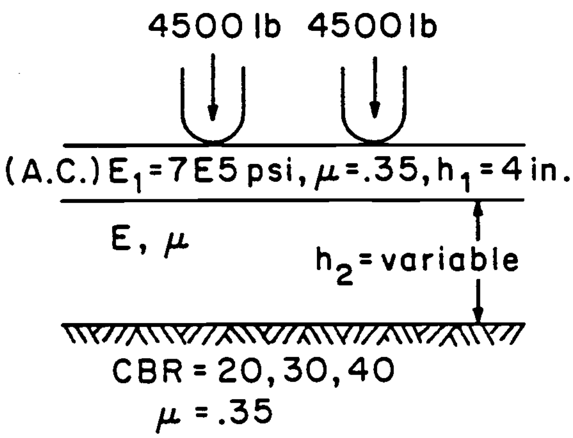
Calculated strains were compared with the limiting compressive and tensile strains criteria given in Figs. 7.2 and 7.3 From the two charts, critical strains can be correlated to total number of load repetitions. For dune sand emulsion mix, since rutting is critical, cumulated rutting in the stabilized layers was calculated from Fig.



1) Full depth pavement



2) Two layer system - local streets



3) Two layer system - highways

Mix type (+5% cem.)	Modulus E, psi	Poisson's ratio, μ
Dune sand	5E5	0.34
Marl	4E5	0.33
Open-graded	1.5E5	0.35

Figure 7.5. Cases analyzed for marl, dune sand and open-graded emulsion mixes.

7.4. Rutting life can then be determined by limiting total pavement and subgrade deformation to 1.0 in (2.54 cm). The minimum number of load repetitions for each case was selected and the final results were presented in the form of charts.

7.7 Design Charts

The results of the structural analysis are presented in the form of design charts. In these charts, total traffic in the form of equivalent 18 kip axle load (EAL) is plotted vs. stabilized layer thickness for different values of subgrade CBR. The three materials evaluated were open-graded emulsion mix, dune sand emulsion mix with 5% cement and the marl emulsion mix with 5% cement (Figs. 7.7-7.15).

It was noted that fatigue criterion was the controlling factor in the case of marl emulsion while rutting in this material was negligible. The subgrade rutting was the controlling factor in the case of open-graded emulsion due to its flexibility. Dune sand emulsion mix with 5% portland cement was generally controlled by fatigue, however for full depth pavement at high load repetitions, rutting was the controlling criteria (i.e., pavement rut was limited to 1.0 in (2.54 cm).

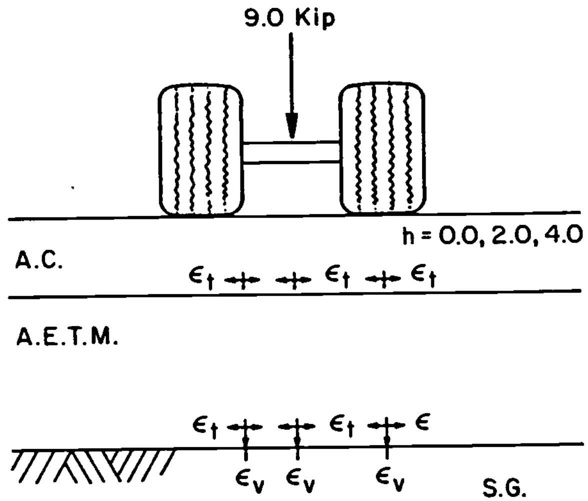


Figure 7.6. Locations of horizontal tensile (ε_t) and vertical compressive (ε_v) strains considered.

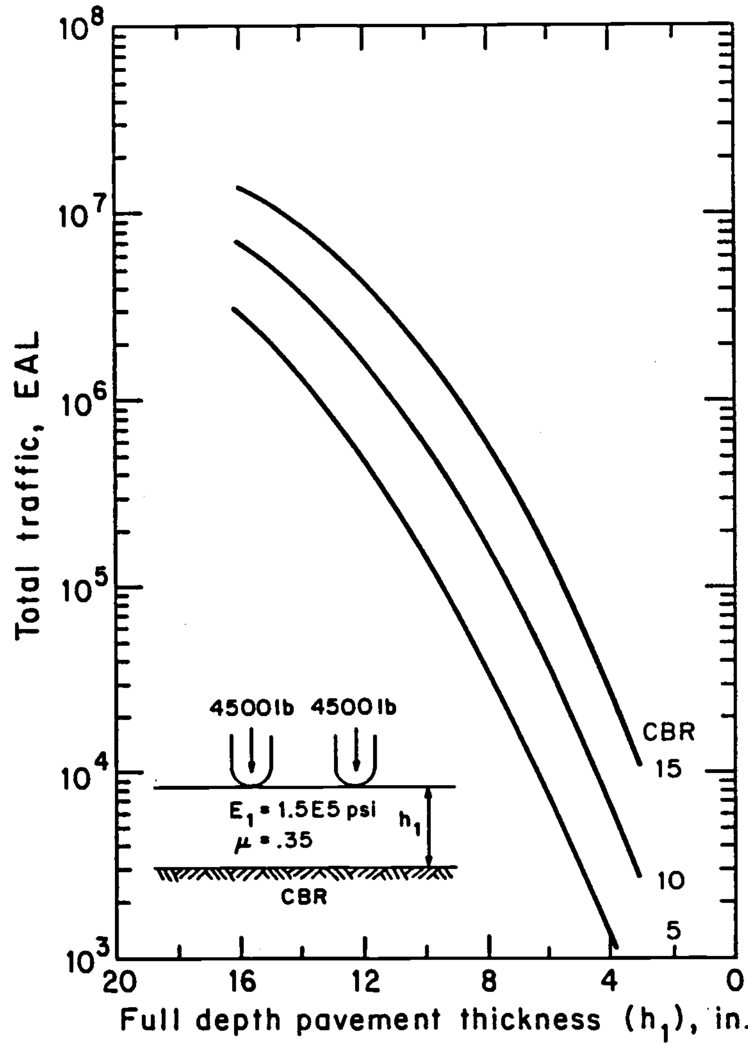


Figure 7.7. Relation between pavement thickness and total traffic for open-graded asphalt emulsion.

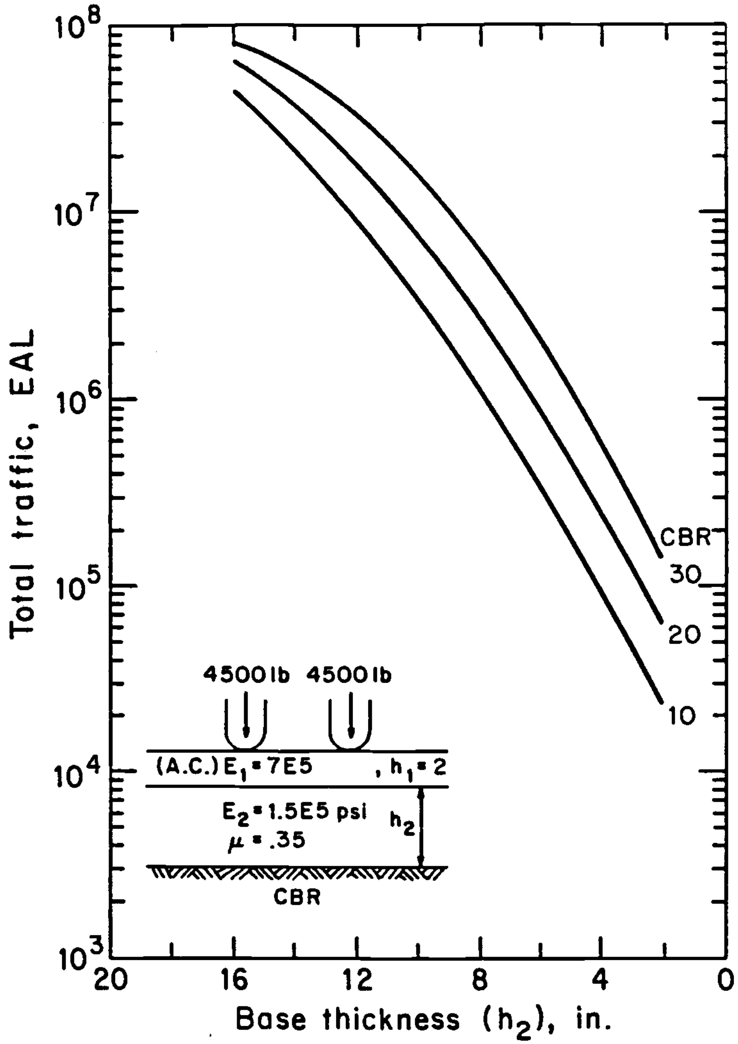


Figure 7.8 Relation between open-graded emulsion base thickness and total traffic.

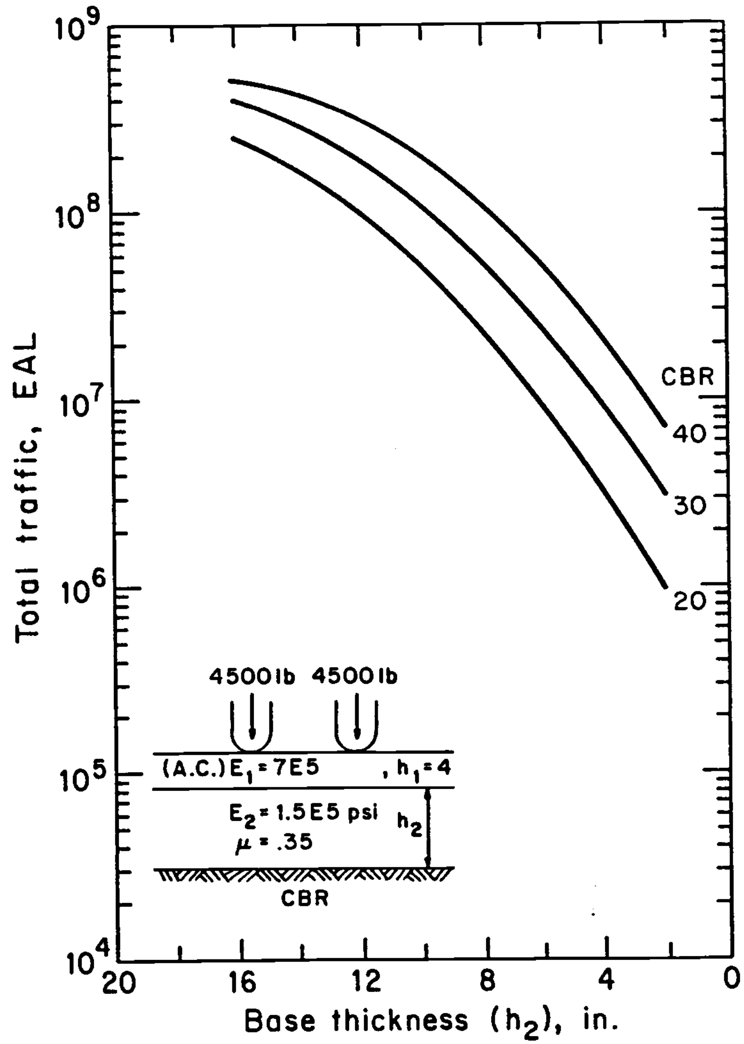


Figure 7.9. Relation between open-graded emulsion base thickness and total traffic.

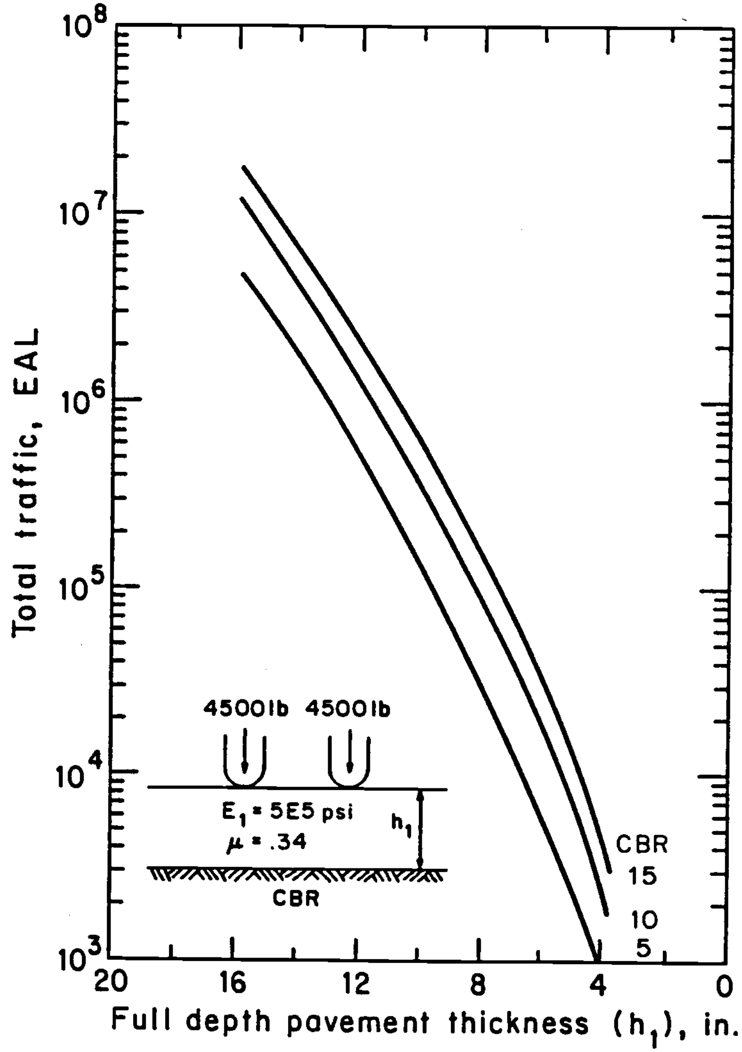


Figure 7.10. Relation between pavement thickness and total traffic for dune sand asphalt emulsion.

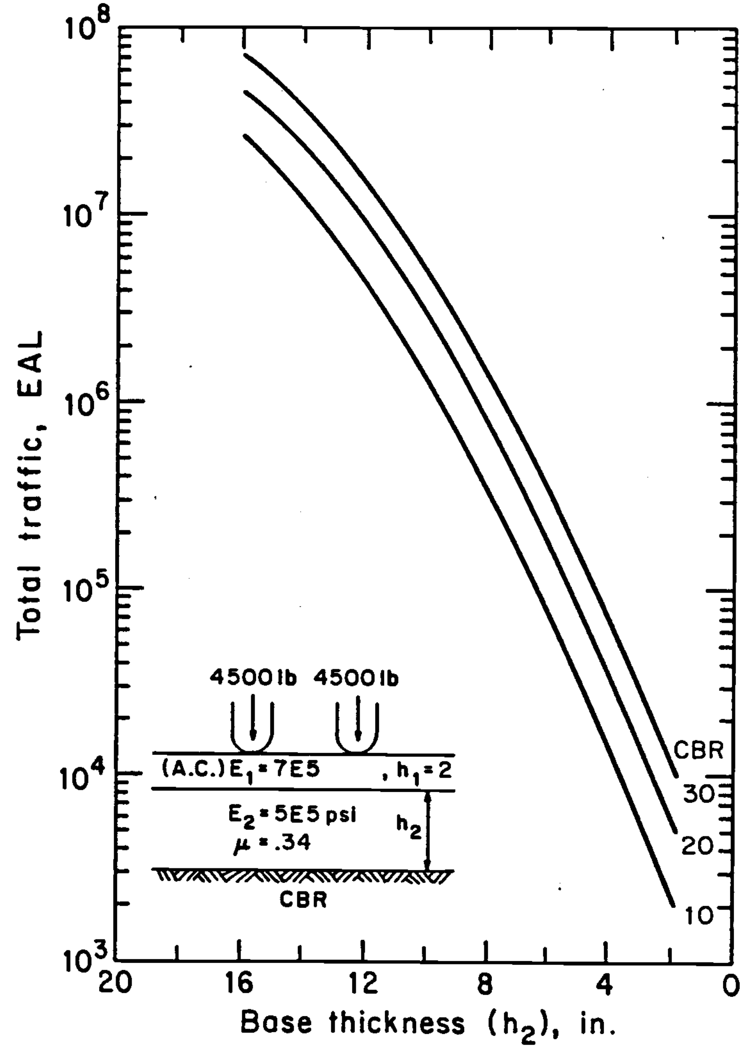


Figure 7.11. Relation between dune sand emulsion base thickness and total traffic.

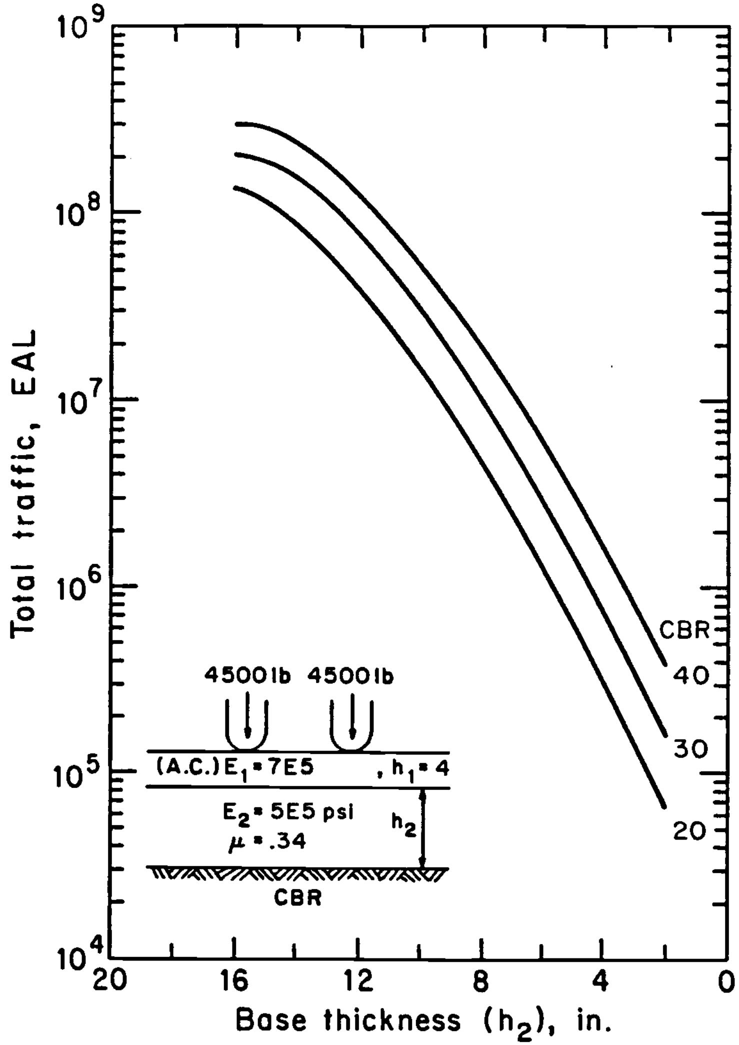


Figure 7.12. Relation between dune sand emulsion base thickness and total traffic.

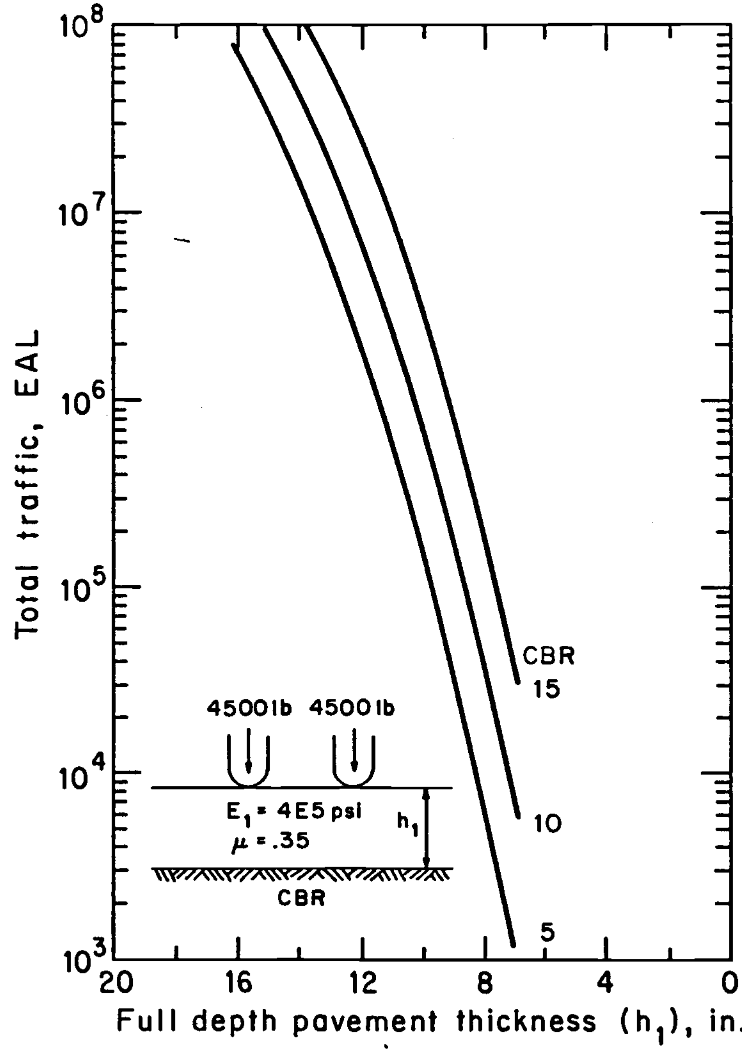


Figure 7.13. Relation between pavement thickness and total traffic for marl asphalt emulsion.

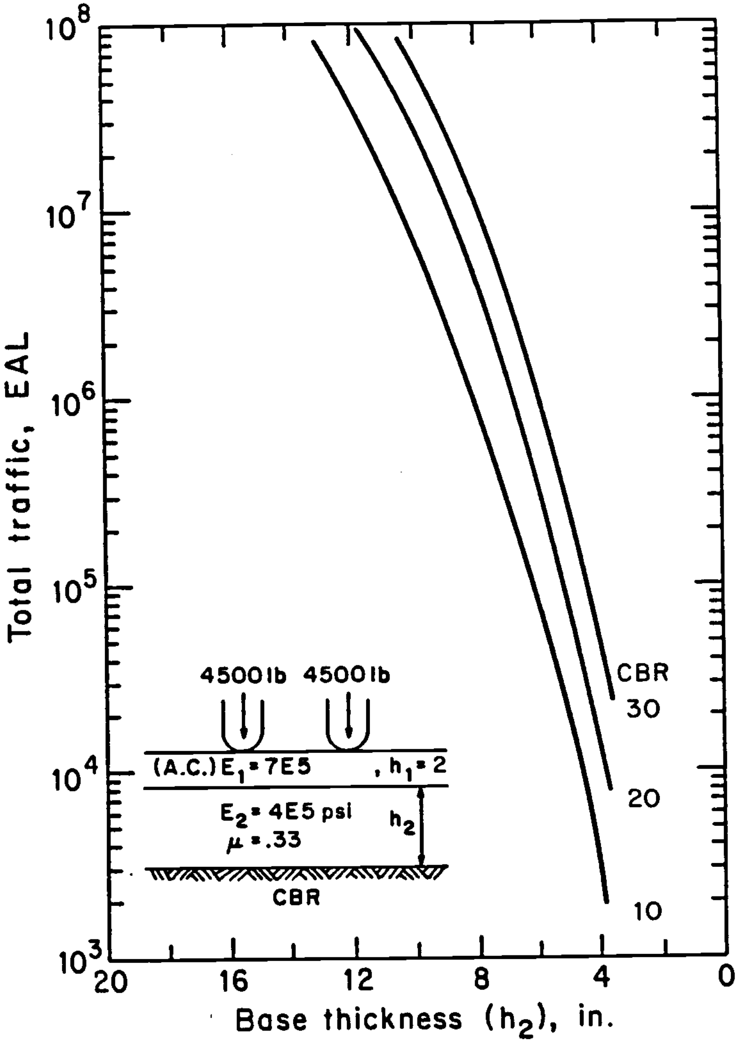


Figure 7.14. Relation between marl emulsion base thickness and total traffic.

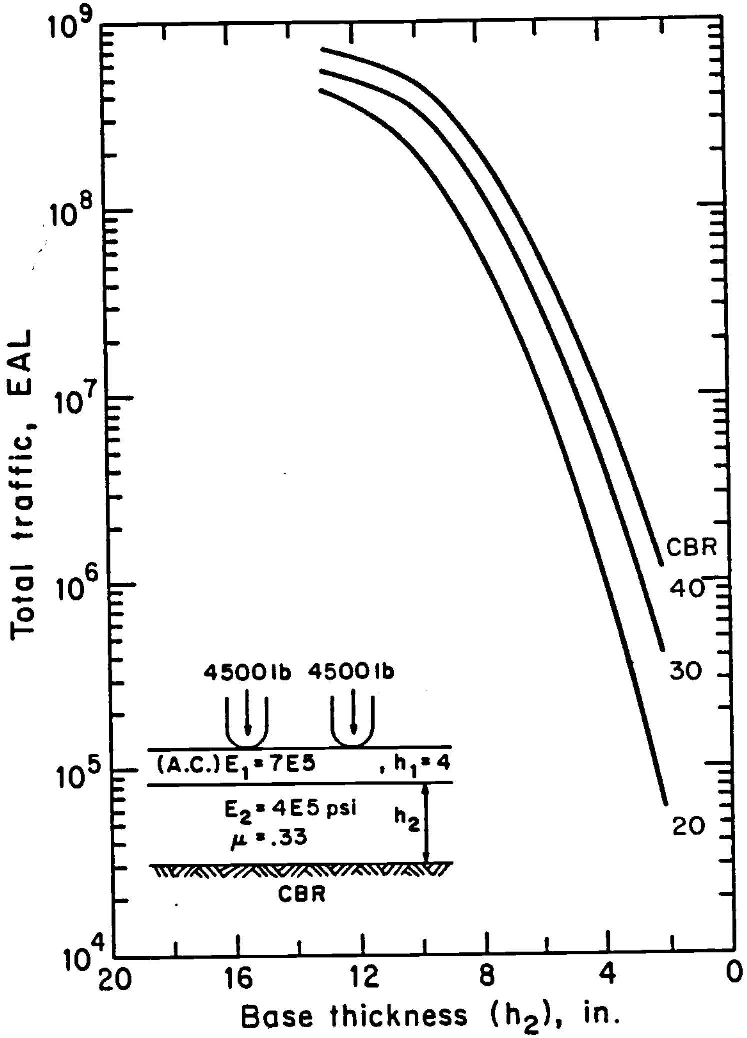


Figure 7.15. Relation between marl emulsion base thickness and total traffic.

7.8 Implementation

The design charts given in Figs. 7.7 to 7.15 were developed for materials at 40°C (104°F), and the results were compared with other researchers' results developed at 77°F [76, 10, 63, 39].

Comparison between open-graded emulsion thicknesses and values provided by Santucci et al. and Evans et al. [76, 63], indicated that the values developed are 1.0 to 2.0 inches higher than their values. This could be attributed to the fact that lower modulus values were used due to the use of higher temperature levels in this research. The design values for open-graded aggregate are close to those values given in ref. [39] for the same conditions.

Values for dune sand and marl emulsion mixes were compared to those values given in ref. [100] for emulsified asphalt mixes made with sands or silty sands. The comparison indicated a close agreement to the given values.

The use of emulsified treated materials for roads and road bases provides an economical means for road construction. Locally constructed roads, usually require a hot asphalt base thickness of 12 cm (5 in) for two lane highways and 15 cm (6 in) for freeways. It also requires a wearing course thickness of 5 cm (2 in) for two lane highways and 10 cm (4 in) for freeways. For the base, the substitution of emulsion treated materials for expensive crushed aggregates (Table 2.3) will result in less expensive roads.

In order to evaluate the economical benefit of using emulsified asphalt mixes for road base construction, it was necessary to compare the cost of base construction using hot asphalt and cold emulsion mixes. Hicks [47] indicated that the cost of a hot asphalt plant is ten times the cost of a cold mix plant with the same production rate. Moreover, a hot asphalt batch plant can be moved and set up for a cost 6 times the cost for moving and setting a cold mix pugmill of the same capacity. A hot mix plant also requires 1.3 gal of drying fuel/short ton of mix (5.42 l/metric ton).

Calculations were carried out to compare the cost of base construction using three materials, asphalt concrete, marl emulsion with 5% cement, and dune sand emulsion with 5% cement. The comparison was carried out for the base of a two lane highway 14 ft (4.27 m) wide. Calculations are shown in Table 7.2 and are based on the approaches described in references 1 and 47. The road in consideration is designed for three million repetitions and has 2 in (5 cm) asphalt concrete wearing course layer. Local specifications require such roads to have a subbase layer with a 20 CBR value. This road requires 5 in (12.5 cm) asphalt concrete base (100), or 6 in (15 cm)

Table 7.2. Equipment, Labor and Materials Cost for Base Construction.

	Asphalt Concrete	Marl Emulsion Mix	Dune Sand Emulsion Mix
(1) Equipment Cost			
Spreading	85.0	70.0	70.0
Compaction	50.0	50.0	50.0
(2) Operator Cost, $/hr			
Spreading	30.0	25.0	25.0
Compaction	25.0	25.0	25.0
(3) Additional Labors	3.0	2.0	2.0
(4) Labor Cost, $/hr	20.0	20.0	20.0
(5) Total Labor & Equipment Cost, $/hr (1+2+(3*4))	250.0	210.0	210.0
(6) Unit Weight lb/ft^3	150.0	122.0	128.0
(7) Material Quantity Short Tons*	2310.0	2255.0	2760.0
(8) Asphalt %	5.5	14.0	10.0
(9) Additives %	3% Lime	5% Cem.	5% Cem.
(10) Plant Cost $/Short Ton	5.0	1.5	1.5
(11) Aggregate Cost $/Short Ton	33.0	5.0	3.0
(12) Material Cost (9 to 12)	94750.0	52062.0	50051.0
(13) Hauling Cost**	6930.0	6765.0	8280.0
(14) Production Rate, Short Tons	200.0	200.0	200.0
(15) Number of Hours for Construction (8/15)	11.5	11.3	13.8
(16) Labor and Equipment Costs, $	2890.0	2375.0	2900.0
(17) Total Cost of 1 Mile Construction, $ (13+14+16)	104570.0	61202.0	61231.0
(18) Hot Mix Cost - Cold Mix Cost	43370.0 ($\simeq$42%)		

* Material quantity = L * (5280 ft/mi) * w * $\frac{h}{12}$ * Unit weight

where, L = road length = 1 mile
w = road width = 14 ft.
h = base thickness

** Assume haul cost of \$0.3/yd^3, and haul distance of 10 miles.

marl emulsion mix (Fig. 7.14), or 7 in (17.5 cm) dune sand emulsion mix with 5% cement (Fig. 7.11).

The compaction procedure and equipment required to lay the bases are assumed to be the same. The volume of cold mix that can be hauled is higher than that of hot mix due to the lower unit weight of cold mix.

The project is assumed to be 24 ft wide (4.27 m), 1.0 mile long and have a 10 mile hauling distance. Calculation steps are shown in Table 7.2. Calculations indicated that hot asphalt concrete base costs about $43,000/mile more than cold mixes (marl emulsion or dune sand emulsion) base. A savings of 42% of the base construction costs can be achieved by using emulsified asphalt mixes.

The reduction of the use of crushed aggregates will substantially reduce the pavement construction costs. Moreover, it will enable the use of locally available sands, portland cement and marginal aggregates which are available at lower costs. Therefore, it is recommended to use emulsions, especially where there is a lack of good low cost aggregate, for base and subbase stabilization and especially for construction of low volume and agricultural roads.

7.9 Use Guidelines

The purpose of this section is to provide guidelines for the use of emulsified asphalt to solve some of the local pavement problems and to reduce road treatment and construction costs. A detailed description of the use of emulsified asphalts for road maintenance and construction is given in Appendix A, Chapter 4.

Emulsified asphalts can be of great advantage when used to solve some of the local road problems, such as:

1) Aggregate associated problems
   - o Stripping
   - o Degradation
   - o Polishing
2) Subbase problems (water susceptible)
3) Lack of good quality aggregate and high cost of crushed aggregate
4) Large network of low volume (dirt) roads
5) Sand dune movements

Locally available aggregate (limestone) contains weak fragments that disintegrate after cycles of wetting and drying. These aggregates which are used for pavement construction disintegrate after a rainy season resulting in stripped pavement surface full of potholes and stripped and exposed aggregate. The effect of water on the aggregate can be minimized by sealing the pavement surface with a fog seal during the late fall. Applications of slow setting emulsified asphalt to the pavement surface at a rate of 0.45 to 0.7 l/m^2 (0.1 to 0.15 gal/yd^2) diluted with water to result in 0.13 l/m^2

(0.03 gal/yd^2) of residual asphalt helps in sealing cracks, surface voids, and preventing raveling.

Badly disintegrated pavement surfaces with cracks 1/4 in wide can be treated using slurry seals. A slurry seal is a mixture of slow setting or quick setting emulsified asphalt and aggregate composed of 50% well-graded sharp sand and 50% limestone screenings. Crack filling and fine seal requires a residual asphalt content of 10-15% and is applied at a rate of 3-5.5 kg/m^2 (6-10 lb/yd^2). Use of slurry seals enables crack filling and exposed aggregate protection from water effects. Slurry seals renew old cracked pavement surfaces and also renews skid resistance of slick pavement surfaces.

Locally available crushed aggregates are expensive and lead to high road construction costs. The use of locally abundant sandy and silty materials (Table A-14) in road base consrtruction is possible when stabilized with emulsified asphalt. Therefore, emulsified asphalt mixes should be used for base construction when construction economics dictate. This will also allow the elimination of the common subbase problem, i.e. rutting in compacted marl. Although subbases are stabilized with lime, they are still prone to rutting when water has access to them. This is a common problem in coastal areas where the water table is close to the surface.

Using emulsified asphalt stabilized materials may eliminate this problem and reduce construction costs. The type of emulsified asphalt to be used can be selected from Table A-8 based on the material's surface charge. Slow setting emulsified asphalt is generally used for sands and silty materials stabilization, except dune sand where CMS-2S yields a better result. Portland cement may be added to reduce curing time.

There are currently 42000 km (25200 miles) of low volume roads (dirt roads) which are kept in shape by regular maintenance (watering and compacting). Such roads can also be maintained by applying a slow setting emulsified asphalt diluted with four parts of water to penetrate sand layers and bond sand grains. This will abate dust and seal the surface from water penetration. Emulsified asphalts should be applied at a rate of 0.1 to 0.5 gal/yd^2 (0.45 to 2.25 l/m^2).

A similar treatment can be applied to prevent sand dunes from moving onto roads. Sand dune movements can be eliminated by spraying diluted slow setting emulsified asphalt on the windward side of the dune. Emulsified asphalt should be applied in parallel lines (across the wind direction) 2 meters (7 ft) wide and 2 meters (7 ft) apart.

7.10 Summary

This chapter describes an attempt to adapt test results to local field use. Material properties derived from experiments, from the field and other specifications were used. Fatigue and rutting results were used to develop the design charts. Three materials (marl, dune sand, and open-graded emulsified asphalt mixes and three types of pavement sections were considered for BISAR analysis. These proposed road sections proved to be economical when used locally in lieu of the current practice. Finally, guidelines for emulsified asphalt use to overcome common local road problems were described.

8.0 CONCLUSIONS AND RECOMMENDATIONS

In this report, a study to evaluate emulsified asphalt for use in Saudi Arabia was undertaken. The intention of this study is to point out the benefits of using emulsion with locally available sands and marginal materials for road construction.

8.1 Conclusions

Significant conclusions resulting from this study include:

1) Emulsified asphalt can be produced from locally available asphalt economically ($\simeq$ \$109/ton) and sold at the low cost of \$122/ton, as discussed in Chapter 2.0.

2) Acquisition of good quality crushed aggregate is one of the Kingdom's road construction problems. It is scarce and expensive.

3) Emulsified asphalts produced in Saudi Arabia are similar to those produced by Chevron U.S.A. Company. Both emulsions have the same treatment effect at 25°C (77°F).

4) Marl and sand emulsion can be used for road construction. Based on fatigue tests, both of them perform satisfactorily. Both of them can be utilized to produce satisfactory, reasonable, economical road sections.

5) Marl emulsion mixes tend to withstand higher loads than dune sand emulsion mixes with low rutting (1/3rd). It also has the capability to withstand high inservice temperatures (>50°C), 122°F).

6) Diametral fatigue test failure criterion for sands seems to be shifted to rutting at low cement levels and high temperatures. The split tensile fatigue test appears to be suitable for testing dense-graded materials or sands at low temperature.

7) Open-graded emulsified asphalt can be tested successfully using beam flexure with no or few difficulties. Results indicate the ability of mix to withstand high strains at high fatigue lives.

8) The fatigue test using a beam resting on elastic foundation provides a realistic way to test road materials. Fatigue lives produced by this test for marl and dune sand with 5% cement are 16 times higher than those resulting from the diametral test.

9) Finite element techniques, which were used to calculate bending modulus, yield a better agreement with diametral modulus values than those values calculated by the beam equation.

8.2 Recommendations

Significant recommendations resulting from this study are:

1) Saudi Arabian emulsion, when mixed with sands, tends to set rapidly, resulting in stripping upon increasing mixing time, with coating less than that of Chevron U.S.A. emulsions. Therefore emulsion formulation should be improved by incorporating distillates such as naptha to improve coating and mixing ability.
2) Emulsified asphalt should be used for stabilizing marginal aggregates and sands for road base construction whenever there is a lack of good quality aggregate.
3) Emulsified asphalt represents an easy means for treatment of low volume roads. In Saudi Arabia, there are more than 40,000 km of agricultural (dirt) roads. Emulsified asphalt should be used to stabilize such road surfaces economically.
4) Saudi Arabia contains a large network of highways compared to its low population, which makes maintenance required to keep these roads in good shape very costly when using hot asphalt mixes. Emulsified asphalt on the other hand provides an easy and economical alternative.

5) Emulsified asphalt should be introduced in Saudi road specifications as a construction and maintenance material rather than as a maintenance material only.

8.3 Recommendations for Further Research

Recommendations for further research include:

1) Observing distress types for these materials based on full-scale field experiments. This will result in a better understanding of asphalt emulsion. It will provide a good basis for emulsion specifications based on actual field conditions.
2) Comparing rutting and fatigue results obtained from diametral tests to that obtained using triaxial tests and field studies. This will aid in development of a model for comparing laboratory results to field results, which would be more useful in predicting pavement behavior.
3) Obtaining optimum cement content for tested materials. Materials tested were mixed with 2% and 5% cement. Cement contents should be varied over a range of economical values. Its effect on fatigue life and rutting should be evaluated to arrive at an economical cement content which will not affect the performance of the mix.

4) Evaluating cure time effects based on field conditions. This should result in more representative curing conditions in the laboratory.

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APPENDICES

APPENDIX A. BACKGROUND OF EMULSIFIED ASPHALTS

APPENDIX A: BACKGROUND OF EMULSIFIED ASPHALTS

1.0. INTRODUCTION

Emulsified asphalts continue to grow in importance for road construction and for a wide variety of industrial uses. The improved formulations are increasing the importance of these products and are bringing their use into new fields, such as agriculture and water conservation.

The use of emulsified asphalt in paving dates back to the early 1900s. The first commercial bituminous emulsions for paving were emulsified-asphaltic oils for dust laying. In the summer of 1905, an emulsion of asphaltic petroleum ammonia was applied in Chicago and Boston [30]. By 1914, the New York State Highway Department was using emulsified asphalt for cold patching [30]. In 1917, the State of Indiana was using cold-premix asphalt concrete which utilized emulsified asphalt as the source of bituminous binder. According to estimates made at the time, by 1931, there were some 37 million gallons of emulsified asphalt sold for paving application [30]. Only anionic emulsions were manufactured until the early 1950s. The performance advantages of cationic emulsions were first demonstrated in Europe at that time. Because of their rapid setting and improved adhesion with a wider variety of aggregates, the cationic emulsions have been steadily displacing the anionic emulsified asphalt [40].

In recent years, the use of emulsified asphalt in pavement mixtures has increased rapidly (Figure A-1). Emulsified asphalt is recognized by most federal, state, and local agencies and authorities as an important bituminous material used in the construction and maintenance of pavements. The shortage of energy and environmental problems has focused attention on increased use of these materials.

1.1 Objective

The objective in this appendix is to give an overview of emulsified asphalt technology. It discusses 1) emulsified asphalt manufacturing, 2) composition, 3) properties, 4) applications related to highway pavements, and 5) advantages and disadvantages.

1.2 General

Asphalt cement is the basis of all asphalt products (Figure A-2). When using asphalt cement with aggregate, it must be liquefied either by heating, by adding solvent or by emulsifying it.

Emulsified asphalt is gaining wide acceptability in road construction and maintenance due to its advantages over other forms of asphalt. The substitution of

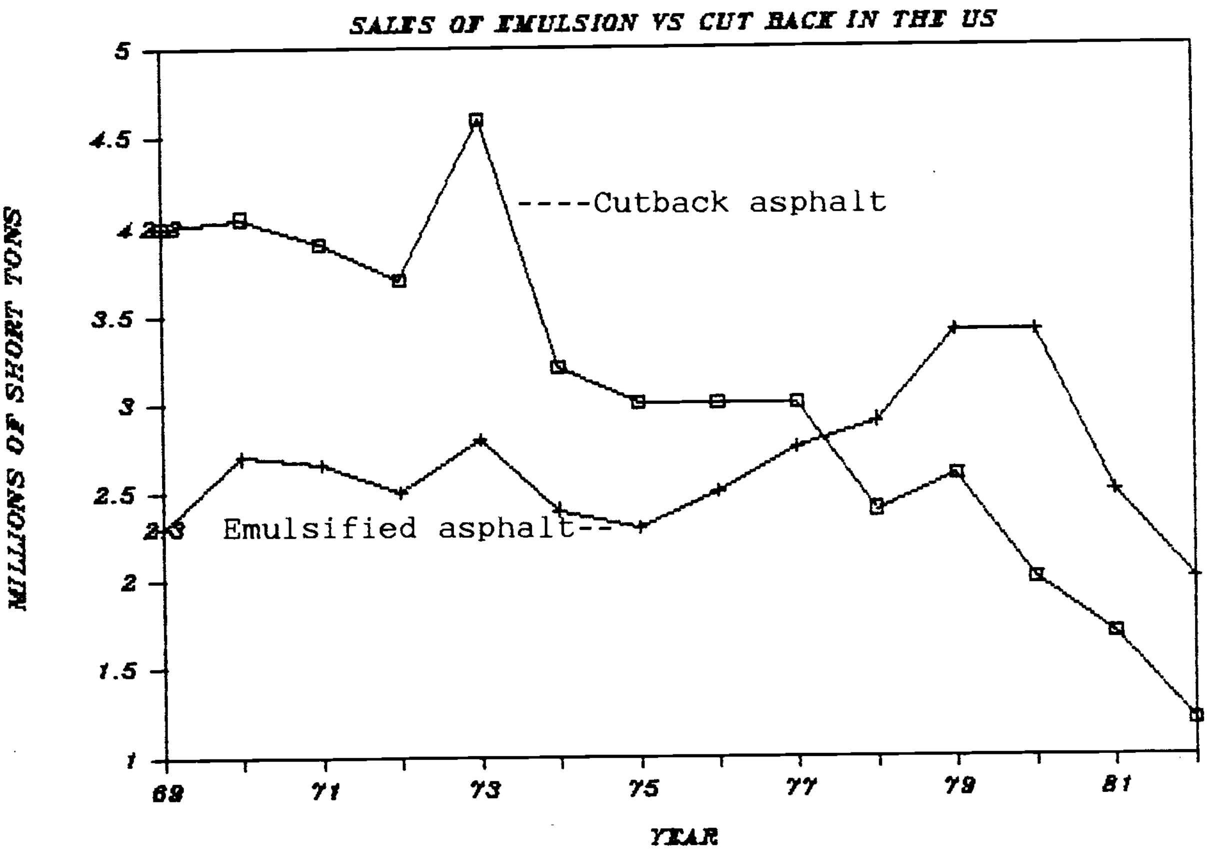


Figure A-1.Asphalt emulsion usage (50).

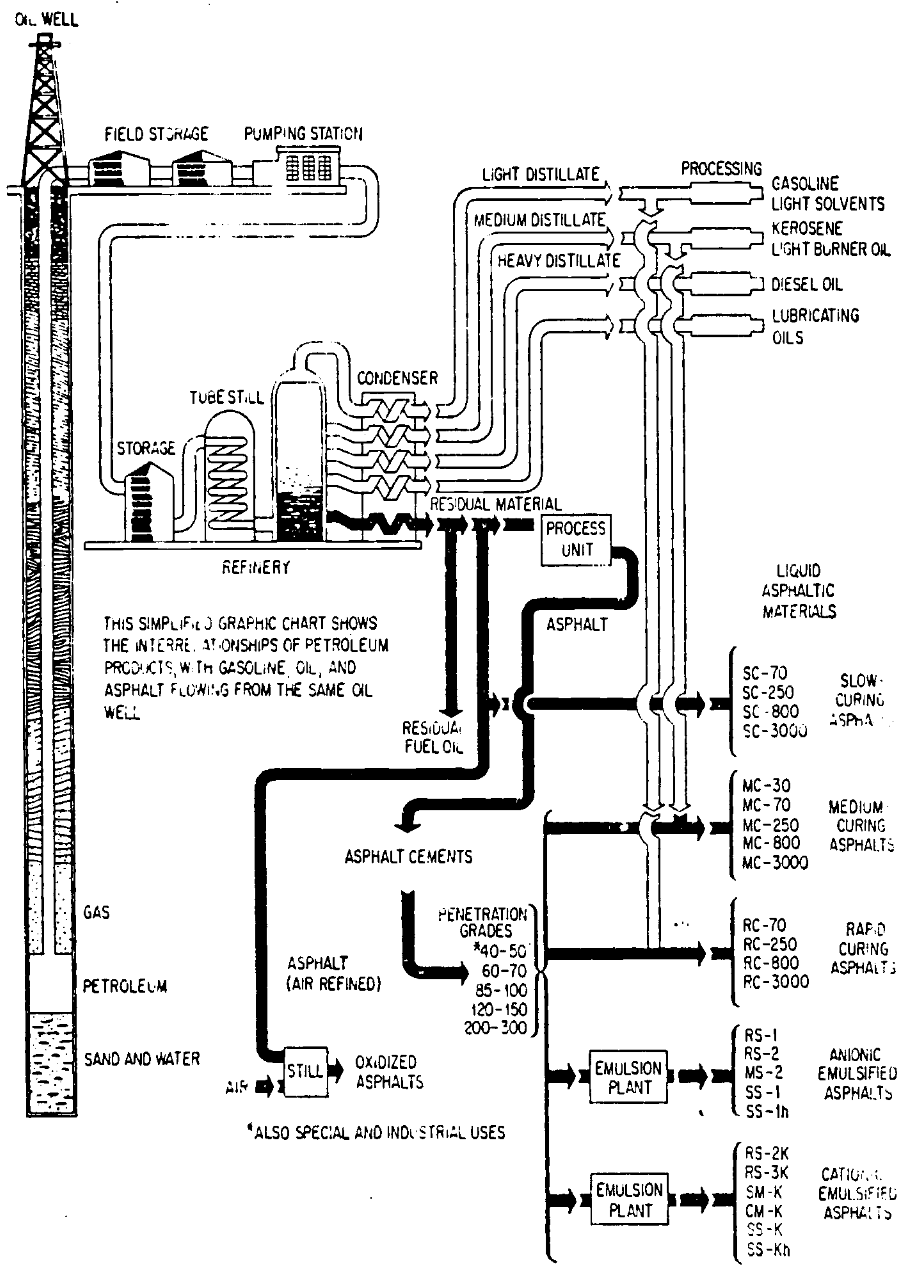


Figure A-2. Petroleum asphalt flow chart.(48)

emulsions for cutbacks and emulsion mixes for conventional hot mixes in highway construction and maintenance operations is one area that shows some potential for reducing energy consumption. This point was stressed by FHWA which issued a note in January, 1974, directly concerned with the use of emulsified asphalts in lieu of cutback asphalts. Use of emulsions led to cost savings by the use of less fuel. It also reduced atmospheric pollution due to the elimination of hydrocarbon emissions.

2.0 DESCRIPTION OF EMULSIFIED ASPHALTS

Emulsified asphalt is a mixture of asphalt cement and water that contains a small amount of an emulsifying agent. It is a heterogeneous system containing two phases (asphalt and water) in which the water generally forms the continuous phase of emulsion, and minute globules of asphalt form the discontinuous phase. The droplets are held in suspension by emulsifiers which impart an electrical charge to their surfaces. This charge combined with a fine particle size keeps the emulsion uniform and stable. Typical mixing-grade emulsified asphalts have median particle sizes from one to eight microns as shown in Figure A-3. Depending no the emulsifying agent, emulsified asphalt may be one of three types: cationic, having electro-positively charged asphalt globules; anionic, having electro-negatively

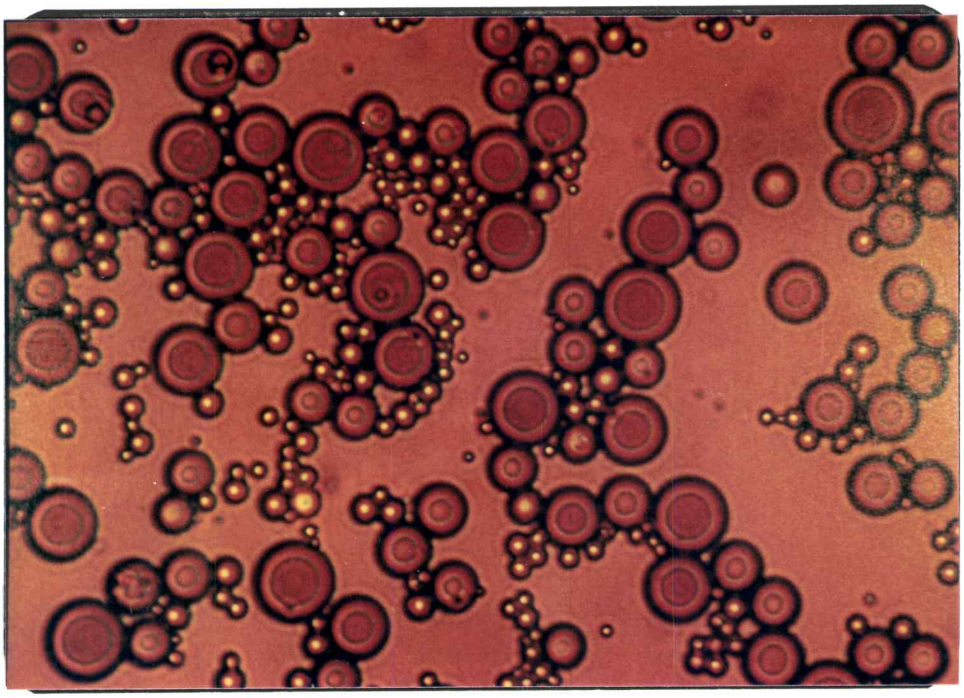


Figure A-3. Relative sizes and distribution of asphalt particles in an emulsion.

charged asphalt globules; or non-ionic, having neutral charge.

2.1 Manufacture of Emulsified Asphalts

Emulsified asphalts can be prepared by different methods. They can be prepared chemically, by reversal of phases, or mechanically.

2.1.1 Chemical Emulsification

Several soft residual/bitumens contain enough acid components of high molecular weight (bitumen napththic acids) to give a satisfactory fine dispersion when, after being sufficiently liquified by heating, they are poured into dilute alkaline solution and vigorously stirred.

2.1.2 Mechanical Emulsification

Emulsified asphalts are produced by dispensing selected paving asphalts into water by means of high-speed mixing equipment and an emulsifying agent. This equipment may be colloid mill, homogenizer, or simple mechanical mixer, depending on the amount of shearing force required. Concurrent streams of molten asphalt cement and water-emulsifying agent mix are directed by a pump into intake of the colloid mill (Figure A-4). The asphalt cement and emulsifying water are subjected to intensive shear stress as they pass through the colloid mill. The newly formed emulsified asphalt may then be pumped through a heat exchanger to

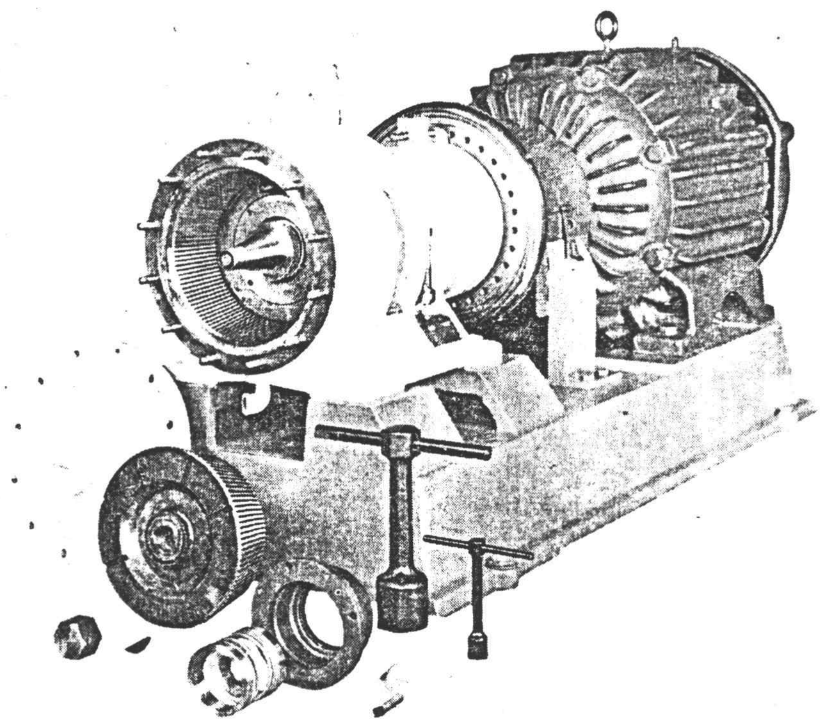


Figure A-4. Colloid mill. (30)

raise the temperature of the incoming emulsifying water just before it reaches the colloid mill. From the exchanger, the emulsion is pumped into bulk storage tanks (Figure A-5). The tanks sometimes are equipped with some type of stirring device to keep the product uniformly blended.

The amount of shear required to give the desired particle size will depend greatly on the particular emulsifier employed. Anionic emulsified asphalt often can be made with low power shearing equipment, such as propeller or turbine mixers. Cationic emulsified asphalt almost always require colloid-mill manufacture. Particle-size distributions are also affected by asphalt type and viscosity, manufacturing temperature, and colloid-mill pressure drop.

2.1.2.1 Colloid mills: Colloid mills are based on the principle that the substances to be mixed must pass a narrow gap between the fixed housing (the stator) and a high-speed disk (the rotor) (Figure A-4) in such a way that the pressure gradient in the mixture of liquids in each part of the gap forms an angle to the direction in which the rotor surface moves there [28]. The spacing between the rotor and stator plates can be changed to give the shear intensity desired. Furthermore, since they can be operated under pressure, colloid mills can be used to emulsify high-melting asphalts that require

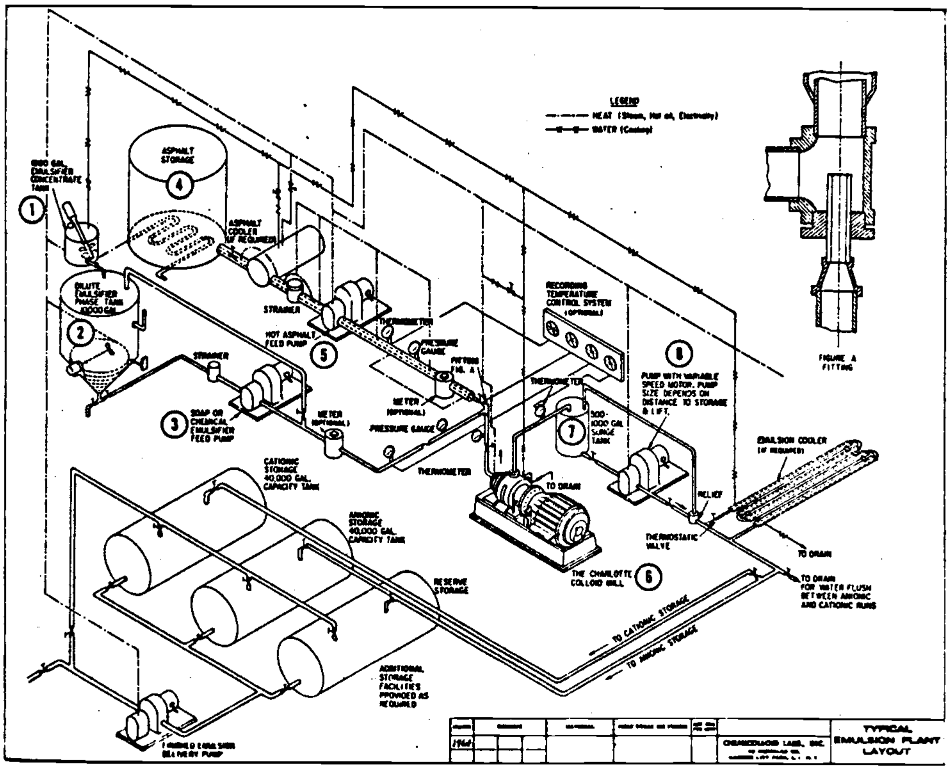


Figure A-5. Typical emulsified asphalt plant layouts.(30)

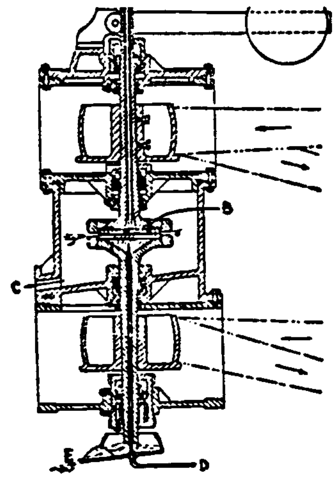
manufacturing temperatures above the normal water boiling point [29].

There are four general types of colloidal mills [27]:

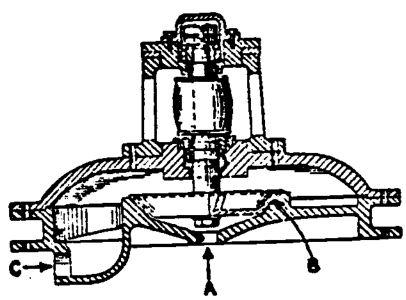
1. The beater type, in which the particles are subjected not only to hydraulic shearing stresses but also to impact stresses produced by revolving blades operating between fixed blades.
2. The smooth-surface type, in which smooth rotating surfaces are contiguous to a smooth stationary surface.
3. The centrifugal smooth-surface type, consisting of either a truncated cone rotating within a stationary cone or flat discs rotating in opposite directions (Figure A-6).
4. The rough-surface type of a rough working surface, which, in addition to the hydraulic shearing stresses, has a second dividing action involving assistance turbulence and heating produced by currents included between the irregular surfaces.

2.2 Chemical components

Emulsified asphalts consist of three chemical components: that is, asphalt (55-70%), water (30-45%),



a. Smooth-surface type of colloid mill with opposed-disc working surfaces. A--material inlet; B--working surfaces; C--material outlet; D--cooling-water inlet; E--cooling-water outlet.



b. Smooth-surface type of colloid mill with truncated-cone working surfaces. A--material inlet; B--working surfaces; C--material outlet.

Figure A-6. Smooth surface-type colloidal mill [27].

and emulsifier (1-2%), which are brought together by a high shearing device. The total emulsifier system, however, may include the emulsifying agent, an activator (or accelerator), in organic salts, a stabilizer or other additives. Each one serves a different function in the emulsified asphalts. Some emulsified asphalt may contain small amounts of solvent.

2.2.1 Asphalt

Asphalt is a complex mixture of hydrocarbons. The molecular weights vary from low (300) to very high (5000) molecular weight [50]. Chemical composition of materials varies in different molecular weight ranges depending upon the crude oil source. In general, they consist of carbon (70-85%), hydrogen (7-12%), nitrogen (0-1%), sulfur (1-7%), oxygen (0-5%) and a small amount of metals. Moreover, asphalt can be separated into asphaltenes, resins, and oils.

The asphaltenes are the high molecular weight materials and are primarily of ring-type structure with very few side chains. Sulfur and nitrogen are incorporated in structures of this type. The resins are intermediate molecular weight materials which contain more side chains than the asphaltenes. They are polar molecules containing some sulfur and nitrogen. This polar nature gives resins the ability to be adsorbed by and to dissolve the asphaltenes. Oil is the lightest molecular weight material in the asphalt. It has large numbers of chains in proportion to the number of rings. Asphaltenes, resins, and oils are often classified according to the ratio of carbon to hydrogen (c/H); that is, asphaltenes c/H ratio greater than 0.6, and oils c/H ratios less than 0.6 [50].

There have been two theories proposed for the arrangement of molecules within asphalt. The first, or colloidal theory, states that the asphaltenes are the micelles of colloidal suspension and are kept floating in the oils phase by the resins which act as peptizing agents. The second, or solubility, theory assumes tha asphaltenes are dissolved in the oil-resin phase and the structure so established does not resemble colloidal suspension [50].

Although hardness of base asphalt cements may be varied as desired, most emulsified asphalts are made with asphalts in the 100-250 penetration range. Harder or softer base asphalt may be used if dictated by climatic conditions. A typically acceptable emulsion-base asphalt using an optimum concentration of emulsifier provides an average particle size and distribution of 28% at <1 micron, 57% at 1-5 microns and 15% at 5-10 microns.

The properties of asphalt that contribute to good emulsification are [35]:

1. Acid number: greater than 0.5 (but less than 2.0 for Anionic)

2. Sulfur content: low

3. pH: less than 7

Those asphalt properties that contribute to poor emulsification are as follows:

1. Acid number: less than 0.5

2. Sulfur content: high

3. pH: greater than 7.

2.2.2 Water

The second largest ingredient in an emulsified asphalt is water. Its contribution to the desired properties of the finished product cannot be minimized. Water wets and dissolves, it adheres to other substances, and it moderates chemical reactions. These are all important factors that can be favorable to the production of satisfactory emulsion. On the other hand, water may contain other matter which affects the production of stable emulsified asphalts [40].

The presence of calcium and magnesium ions (Ca^{++} and Mg^{++}) could benefit the formulation of cationic emulsified asphalts. Calcium chloride is often added to cationic formulations to enhance storage stability. Calcium and magnesium ions could be detrimental to the formulation of anionic emulsified asphalt because of the formulation of water insoluble calcium and magnesium salts due to reaction with the water-soluble sodium or potassium organic acid salts normally used as anionic emulsifiers.

The presence of carbonate and bicarbonate ions could be detrimental to formation of stable cationic emulsified asphalt (if acid is not used), particularly the rapid setting type of cationic emulsified asphalt. The more water-insoluble salt will tend to form due to reaction with the water-soluble amine hydrochlorides normally used as cationic emulsifier. By contrast, the presence of carbonate and bicarbonate ions could be beneficial to the formation of anionic emulsified asphalt because of their buffering effect [14]. Water containing foreign matter should not be used in emulsion production. It may adversely affect performance and cause premature breaking.

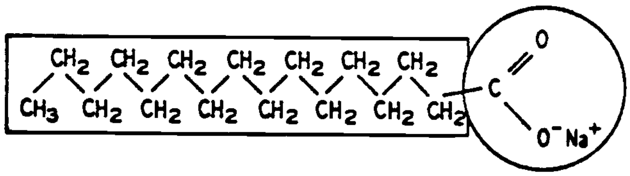
In summary, water used to produce emulsified asphalts should be reasonably pure (low in Ca^{++}, Mg^{++} and sulfate ions) and free from foreign matter and should be considered an important item.

2.2.3 Emulsifying Agent

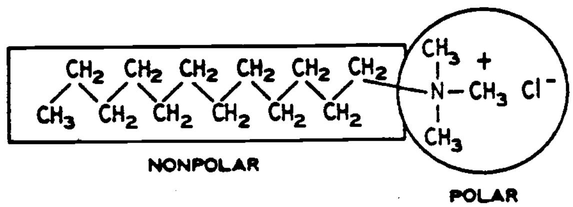
The properties of an emulsified asphalt depend greatly upon the chemical used as emulsifier. It is a surface-active agent that promotes suspension of asphalt droplets in water. The emulsifier also permits breaking (setting or asphalt coalescence) at the proper time. It changes the surface tension at the area of contact between the asphalt droplets and the water available. Chemical emulsifiers cover a wide range; therefore each must be selected for compatibility with the asphalt cement being used.

2.2.3.1 Types of emulsifiers: An emulsifying agent must have special solubility characteristics. It must be compatible with both the oil and water phase. This is possible if the molecule possesses both polar and nonpolar portions. Figure A-7a shows sodium palmite moleculte s. The large nonpolar alkyl portion on the left side of the figure imparts oil solubility while the polar sodium carboxylate group of the molecule on the right side imparts water solubility. If upon ionization the polar portion of the molecule, which governs its property as emulsifying agent, contains the negative charge, the agent is called anionic. If the polar portion of the molecule contains a positive charge, then the emulsifier is cationic and droplets bear a positive charge such as lauryltrimethyl amomonium chloride (Figure A-7b). A third type of emulsifying agent is one which does not dissociate at all and is called nonionic agent such as polyoxyethylene lauryl ether (Figure A-7c). This type of emulsion has no practical importance in highway construction [30].

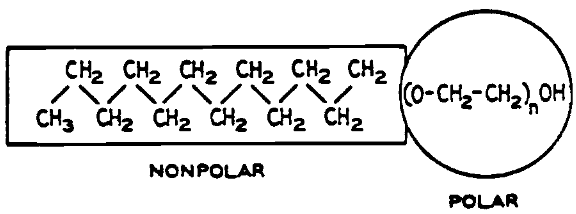
When an emulsifying agent is placed in water only, the molecule migrates to the surface and orients at the air-water interface in a manner similar to that shown in Figure A-8a, or it shields itself from water by



a) Sodium palmitate(Left,nonpolar. Right,polar)



b) Lauryltrimethylammonium chloride--cationic.



c) Polyoxyethylene lauryl ether--nonionic.

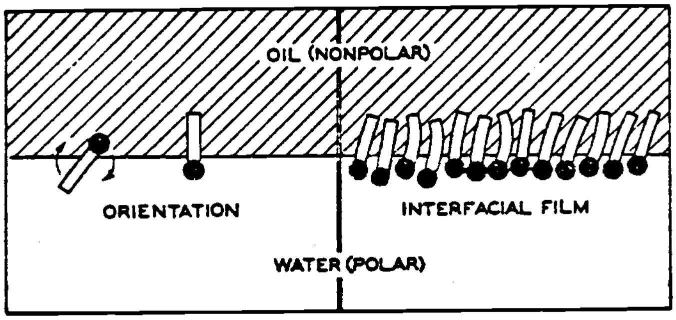
Figure A-7. Typical emulsifying agents.(30)

aggregating as shown in Figure A-8b. Such clusters of molecules in which the hydrocarbon trails are shielded from the water by polar heads are known as micelle.

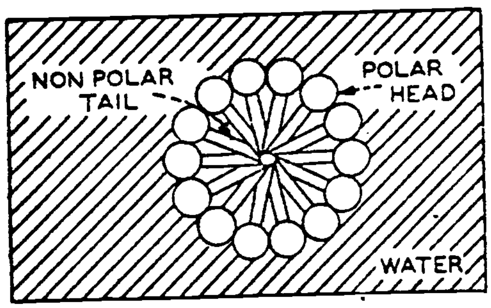
The three chemical types of emulsifying agents share one common property; they are adsorbed at an interface between a liquid and air, solid, or another liquid. These molecules are surface active and when placed in oil-water systems tend to orient in a very specific manner. The polar portion with its affinity for water will orient into the water phase. The non-polar part will orient into the oil phase (Figure A-8a, left). This special orientation property causes the formation of distinct film of emulsifier molecules (interfacial film) (Figure A-8a, right).

Once emulsifier is present in a system in quantities large enough to form micelles, the micelles can absorb into their hydrocarbon centers a certain quantity of nonpolar oil as shown in Figure A-8c.

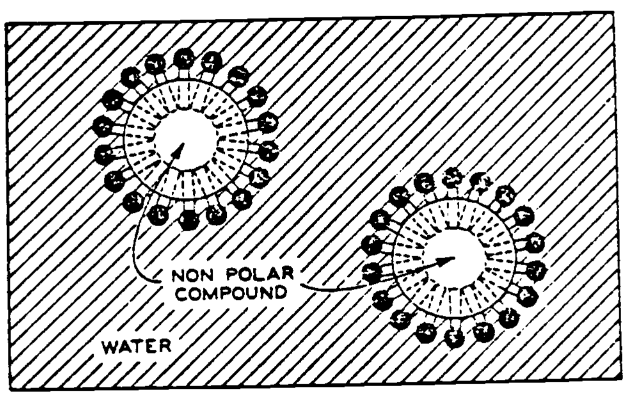
2.2.3.2 <u>Emulsification of asphalt</u>: Many asphalts contain enough acid components of high molecular weight (asphaltogenic acids) to produce fine dispersions of asphalt in water when hot liquid asphalt is agitated with dilute alkaline solution [30]. Such asphalts are called emulsifiable asphalts. Those asphalts containing no acids are classified as nonemulsifiable. With such asphalts it is necessary to add suitable acids to the



a)Interfacial orientation and film formation.



b)Soap micelle.



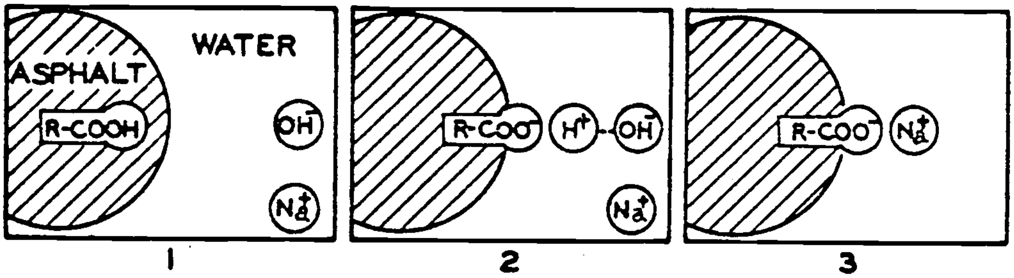
c)Emulsified droplets.

Figure A-8. Emulsifier agent behavior.(30,31) asphalt prior to emulsification in simple mixing equipment. The principle of insitu emulsification of asphalt is presented in Figure A-9.

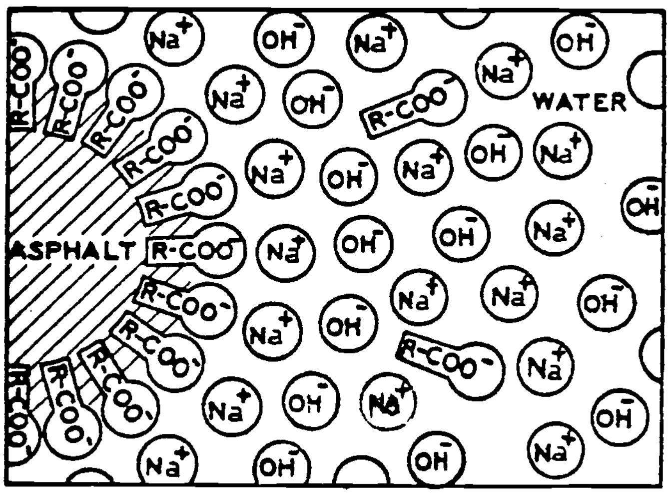
For the purpose of cationic emulsification, all asphalts may be considered nonemulsifiable, for all of the cationic emulsifying agent must be added to the system. Insitu emulsification of asphalt in simple mixing equipment is possible with cationic emulsifiers as well as anionic [31]. insitu cationic emulsification of asphalt (Figure A-10) is possible if the asphalt is first treated with a high molecular weight amine before dispersion in a dilute solution of water-soluble acid. The amount of acid contained in the water is in excess of that needed to neutralize the amine. Hydrochloride acid is commonly used. The emulsified droplets bear a positive charge and are surrounded by negatively charged chloride ions [30].

2.2.3.3 Emulsifying compounds:

Anionic emulsified asphalts: Almost every known type of anionic surfactant appears in the emulsified asphalt literature. In the early days of emulsified asphalt production, materials such as animal blood, clay, and soaps were used as emulsifying agents. Petroleum-derived materials include napthenates, sulfonates, cresylates, and wax acid soaps, all of which are generally used as sodium salts.

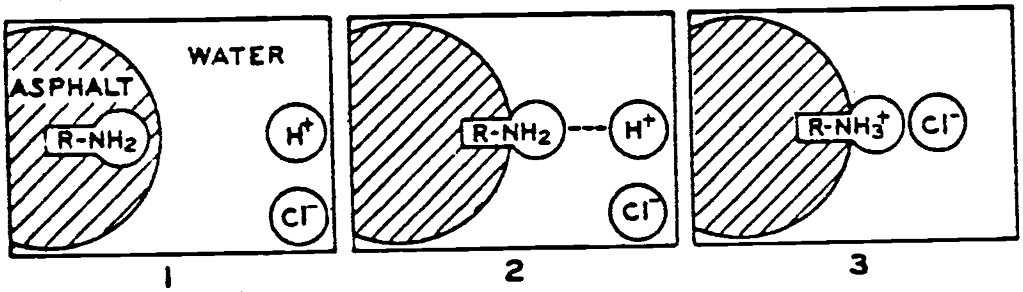


a) In situ emulsification of asphalt, anionic emulsion.

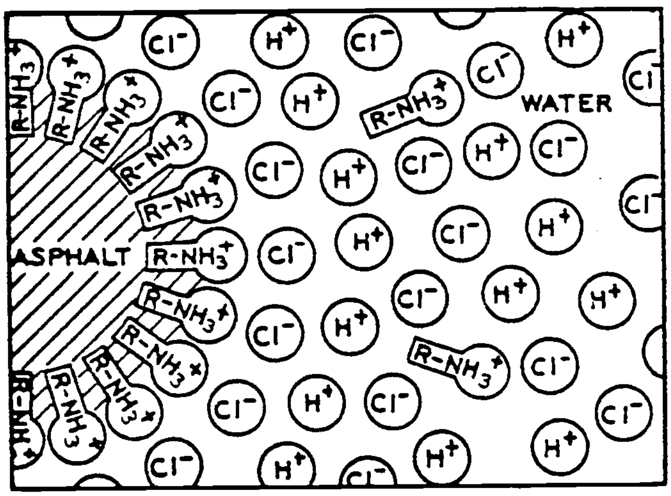


b) Emulsified asphalt droplet, anionic emulsion.

Figure A-9. Schematic of anionic emulsified asphalts.(31)



a) In situ emulsification of asphalt, cationic emulsion.



b) Emulsified asphalt droplet, cationic emulsion.

Figure A-10. Schematic of cationic emulsified asphalt.

As the demand for emulsified asphalts increased, new and more efficient emulsifying agents were found. Several chemical emulsifiers now are commercially available. The most often used are fatty acids, wood product derivatives, and tall oils, all of which are reported to improve the adhesion of the deposited asphalt to aggregate [26, 29, 47]. Rosinsoaps and lignin sulfonates, such as sodium ammonium and calcium salts are emulsifiers widely used to make SS-type emulsified asphalt.

Cationic emulsified asphalts: Simple C_{12} to C_{18} monoalkylamine hydrochloride or acetate salts were used to make the first cationic emulsified asphalts. Most cationic emulsifiers are now fatty amines. The amines are converted into soap by reacting with acid, usually hydrochloric. Another type of emulsifying agent, fatty quarternary ammonium salts, is used to produce cationic emulsions. They are water-soluble salts as produced and do not require the addition of acid to make them water-soluble. In practice, the choice of cationic emulsifying agent is limited to three main types [14].

o Fatty Amines, having the general formula $R\text{-}CH_2\text{-}NH_2$ obtained from fatty acids by amidation, dehydration and hydrogenation and especially their derivatives:

- diamines having the general formula

$$R\text{-}CH_2\text{-}NH\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}NH_2$$

- polyamines obtained by the addition of acrylonitrile on the lower amine.

The major part of road building cationic emulsifiers belongs to this type. Since the spreading coefficient increases as the number of amine groups increases, and a diamine will give a finer emulsion and polyamine gives a slower setting emulsion.

o Amido Amines, obtained by the reaction of fatty acid on a polyamine, is characterized by a formula of the following type:

$$R-CO-NH-CH_2-CH_2-CH_2-NH_2$$

o Nitrogenous hetrocydes of the imidazoline type of which the most simple formula is [14]:

$$R-C\begin{matrix} N-CH_2 \\ \\ NH-CH_2 \end{matrix}$$

These are emulsifiers with a high spreading coefficient. They thus give a coarser particle-size distribution than the amines. This particle-size factor outweighs the electrostatic repulsion factor and the emulsions obtained in fact have a fairly rapid setting rate.

The other types of chemicals can be used as stabilizers. They are:

o The quaternary ammonium compounds used in the form of salt with the following general formula:

$$\left[\begin{matrix} R_1 & & R_3 \\ & N & \\ R_2 & & R_4 \end{matrix}\right]^{+} X^{-}$$

o Oxythylene Amines for example [14]:

$$R-N\begin{matrix} (CH_2 - CH_2O)_x-H \\ \\ (CH_2 - CH_2O)_y-H \end{matrix}$$

used in the form of hydrochloric salt.

The choice of emulsifier and amount is made in accordance with the type and class of the emulsion. Each manufacturer has his own procedure for using his agent in emulsified asphalt production. In most cases, the agent is combined with the water before introduction into the colloidal mill. In other cases, it may be combined with the asphalt cement just before it goes into the colloidal mill. Additives (such as calcium chloride, sugars, gelatin, glues, ammonium chloride, nitrate and sodium silicate) sometimes are also necessary to modify one or more properties of emulsified asphalt, such as viscosity, adhesion to mineral surfaces, or stability [29].

2.3 Classes of Emulsified Asphalts

The classes of emulsified asphalts are determined by the kind of emulsifier used. There are three classes: anionic, cationic and nonionic.

o Anionic Emulsified Asphalts: When emulsifier is mixed with water and asphalt, if after ionization the surface of asphalt bears a negative charge, the emulsified asphalts are referred to as anionic.

o Cationic Emulsified Asphalts: If after ionization the surface of asphalt bears positive charge, the emulsified asphalt is referred to as cationic.

o Nonionic Emulsified Asphalts: When nonionic emulsifier is mixed with water and asphalt, the hydrophillic head dissolves without ionization and gives a nonionic emulsified asphalt.

2.4 Types of Emulsified Asphalts

Emulsified asphalts are further classified on the basis of how quickly the asphalt will coalesce (revert to asphalt cement) which is controlled by the amount and type of emulsifier. There are three types of emulsified asphalts:

1. Rapid Setting (RS)
2. Medium Setting (MS)
3. Slow Setting (SS)

The rapid setting materials have a relatively low concentration of emulsifier and therefore are very susceptible to breaking. RS emulsified asphalts are generally manufactured with 120-150 or 150-200 penetration base asphalt. Depending on the amount of asphalt used, there are two grades available, designated as 1 and 2. The RS-2 material has a larger percentage of asphalt in the emulsion than the RS-1.

The medium setting emulsified asphalts differ from the RS ones in the quantity and/or type of emulsifier. These materials can be mixed with coarse aggregates containing no fines. ASTM lists specifications for three MS emulsified asphalts, MS-1, MS-2, and MS-3 (MS-2h): as the number increases, the proportion of asphalt in the emulsion increases.

The slow setting emulsified asphalts are the most stable of the emulsified asphalts and can be mixed with either well-graded aggregates or with dense-graded aggregate, and are therefore referred to as dense aggregate mixing emulsions. There are two grades of this emulsion: SS-1 and SS-2 or SS-1h. The SS-1h emulsified asphalt differs from the SS-1 emulsified asphalt in that harder asphalt (40-50 or 60-70 pen.) is used.

The letter "C" in front of the emulsified asphalt type denotes cationic. The absence of the "C" denotes anionic.

Three grades of high-float medium-setting anionic emulsified asphalts designated HFMS have been added to Standard ASTM Specifications. These grades are used primarily in cold and hot plant mixes, coarse aggregate seal coats, and road mixes. High float emulsified asphalts have a specific quality that permits a thicker film coating without danger of runoff. Asphalt residue has less temperature-susceptibility. It has improved characteristics at high and low temperatures, and has high penetration but is resistant to flow. Therefore, high float emulsfied asphalts will coat the surface of open-graded mixes with thick films of asphalt.

A thick-set type of emulsified asphalt (QS) has been developed for slurry seals. It has a quick-setting property which solves one of the major problems with the use of slurry seals. Several hours can be required with an SS emulsified asphalt, whereas a QS emulsified asphalts slurry seal can be open to traffic 45 minutes after construction. QS emulsified asphalts get their initial strength from a chemical reaction between aggregates and asphalt droplets and not from dehydration processes.

The choice of type depends upon the use to which the emulsified asphalt is put (Table A-1) and will be discussed later.

Table A-1. Guide for use of asphalt emulsions (8).

TYPE OF CONSTRUCTION	EMULSIFIED ASPHALTS													
	ANIONIC								CATIONIC					
	RS-1	RS-2	MS-1 HFMS-1	MS-2, HFMS-2	MS-2h, HFMS-2h	HFMS-2s	SS-1	SS-1h	CRS-1	CRS-2	CMS-2	CMS-2h	CSS-1	CSS-1h
ASPHALT – AGGREGATE MIXTURES														
ASPHALT CONCRETE AND HOT LAID PLANT MIX														
PAVEMENT BASE AND SURFACES														
HIGHWAYS														
AIRPORTS														
PARKING AREAS														
DRIVEWAYS														
CURBS														
INDUSTRIAL FLOORS														
BLOCKS														
GROINS														
DAM FACINGS														
CANAL AND RESERVOIR LININGS														
COLD-LAID PLANT MIX[18]														
PAVEMENT BASE AND SURFACES														
OPEN-GRADED AGGREGATE				X	X						X	X		
WELL GRADED AGGREGATE						X	X	X					X	X
PATCHING, IMMEDIATE USE							X	X					X	X
PATCHING, STOCKPILE														
MIXED-IN-PLACE (ROAD MIX)[10]														
PAVEMENT BASE AND SURFACES														
OPEN-GRADED AGGREGATE				X	X						X	X		
WELL-GRADED AGGREGATE						X	X	X					X	X
SAND						X	X	X					X	X
SANDY SOIL						X	X	X					X	X
PATCHING, IMMEDIATE USE						X	X	X					X	X
PATCHING, STOCKPILE														
RECYCLING														
HOT MIX														
COLD-MIX[19]				X	X	X	X	X			X	X	X	X
ASPHALT – AGGREGATE APPLICATIONS														
SURFACE TREATMENTS														
SINGLE SURFACE TREATMENT	X	X							X	X				
MULTIPLE SURFACE TREATMENT	X	X							X	X				
AGGREGATE SEAL	X	X	X						X	X				
SAND SEAL	X	X	X						X	X				
SLURRY SEAL							X	X					X	X
ASPHALT APPLICATIONS														
SURFACE TREATMENT														
FOG SEAL			X				X[2]	X					X[2]	X[2]
PRIME COAT				X[1]			X[1]	X			X[1]		X[1]	X[1]
TACK COAT	X		X				X[2]	X	X				X[2]	X[2]
DUST LAYING							X	X					X	X
MULCH							X	X						
MEMBRANE														
CANAL AND RESERVOIR LININGS														
EMBANKMENT ENVELOPES														
CRACK FILLING														
ASPHALT PAVEMENTS							X[1]	X					X[1]	X
PORTLAND CEMENT CONCRETE PAVEMENTS														

2.5 Storage

The storage and handling of emulsified asphalts requires precautions beyond those used for other asphalt material types. Improper handling or storage of emulsified asphalt may cause breaking, thereby making it useless.

Asphalt should be stored at temperatures between 50°F (10°C) and 185°F (85°C) depending on the use as shown in Table A-2. Water or low pressure stream can be used to heat emulsified asphalt storage tank with heating coils if the temperature at the coil surface does not exceed 185°C (85°C). Heating emulsified asphalt above 85°C will cause the evaporation of water, resulting in increase in viscocity and an asphalt layer in the tank [40]. Heating with a coil surface temperature above 212°F will cause breakdown of emulsified asphalt.

Emulsified asphalt should not be allowed to freeze. This breaks the structure and causes the separation of asphalt and water. Pumps, valves, and lines, therefore, should be protected from freezing in winter.

Storage tanks should be insulated to protect emulsions from freezing. A skin of asphalt forms on the emulsified asphalt surface when exposed to air. Therefore, it is best to use tall vertical tanks or to keep horizontal tanks full to minimize the area exposed to air. Propellers or a circulating system may be used

Table A-2. Storage Temperatures for Emulsified Asphalts [23].

Grade	Temperature, °C (°F) Minimum	Temperature, °C (°F) Maximum
RS-1	20 (70)	60 (140)
RS-2, CRS-1, CRS-2	50 (125)	85 (185)
SS-1, SS-1h, CSS-1, CSS-1h, MS-1	10 (50)	60 (140)
CMS-2, CMS-2h, MS-2, MS-2h, HFMS-2h	50 (125)	85 (185)

to minimize surface skin formation if over-mixing or over-pumping is avoided. In tanks that have no such systems, a very light film of kerosene or oil on the surface can reduce skin formation. Cathodic protection should be used to avoid possible corrosion of walls and heating coils.

3.0 PROPERTIES AND SPECIFICATIONS

3.1 Properties

Emulsified asphalts are two-phase physiochemical systems, with properties which readily can be varied to obtain optimum properties. The performance of the emulsifier is affected by its properties. The most important properties that affect emulsified asphalt performance are discussed below.

3.1.1 Asphalt Content

Asphalt content is the amount of dispersed asphalt by weight in the emulsified asphalt. Standard practice is to give an emulsified asphalt containing considerably more than the minimum asphalt requirements. Emulsified asphalts with high asphalt content have better properties both in laboratory tests and in field performance [30]; however, there is an upper limit to the ue of asphalt content (80%). The increased viscosity and asphalt content usually give an increase in the film deposited when using MS-2 or RS-2 instead of MS-1 or RS-1.

The American Society for Testing and Materials (ASTM) uses a distillation method for determining the water content of emulsified asphalt. Specifications for emulsified asphalt are given by ASTM and AASHTO and are shown in Tables A-3 and A-6 for anionic emulsified asphalts and Tables A-4 and A-5 for cationic emulsified asphalts.

3.1.2 Viscosity

Viscosity depends essentially on the binder content. It increases slowly with asphalt content up to approximately 65% asphalt by weight of total emulsified asphalt and rapidly thereafter. It is further influenced by particle size distribution. In fact, the finer the particle size and the more uniformly graded the particles, the higher will be the viscosity. Asphalt from different sources will give emulsified asphalts with different viscosity. Viscosity of emulsions can be changed (higher or lower) by adding chemicals such as calcium chloride, starch, gelatin, glue, phenokes [29].

Emulsified asphalt viscosity affects the film thickness on road aggregate. Emulsified asphalts of high viscosity are used when relatively thick films of plated asphalt are desired. Emulsified asphalts of low viscosity are used when small aggregate particles must be evenly coated.

Table A-3. Requirements and applications for anionic emulsified asphalt, ASTM(42).

Type	Rapid-Setting				Medium-Setting					
	RS-1		RS-2		MS-1		MS-2		MS-2h	
Grade	min	max	min	max	min	max	min	max	min	max
Tests on emulsions										
Viscosity, Saybolt Furol at 77°F (25°C), s	20	100			20	100	100		100	
Viscosity, Saybolt Furol at 122°F (50°C), s			75	400						
Storage stability test, 24-h, %		1		1		1		1		1
Demulsibility,[A] 35 ml, 0.02 *N* CaCl, %	60		60							
Coating ability and water resistance										
Coating, dry aggregate					good		good		good	
Coating, after spraying					fair		fair		fair	
Coating, wet aggregate					fair		fair		fair	
Coating, after spraying					fair		fair		fair	
Cement mixing test, %										
Sieve test, %		0.10		0.10		0.10		0.10		0.10
Residue by distillation, %	55		63		55		65		65	
Tests on residue from distillation test										
Penetration, 77°F (25°C), 100g, 5 s	100	200	100	200	100	200	100	200	40	90
Ductility, 77°F, (25°C), 5 cm/min cm	40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5	
Float test, 140°F (60°C), s										
Typical applications[B]	surface treatment, penetration macadam, sand seal coat, tack coat, mulch		surface treatment, penetration macadam, coarse aggregate seal coat (single and multiple)		cold plant mix, road mix, sand seal coat, crack treatment, tack coat		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat, sand seal coat		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat	

Footnotes for Table 1 appear on the following page.

Table A-3 (continued).

Type	Medium-Setting								Slow-Setting			
	HFMS-1		HFMS-2		HFMS-2h		HFMS-2s		SS-1		SS-1h	
Grade	min	max	min	max	min	max	min	max	min	max	min	max
Tests on emulsions:												
Viscosity, Saybolt Furol at 77°F (25°C), s	20	100	100	...	100	...	50	...	20	100	20	100
Viscosity, Saybolt Furol at 122°F (50°C), s	...	...	...	...	...	...	...	...	...	...	...	...
Storage stability test, 24-h, %	...	1	...	1	...	1	...	1	...	1	...	1
Demulsibility,[A] 35 ml, 0.02 N $CaCl_2$, %	...	...	...	...	...	...	...	...	...	...	...	...
Coating ability and water resistance:												
Coating, dry aggregate	good		good		good		good		...			
Coating, after spraying	fair		fair		fair		fair		...			
Coating, wet aggregate	fair		fair		fair		fair		...			
Coating, after spraying	fair		fair		fair		fair		...			
Cement mixing test, %	...	...	...	...	...	...	...	...	...	2.0	...	2.0
Sieve test, %	...	0.10	...	0.10	...	0.10	...	0.10	...	0.10	...	0.10
Residue by distillation,	55		65		65		65		57		57	
Tests on residue from distillation test:												
Penetration, 77°F (25°C), 100 g, 5 s	100	200	100	200	40	90	200	...	100	200	40	90
Ductility, 77°F, (25°C), 5 cm/min, cm	40		40	...	40	...	40	...	40	...	40	...
Solubility in trichloroethylene, %	97.5		97.5		97.5	...	97.5	...	97.5	...	97.5	...
Float test, 140°F (60°C), s	1200		1200		1200	...	1200	...	...	...	...	...
Typical applications[B]	cold plant mix, road mix, sand seal coat, crack treatment, tack coat		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment road mix, tack coat, and seal		cold plant mix hot plant mix coarse aggregate seal coat (single and multiple), crack treatment road mix tack coat		dense-graded cold plant mix and road mix, stockpile mix, crack treatment, patching mix		cold plant mix, road mix, slurry seal coat, tack coat, fog seal, dust layer, mulch			

[A] The demulsibility test shall be made within 30 days from date of shipment.
[B] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

Table A-4. Requirements and typical application for cationic emulsified asphalt, ASTM(42).

Type	Rapid-Setting				Medium-Setting				Slow-Setting			
Grade	CRS-1		CRS-2		CMS-2		CMS-2h		CSS-1		CSS-1h	
	min	max	min	max	min	max	min	max	min	max	min	max
Test on emulsions:												
Viscosity, Saybolt Furol at 77°F (25°C), s									20	100	20	100
Viscosity, Saybolt Furol at 122°F (50°C), s	20	100	100	400	50	450	50	450				
Storage stability test, 24-h, %		1		1		1		1		1		1
Classification test	passes		passes									
Coating, ability and water resistance:												
Coating, dry aggregate					good		good					
Coating, after spraying					fair		fair					
Coating, wet aggregate					fair		fair					
Coating, after spraying					fair		fair					
Particle charge test	positive		positive		positive		positive		positive		positive	
Sieve test, %		0.10		0.10		0.10		0.10		0.10		0.10
Cement mixing test, %										2.0		2.0
Distillation:												
Oil distillate, by volume of emulsion, %		3		3		12		12				
Residue, %	60		65		65		65		57		57	
Tests on residue from distillation test:												
Penetration, 77°F (25°C), 100 g, 5 s	100	250	100	250	100	250	40	90	100	250	40	90
Ductility, 77°F (25°C), 5 cm/min, cm	40		40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5	
Typical applications[A]	surface treatment, penetration macadam, sand seal coat, tack coat, mulch		surface treatment, penetration macadam, coarse aggregate seal coat (single and multiple)		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat, sand seal coat		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat		cold plant mix, road mix, slurry seal coat, tack coat, fog seal, dust layer, mulch			

[A] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

Table A-5. Requirements and typical applications for cationic emulsified asphalt , AASHTO(42).

Type	Rapid-Setting				Medium-Setting				Slow-Setting			
Grade	CRS-1		CRS-2		CMS-2		CMS-2h		CSS-1		CSS-1h	
	min	max	min	max	min	max	min	max	min	max	min	max
Test on emulsions:												
Viscosity, Saybolt Furol at 77°F (25°C), s									20	100	20	100
Viscosity, Saybolt Furol at 122°F (50°C), s	20	100	100	400	50	450	50	450				
Storage stability test, 24-h, %		1		1		1		1		1		1
Classification test	passes		passes									
Coating, ability and water resistance:												
Coating, dry aggregate					good		good					
Coating, after spraying					fair		fair					
Coating, wet aggregate					fair		fair					
Coating, after spraying					fair		fair					
Particle charge test	positive		positive		positive		positive		positive		positive	
Sieve test, %		0.10		0.10		0.10		0.10		0.10		0.10
Cement mixing test, %										2.0		2.0
Distillation:												
Oil distillate, by volume of emulsion, %		3		3		12		12				
Residue, %	60		65		65		65		57		57	
Tests on residue from distillation test:												
Penetration, 77°F (25°C), 100 g, 5 s	100	250	100	250	100	250	40	90	100	250	40	90
Ductility, 77°F (25°C), 5 cm/min, cm	40		40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5	
Typical applications[a]	surface treatment, penetration macadam, sand seal coat, tack coat, mulch		surface treatment, penetration macadam coarse aggregate seal coat (single and multipl		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat, sand seal coat		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat		cold plant mix, road mix, slurry seal coat, tack coat, fog seal, dust layer, mulch			

[a] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

Table A-6. Requirements and typical applications for anionic emulsified asphalt, AASHTO(42).

Type	Medium-Setting								Slow-Setting			
	HFMS-1		HFMS-2		HFMS-2h		HFMS-2s		SS-1		SS-1h	
Grade	min	max	min	max	min	max	min	max	min	max	min	max
Tests on emulsions:												
Viscosity Saybolt Furol at 77°F (25°C), s	20	100	100	.	100		50	...	20	100	20	100
Viscosity Saybolt Furol at 122°F (50°C), s	.	...	...	...	...					.		..
Settlement,[a] 5-day, %	...	5	...	5	...	5	...	5	...	5	..	5
Storage stability test,[b] 24-h, %	.	1	...	1	...	1	...	1		1		1
Demulsibility,[c] 35 ml, 0.02 N $CaCl_2$, %	.	...	..	..	...	..	...	.	..			.
Coating ability and water resistance:												
Coating, dry aggregate	good		good		good		good		.		..	
Coating, after spraying	fair		fair		fair		fair		..		.	
Coating, wet aggregate	fair		fair		fair		fair		..		..	
Coating, after spraying	fair		fair		fair		fair					
Cement mixing test, %	.	...	...	..	...		...	...		2.0	.	2.0
Sieve test, %	...	0.10	.	0.10	..	0.10	...	0.10		0.10	.	0.10
Residue by distillation, %	55	...	65	.	65		65	.	57	.	57	
Tests on residue from distillation test							1	7				
Penetration, 77°F (25°C), 100 g, 5 s	100	200	100	200	40	90	200	..	100	200	40	90
Ductility, 77°F, (25°C), 5 cm/min, cm	40	..	40	..	40		40		40	.	40	
Solubility in trichloroethylene, %	97.5	...	97.5	..	97.5		97.5	.	97.5	.	97.5	.
Float test, 140°F (60°C), s	1200	...	1200	...	1200		1200	.	.	.	.	.
Typical applications[d]	cold plant mix, road mix, sand seal coat, crack treatment, tack coat		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment road mix, tack coat, and seal		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment road mix, tack coat		dense-graded cold plant mix and road mix, stockpile mix, crack treatment, patching mix		cold plant mix, road mix, slurry seal coat, tack coat, fog seal, dust layer, mulch			

[a] The test requirement for settlement may be waived when the emulsified asphalt is used in less than 5 days time, or the purchaser may require that the settlement test be run from the time the sample is received until the emulsified asphalt is used, if the elapsed time is less than 5 days.

[b] The 24-h storage stability test may be used instead of the 5-day settlement test.

[c] The demulsibility test shall be made within 30 days from date of shipment.

[d] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

If Nr is the ratio of emulsion viscosity to viscosity of continuous phase, and Cv is the parts by volume of the disperse phase, then the viscosity vs. asphalt content can be explained by the following equation:

$Nr = (1+1.25\ Cv)/(1-1.28\ Cv)^2$...(Eiler's Equation) (A-1)

Saybolt Furol viscosity method is used to measure viscosity according to specifications (Tables A-3, A-4, A-5 and A-6). According to R. L. Ferm [29], capillary viscometers do not work well with emulsions, which tend to foam due to their surface-active components. However, rotational viscometers do work well with emulsions. Emulsified asphalts are not all newtanian so it is best to

standardize or one method used by everyone.

3.1.3 Particle Size Distribution

The size distribution of emulsified asphalts is of the logarithmic-normal type. It is represented by an S-curve [14], characterized by two parameters (Figure A-11):

o An average value D defining fineness; this is the abscissa of the 50 percent point on the curve.

o The standard deviation of the distribution defined by

$$\sigma = 1/2 \text{ Log } D_{85}/D_{16} \quad . \ . \ . \ . \ . \ . \ . \quad (A-2)$$

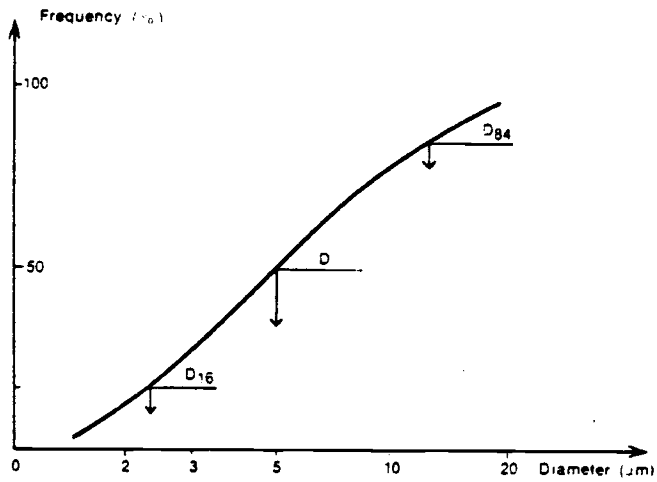


Figure A-11. Size distribution curve of a bituminous emulsion [14].

in which D_{84} and D_{16} are respectively the abscissas of the 84 percent and 16 percent points. It represents the degree of dispersion of emulsified asphalt.

Particle size has an effect on emulsified asphalt properties. Different parameters influence particle size. Particle size distribution results from the emulsification process. It therefore depends on:

1) The mechanical energy and consequently such factors as:
   - characteristics of mill
   - viscosity of phases with the implications involved as regards binder and aqueous-phase temperature.
2) The physical and mechanical energy contributed by the emulsifying agent which should lower the interfacial tension between the hydrocarbon phase and the aqueous phase; it will therefore depend on the type of emulsifying agent and its content and on its neutralization rate (pH).

Asphalt particle size is usually determined with the optical microscope after diluting the emulsion. A more rapid and accurate method employs the Coulter counter. Spectrophotometric methods have also been used to determine the mean surface area, and thus the main particle size of emulsified asphalt [29].

3.1.4 pH

The emulsifier acts in anionized form and, consequently, the neutralization rate has a major influence on the characteristics of the emulsion. The increase in the acid quantity increases the storage stability and reduces the setting rate. However, the adhesivity of the residual bitumen is good only within a pH band depending on the emulsifying agent. A large excess of acid will thus have the consequence of a loss of adhesivity. According to Armak [35], a pH less than 7 contributes to a good emulsification of asphalt.

3.1.5 Zeta Potential

Zeta potential is a relatively new concept for use in emulsified asphalt [35]. It is determined by the motion of colloidal particles in an electrical field, and this electrophoretic mobility can be measured with an instrument called Zeta Meter.

There is a difference in the electrical potential between the surface of a dispersed colloidal particle and the bulk aqueous solution. The existence of zeta potential is brought about by the adsorption of ions onto a colloidal particle surface (asphalt). The asphalt particles assume the overall character of ions adsorption. A double layer of ions and counter-ions exist in solution surrounding each particle of dispersed asphalt (Figure A-12). The extent of attraction and

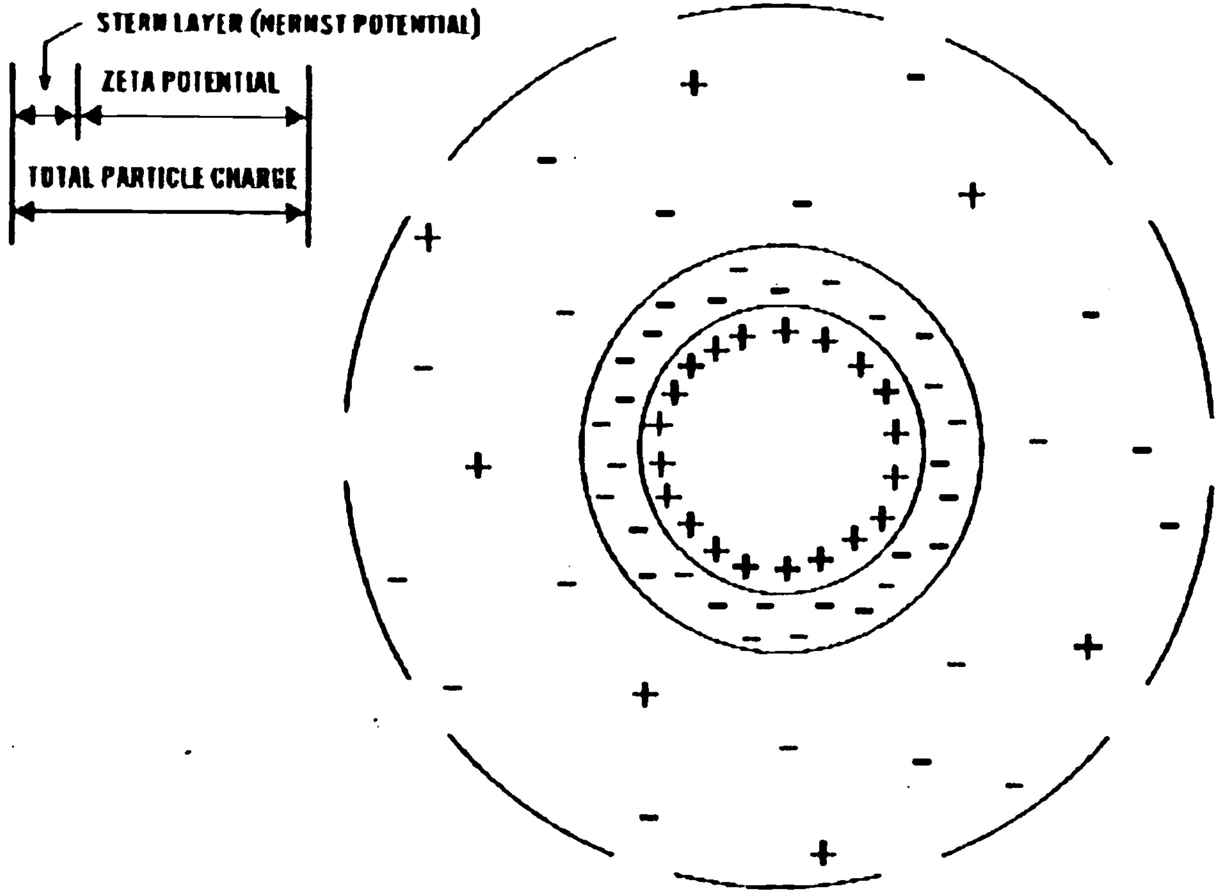


Figure A-12. The ionic double layer [18].

quantity of counter-ions depend on the concentration, pH and ionic intensity of the emulsifier.

This double layer affects mobility of charged asphalt particles and the stability of the system. The greater the double layer, the greater zeta potential (Figure A-13) which causes restricted droplet movement because of the close packing of the double layers. This results in high viscosity (Figure A-14). In most cases, a large zeta potential indicates large repulsive forces between individual particles in an emulsified asphalt and good stability [14].

pH and emulsifier type and concentration are the most important factors affecting colloidal adsorption and double layer. As the concentration of emulsifier is increased, the double layer is compressed and zeta potential is decreased. The zeta potential for anionic and cationic surfactants normally used as emulsifiers for asphalt range from -80 millivolts (mv) to -30 mv for the anionic type and +128 mv to +18 mv for cationic type.

Since almost all naturally occurring aggregates used in road construction possess a negative surface charge, a partially predicative relationship exists between the zeta potential of aggregates, their surface area and the zeta potential of cationic surfactants. Since anionic surfactants possess a negative charge, the same as most aggregates, and nonionic surfactants possess no charge,

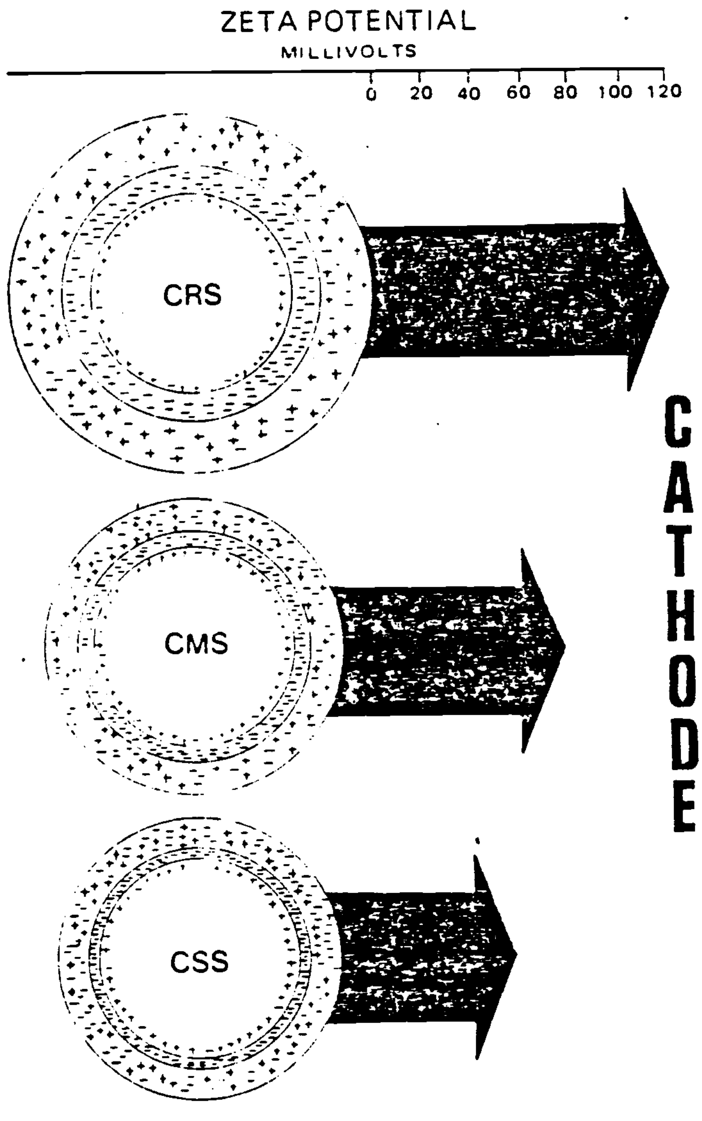


Figure A-13. Zeta potential [35].

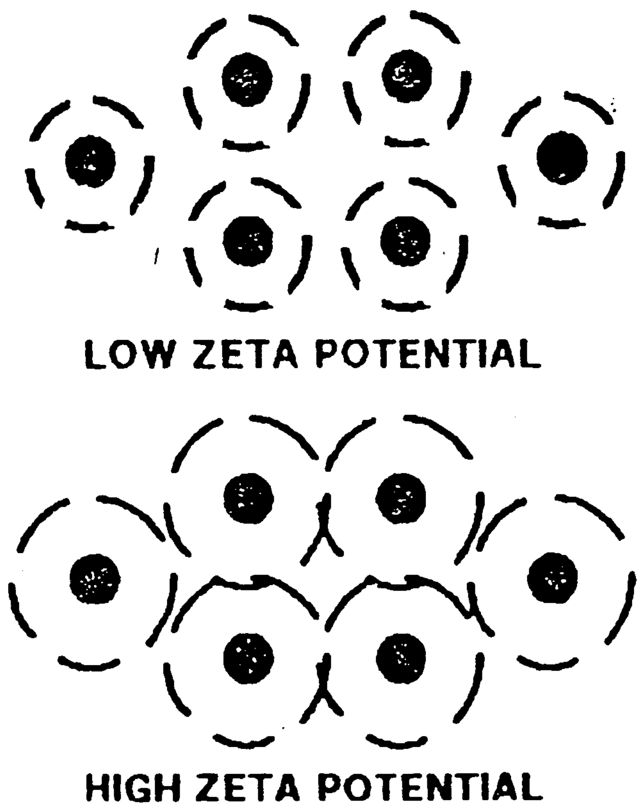


Figure A-14. Role of zeta potential in emulsion viscosity [18].

they both deposit asphalt onto an aggregate surface primarily through evaporation and absorption of the continuous water-phase of emulsion. When sufficient water has been depleted from the emulsified asphalt layer, an unstable condition is reached where the asphalt cannot remain in suspension and it pads out and coalesces on the surface of the aggregate [1, 30, 31, 35].

Cationic emulsified asphalt, by contrast, begins to deposit on the surface of aggregate at the moment of contact. The influence of the negative surface charge of aggregate and its surface area causes cationic emulsified asphalt to be adsorbed by the aggregate by cathodic effect. This affinity of an aggregate for cations is stronger than its affinity for water. Therefore, water is displaced. Asphalt films deposited in this manner are very difficult to remove by the action of subsequent water. In effect the cationic surfactant provides an anti-stripping action similar to that obtained with oil-soluble anti-stripping agents in asphalt cement and cutbacks [1, 31].

3.1.6 Stability

Emulsified asphalt is a dispersion of asphalt in water. Asphalt dispersion will not hold unless emulsifying agent is present in the system. Emulsifiers reduce the interfacial tension between the oil or asphalt and water which enable them to mix.

Five types of emulsified asphalt stability are recognized: chemical, storage, freezing, mechanical, and mixing. Chemical stability is the stability of emulsion to resist flocculation because of improper formulation or because of contamination of salts. Chemical stability is achieved by adjusting the concentration of the various emulsifying components to build up surface charge on the emulsified droplets and avoid breakdown. Mechanical stability, which is the ability of emulsions to withstand pumping and handling, has little correlation with chemical stability. Freezing stability is improved by using emulsifiers that do not solidify at low temperatures.

In storage, stability is indicated by settlement of which the velocity:

$$V = \frac{2\ gr^2\ (d_1 - d_2)}{9\ n_2} \quad \text{(Stoke's equation) (A-3)}$$

where,

g = gravitational constant

r = radius of the droplets

d_1 = the density of dispersed phase

d_2 = the density of continuous phase

n_2 = the viscosity of continuous phase.

Coagulation then occurs in two stages: flocculation which is a reversible phenomenon during which the particle agglomerate, and coalescence which is an irreversible phenomenon in which the agglomerated particles combine to form larger ones. These two phenomena are inseparable and it is the slowest which determines breaking rate. It is possible to slow down settlement by varying the size of particles (r). Also, increasing viscosity (n) by the use of chemicals decreases the rate of settlement V. The average particle diameter varies nearly as the logarithm of emulsifier concentration, as may be seen in Figure A-15, whereas the setting index (setting rate estimate from setting test using siliceous filler and 100 g of emulsion) decreases in inverse proportion to concentration (Figure A-16) [14].

Storage stability is determined by observing the formation of shot, settlement, creaming or changes of viscosity of emulsified asphalt sample over a period of time. Well-formulated emulsified asphalts should show little or no change in properties after six months of storage and are often found to be little changed after several years of storage if protected from evaporation [29].

The various grades of paving emulsified asphalts are designed to have different stabilities on contact with mineral aggregates. The RS and CRS emulsified asphalts should coalesce almost immediately when brought into

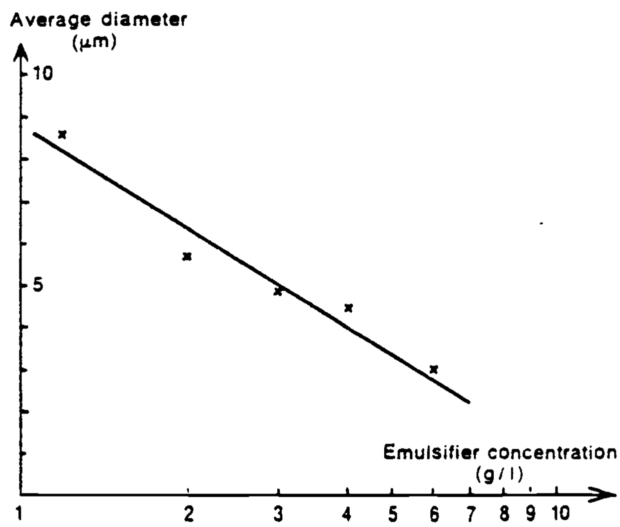


Figure A-15. Variation of average particle diameter as a function of the amount of emulsifier [14].

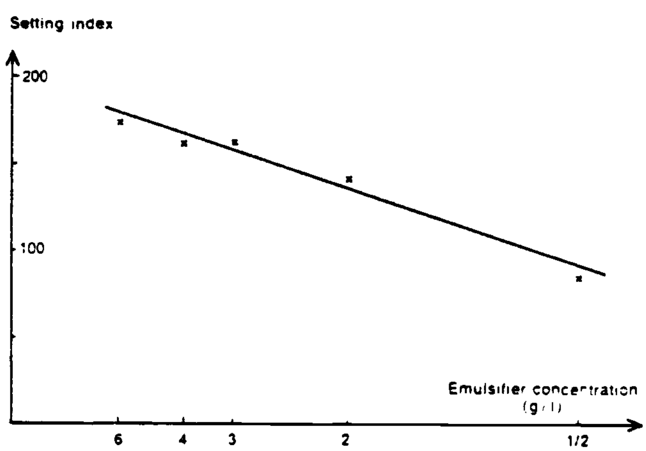


Figure A-16. Variation of setting index as a function of the amount of emulsifier [14].

contact with a mineral surface. The rate of coalescence will depend mainly on the particular emulsifier used and its concentration (Figure A-16), the nature of the aggregate, temperature and the amount of shear developed by the application technique. The SS emulsified asphalts have such great stability that they can be mixed with the aggregate for a prolonged time without any coalescence. The MS are of intermediate stability.

Setting rate is affected by the type of aggregate used and in particular to its mineralogical nature and its size distribution. The higher the proportion of filler, the faster the setting rate because it is a surface phenomenon and the filler has a tendency to absorb water. This is quite clear in the case of slurry seal where setting rate is of considerable importance. For a given aggregate, rate of break will be controlled by adjusting the pH, the amount and nature of emulsifier and the size distribution.

These are the most important properties together with coatability, determine the adequacy of emulsified asphalt, and should meet the specifications (Tables A-3, A-4, A-5 and A-6).

3.2 Aggregate - Emulsified Asphalt System

The composition and structure of aggregate is one of the most important factors that affect the adhesion in an asphalt-aggregate system. Siliceous aggregates become negatively charged in the presence of water. As a result, the surface of the aggregate is electronegative. On the other hand, some types of aggregate, such as limestone, bear a positive surface charge in the presence of water. Dolomite and quartz are examples of extremely electropositive and electronegative aggregates, respectively. Typical aggregates that bear mixed charges include traprock, basalt, and siliceous limestone (Figure A-17).

Aggregates that bear mixed charges may be considered as aggregates that lie between the extremes represented by dolomite and quartz. Their surface characteristics are largely determined by which charge is predominant.

If the charges of aggregate and asphalt emulsified asphalt are different, a good coating may be expected, but if they are similar, the prospects of obtaining a good asphalt-aggregate coating is poor. This explains the satisfactory performance of anionic emulsions when used with limestones. The adhesion of asphalt is promoted by the difference in charges (Figure A-18). In this system, the anionic emulsifier functions as a "bridge" between the asphalt and aggregate. On the other hand, when anionic emulsified asphalt is used with electronegative aggregates such as silica and quartz, a poor adhesion results due to the repulsion between asphalt and aggregate [30, 31].

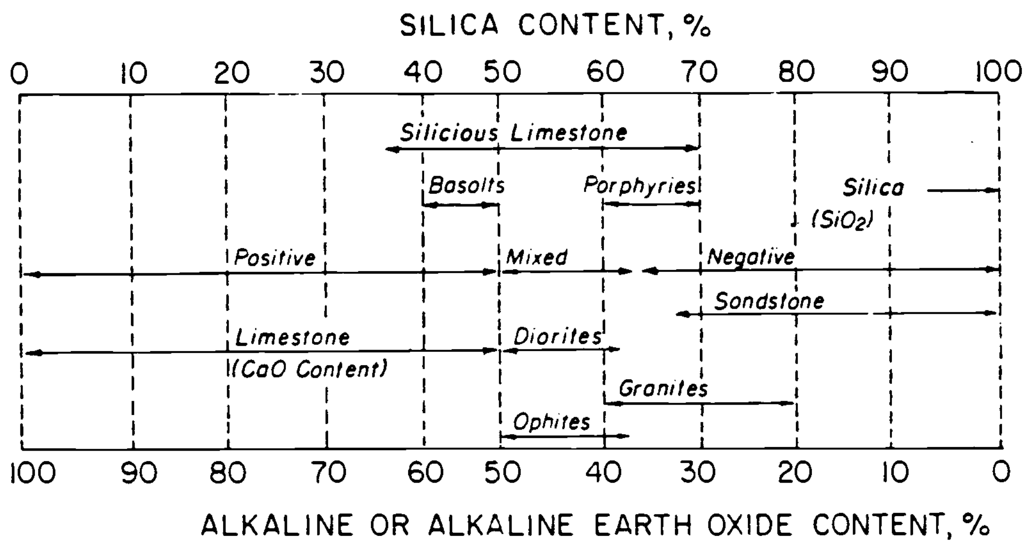


Figure A-17. Classification of aggregates (after Martens and Wright).

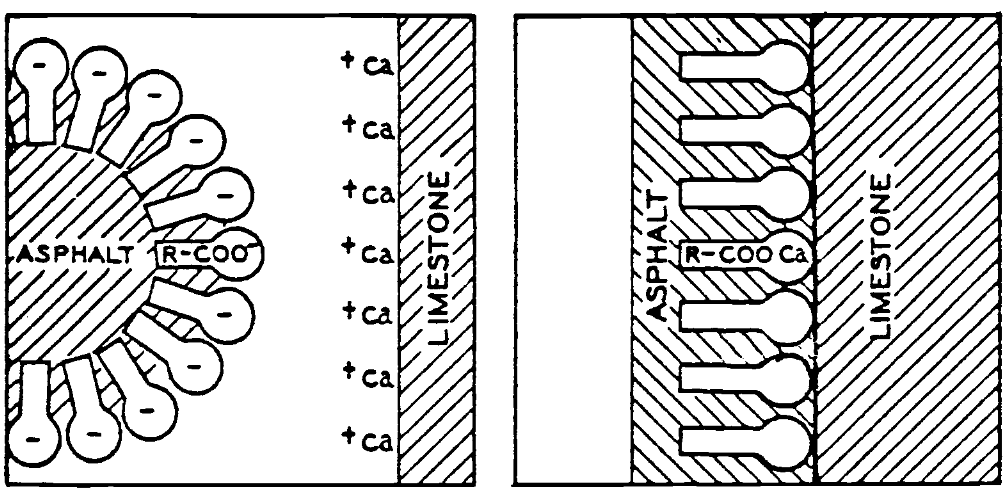


Figure A-18. Action of anionic asphalt emulsion on calcareous (limestone) aggregates [31].

Cationic emulsified asphalt droplets are attracted to the surface of the electronegative aggregate as shown in Figures A-19 and A-20. The emulsifier is drawn to the surface of the aggregate and the non-polar tail of the emulsifier pulls the asphalt to the surface too. Therefore, cationic emulsifier functions as the "bridge" or bonding agent [31].

Aggregates that bear about equal amounts of electronegative and electropositive surface charges can be used with either cationic or anionic emulsified asphalts. The cationic emulsions seem to be somewhat more versatile, for they can be used with a somewhat broader range of aggregate than the anionic emulsified asphalts (Figure A-21). The best type to be used should be determined by coating test [ASTM].

3.3 Evaluation of Specifications

Table A-7 summarizes for each property its factors and requirements. It also gives a summary for each test. Test methods are very important to ensure a proper composition of emulsified asphalts as well as proper performance during service. It is noted that an improved method for rate of set is needed. Viscosity at 77°F (25°C) also needs to be determined [40].

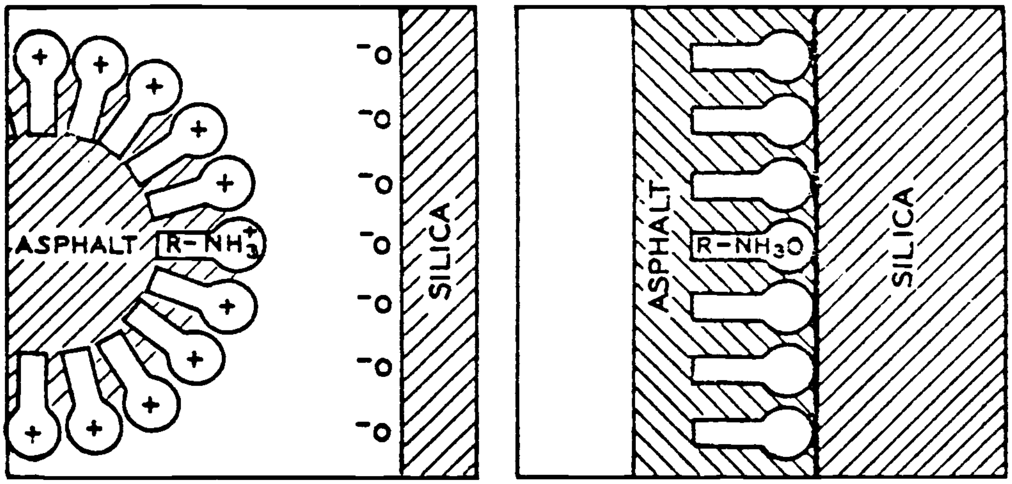


Figure A-19. Action of cationic asphalt emulsion on silica [31].

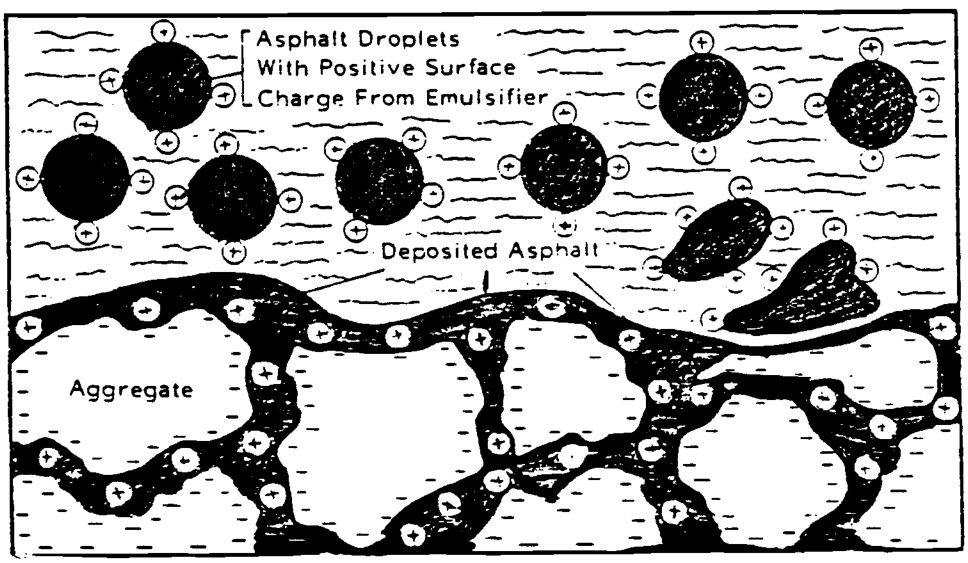


Figure A-20. The mechanism of asphalt deposition from cationic emulsions [21].

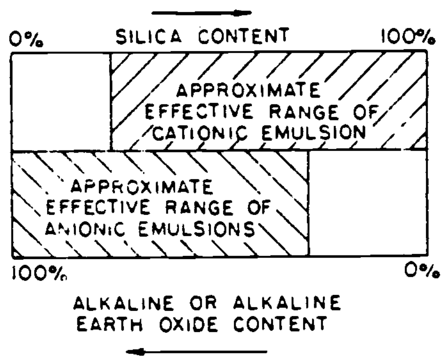


Figure A-21. Approximate effective range of cationic and anionic emulsions on various types of aggregates (after Martens and Wright).

Table A-7. Summary of emulsion tests (41).

Property	*Factor*	*Requirement*	*Test*	
CONSTANCY	A) Uniformity	Product must have the same handling, mixing and setting characteristics from shipment to shipment	*Residue:	Proportions of asphalt & water (Indication of uniformity of manufacture.) Residue is measured by dehydrating the emulsion by evaporation or distillation
	B) Storage Stability	Product must be capable of storage without excessive damage or change.	*Sieve:	Amount of oversize particles, shot and slugs retained on #20 mesh sieve.
			*Settlement: *Storage Stability:	Amount of settlement of asphalt particles in 5 days — one day for storage stability test. The difference in residue between top and bottom is measured.
			Freeze-Thaw	Most emulsions are damaged by freezing.
CLASSIFICATION	A) Differentiate mixing grade product from rapid set types. (Select proper grade)		*Demulsibility	Amount of coagulation on addition of a salt-calcium chloride with anionic emulsion; Aerosol OT with cationic emulsion.
	B) Differentiate cationic from anionic emulsions. (Prevent mixing of grades which could result in breakdown)		*Particle Charge Test:	Deposition of asphalt on an electrode.
			pH:	Cationics are acid with a pH of less than 7. Anionics are alkaline with a pH greater than 7. Water has a pH - 7.
CONSTRUCTION CHARACTERISTICS	A) Handling	Product must be safe to handle and capable of being pumped and sprayed without breakdown or run-off.	*Consistency	Emulsion viscosity
			Pumping Stability:	No test in current specifications.
	B) Rate of Set	The product must break rapidly and hold aggregate under the action of traffic	Dehydration	Amount of water lost in 96 hours at 100°F. (Note: Improved test method for Rate of Set is needed.)
	C) Mixing Stability	The product must mix with water and aggregate without balling or breakdown. Once mixed, the mix must cure rapidly to an asphalt film	*Cement Mixing:	Emulsion mixed with cement
			*Stone Coating-Water Resistance:	Job (or reference) aggregate is mixed with the emulsion to determine coating and early rain resistance
			Miscibility With Water:	Ability to mix with water without coagulation
DURABILITY	A) Traffic Densification	Properly designed pavements must not bleed under repeated load application by heavy traffic.	*Penetration: *Float Test: *Residue:	Consistency of base asphalt after laboratory distillation
	B) Resistance to Stripping	Mixes must not strip when in prolonged contact with water.	Adhesion Test	Made on job aggregate or a reference aggregate
	C) Long-Term Service Life	Asphalt must remain flexible at cold temperatures and not deteriorate on long-term weathering in a pavement	*Penetration & Ductility After Laboratory Distillation: Specification Tests On Original Asphalt:	
ASPHALT PURITY	A) Ensure Presence of Asphalt	Keep to a minimum the additives, emulsifiers and fillers used to emulsify the asphalt.	*Solubility Of The Asphalt After Laboratory Distillation:	

**Included in AASHTO T 59 and ASTM D 244*

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4.0 EMULSIFIED ASPHALT APPLICATIONS

4.1 Technology of Paving with Emulsions

Emulsified asphalts are used in plant mixes, road mixes, and in various types of treatments and seals (Table A-8). They can also be ued for a number of other applications connected with both construction and maintenance of paved surfaces. Their energy-saving advantage and versatility are valid reasons for their growing use.

4.1.1 Spray Applications

4.1.1.1 Prime coat: A prime coat is an application of low viscosity asphalt to granular base to bind the upper part and provide a thin layer of asphalt to permit binding to pavement surfaces. It also helps in preventing decompaction of open type bases and water-proof the surface of the base.

The quantity of asphalt to be used depends upon the nature of the granular base and weather conditions. Generally, between 0.1 and 0.3 gal/yd^2 (0.63-1.9 l/m^2) of SS-1, SS-1h, CSS-1 of CSS-1h would be used for this purpose. If an excess of asphalt residue is found on the surface, a very light sand dusting will solve the problem [41].

4.1.1.2 Tack coat: An asphalt tack coat is a very light application of asphalt, usually emulsified asphalt

Table A-8. General uses of emulsified asphalt.

D 3628

NOTE—Only those grades of emulsified asphalt in general use have been indicated herein. It is possible that under certain variations of aggregates, or climatic conditions, or both, additional selections might be appropriate. Where the use of emulsified asphalt for applications other than those listed in the table are contemplated, the emulsion supplier should be consulted.

Type of Construction[A]	Specification D 977							Specification D 2397 (Cationic)					
	RS-1	RS-2	MS-1, HFMS-1	MS-2, HFMS-2	MS-2h, HFMS-2h	SS-1	SS-1h	CRS-1	CRS-2	CMS-2	CMS-2h	CSS-1	CSS-1h
Bituminous-aggregate mixtures													
For pavement bases and surfaces													
Plant mix (hot) (D 3515)	.	...	..	..	X[B]	...	...	...	...	...		...	...
Plant mix (cold)													
Open-graded aggregate		..	.	X	X	.	...	..	...	X	X	...	...
Dense-graded aggregate	.	..	...	..	..	X	X	...	...	...		X	X
Sand	.	..	...	..	...	X	X	...	...	...		X	X
Mixed-in place													
Open-graded aggregate		...	X	X	X	...	...	...	...	X	X	...	...
Dense-graded aggregate	.	...	...	...	..	X	X	...	...	...		X	X
Sand	..	...	..	...	...	X	X	..	...	...		X	X
Sandy soil	..	..	..	..	...	X	X	...	...	...		X	X
Slurry seal	..	...	..	..	...	X	X	...	...	...		X	X
Bituminous-aggregate applications													
Treatments and seals.													
Single surface treatment (Chip Seal)	X	X	..	..	...	...	...	X	X	...	..	...	...
Multiple surface treatment	X	X	.	..	...	...	...	X	X	...	.	...	...
Sand seal	X	X	X	..	...	..	...	X	X	...	..	...	...
Penetration macadam													
Large voids		X	..	..	...	..	..	..	X	...		..	...
Small voids	X	..	...	...	...	...	...	X	...	...		...	...
Bituminous applications:													
Fog seal	.	.	X[C]	..	...	X[D]	X[D]	..	..	...		X[D]	X[D]
Prime coat-penetrable surface		..	..	.	..	X[D]	X[D]	...	...	...		X[D]	X[D]
Tack coat	..	..	X[C]	..	..	X[D]	X[D]	...	...	...		X[D]	X[D]
Dust binder	...	...	..	.	..	X[D]	X[D]	..	..	...		X[D]	X[D]
Mulch treatment		...	..	..	...	X[D]	X[D]	...	...	...		X[D]	X[D]
Crack filler	..	...	..	X	X	X	X	...	...	X	X	X	X
Maintenance mix													
Immediate use	.	...	X	X	X	...	..	...		X	X	...	...

[A] For definitions of terms used in this table, refer to Section 2.
[B] Specification D 3515 permits the use of other emulsion grades by note, "Grades of emulsion other than MS-2h may be used where experience has shown that they give satisfactory performance."
[C] Diluted with water by the manufacturer
[D] Diluted with water

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diluted with water. It is used to ensure a bond between the surface being paved and overlaying course and therefore prevent slip plane from developing. It acts as an adhesive film to provide such a bond.

It is necessary to use a tack coat each time if the surface to receive the overlay is old and dried. Tack coats are omitted betwen courses if new pavement of the overlaying course is placed within two or three days and the first course is not contaminated by sand or dust. Tack coats should be very thin and they must blanket uniformly the entire surface area to be covered. Thick tack coats may cause creeping or pushing of the overlay or bleeding of the asphalt surface [40].

The common types of emulsified asphalts for tack coats are SS-1, SS-1h, CSS-1 and CSS-1h. The emulsified asphalt is diluted with equal parts of water by adding water to emulsified asphalt to produce tack coat material. Tack coat is best applied when the surface is dry and has a surface temperature above 27^{o}C (81^{o}F). It is usually applied at a rate from 0.05 to 0.15 gal/yd^2 (0.32-0.95 l/m^2).

Even though its application is sometimes omitted, a tack coat has a positive role in construction.

4.1.1.3 Fog seal: A fog seal is a light application to an existing surface of slow-setting emulsified asphalt thinned with water. It can be diluted in varying proportions to up to one part emulsified asphalt to five parts water. The fairly low-viscosity diluted emulsified asphalt flows easily into the cracks and surface voids. This action will prolong pavement life and delay time when major maintenance or reconstruction is needed. Grades of emulsified asphalt used most frequently are SS-1, SS-1h, CSS-1, and CSS-1h.

Fog seal can be a helpful maintenance aid. It is used to renew old asphalt surfaces that have become dry and brittle with age and to seal small cracks and surface voids. Also, open-graded friction courses with too little asphalt binder are treated with fog seals to prevent loss of surface stones under traffic. The total amount of fog seal normally used is 0.1 to 0.2 gal/yd^2 (0.63-1.27 l/m^2) [40].

4.1.1.4 Dust palliative: The use of emulsified asphalt offers a practical and easy solution to the problem of high accidents and the dust problem of an unpaved road. A diluted emulsified asphalt is sprayed directly on the unpaved raod surface. This method is known as dusty laying or dust palliative.

When used for dust relief, an SS-1, SS-1h, CSS-1 and CSS-1h emulsified asphalt is mixed with five or more parts water, by volume. The diluted material is sprayed in repeated light applications on the unpaved surface at a rate of 0.1 to 0.5 gal/yd^2 (0.63-3.17 l/m^2). If the road surface is porous or contains relatively large surface voids, a greater amount of the diluted emulsified asphalt can be applied. If the traffic is heavy it may be necessary to reapply this material at regular intervals.

4.1.1.5 Curing seal: Curing seal is a light application of asphalt to newly constructed cement or lime stabilized materials. It is used to retard water evaporation which is necessary for hydration. Usually SS or CSS emulsified asphalts are used at an application rate of about 0.2 gal/yd^2 [22].

Emulsified asphalt seal coats and surface treatments are summarized in Table A-9.

4.1.2 Seal Coats (Surface Treatments)

Seal coat is a surface treatment usually performed by spraying an emulsified asphalt on a weathered road, followed by the immediate application of suitable aggregate. Generally, the final surface is rolled to ensure good contact between the covering aggregate and road surface. Road surface should be cleaned prior to application of asphalt. Hard, dust-free, crushed rock chips about 1/4 to 3/8 in (0.635 to 0.95 cm) size are the best aggregates to use. Coarse sands have been used successfully in areas where rock is not available. Emulsified asphalt applications vary with the nature of

Table A-9. Emulsified Asphalt Seal Coats and Surface Treatments [41].

System	Description and Uses	Emulsified Asphalt	Construction Hints
SAND SEAL	Restores uniform cover. In city street work, improves street sweeping, traffic line visibility. Enriches dry, weathered pavements; reduces raveling.	CRS-1 or RS-1	Spray-applied with sand cover. Roll with pneumatic roller. Avoid excess binder
CHIP SEAL	Single most important low cost maintenance method. Produces an all-weather surface, renews weathered pavements, improves skid resistance, lane demarcation, seals pavement.	CRS-2 or RS-2	Spray-applied. Many types of textures available. Key to success: Coordinate construction, use hard, bulky grained, clean aggregate, and have properly calibrated spray equipment.
DOUBLE SEAL	Similar to chip seal except the second chip application uses a small sized stone. Durable, provides some leveling, available in a number of textures.	CRS-2 or RS-2	See Chip Seal.
TRIPLE SEAL	Three applications of binder and 3 sizes of chips are applied. Provides up to a 2 cm thick, flexible pavement. Levels as well as providing a seal, tough wearing surface.	CRS-2 or RS-2	Spray-applied in three lifts. Drag broom between lifts to provide leveling.
DRAG SEAL	Low cost method of improving the riding quality of rough pavements. A rain-resistant medium-set emulsified asphalt is applied followed by chips. The pavement is drag-broomed to level spots and depressions. A second application of binder followed by a choke aggregate or sand is applied.	CMS-2 or MS-2	The CMS-2 and MS-2 tolerate more mixing and drag-brooming than the rapid-set emulsions. Use a wetting agent in the steel wheel roller to reduce pickup.
SLURRY SEAL	Used in airport and city street maintenance where loose aggregate cannot be tolerated. Seals, fills minor depressions, provides an easy-to-sweep surface. Made with crushed aggregate mixed with quick-set emulsified asphalt. The liquid slurry is machine-applied with a sled-type box containing a rubber-edged strike-off blade.	QS* grades	Pretest the aggregate and emulsion mix to achieve desired workability, setting rate and durability. Calibrate equipment prior to starting the project.
CAPE SEAL	Combines a single chip seal with a slurry seal. Provides the rough, knobby surface of a chip seal to reduce hydroplaning yet has a tough sand matrix for durability.	CRS-2 and QS* grades, SS-1, SS-1h, CSS-1, or CSS-1h	Apply a large aggregate single chip seal. Broom and apply slurry seal. Have the strike-off ride on the rock surface to form the matrix.
	Test track data indicate better studded tire damage resistance than a chip seal.		Avoid excess slurry as this destroys the knobby stone texture desired.

*Not Standardized

the surface and are generally in the range of 0.25 to 0.35 gal/yd^2 (1.58-2.22 l/m^2).

Emulsified asphalts for the seal coating are of the RS or CRS type. Cationic emulsions generally have superior performance in comparison with anionics for seal coating. Most seal coating today is done with cationics due to their advantages such as faster set, early rain resistance and better adhesion to wider varieties of aggregates.

Seal coats have the advantage of relatively low cost and almost immediate use by traffic after laydown. A disadvantage is the hazard of flying rock chips when the surface is new. This can be minimized by brooming off excess rock chips as soon as construction is finished. The seal coat can give optimum maintenance value only if applied before excessive deterioration of the pavement has taken place. The value of maintaining an intact seal coat to prevent entrance of water into the road base and the resulting damage to the base cannot be overemphasized.

4.1.3 Sand Seal

Sand seal is defined as a spray application of emulsified asphalt followed with a light covering of fine aggregate such as clean sand screenings. This operation can be useful in correcting a number of pavement problems. It is used to enrich dry, weathered or oxidized surface and to prevent intrusion of moisture and air and to develop a skid-surface texture.

Usually, RS-1, RS-2, CRS-1 or CRS-2 are used at a rate of about 0.15 to 0.2 gal/yd^2 (0.95 to 1.27 l/m^2). This is followed by 10 to 15 lb/yd^2 (2.73 to 4.1 kg/m^2) of sand [41].

4.1.4 Slurry Seal

Slurry seal is a mixture of well-graded fine aggregate, mineral filler, emulsified asphalt, and water applied to the pavement as a surface treatment. It has the advantage of speed, economy and a smooth surface, free of rock chips that can be loosened by traffic.

Slurry seal mixtures usually contain 15-25% emulsified asphalt and sufficient additional water to give maximum fluidity without segregation of the fine aggregate. It is applied in a thickness of 1/8 to 1/4 in (0.32 to 0.635 cm). It comes directly from a travelling mixing plant into an attached spreader box that spreads the slurry mix. The three generally used gradings are shown in Table A-10. Type I is used for maximum crack penetration. Type II is used to seal and correct problems of raveling, oxidation, and to improve skid resistance. Type III is used to correct severe conditions. Emulsified asphalt used in the slurry mix may be SS-1, SS-1h, CSS-1, or CSS-1h. Quick-setting (QS) emulsified asphalt is used when early opening to traffic is necessary [40].

Table A-10. Slurry Mixture Gradings [41].

Type of Slurry	I	II	III
General Usage	Crack filling & fine seal	General seal. medium textured surfaces	1st and/or 2nd application, two-course slurry. highly textured surfaces
Sieve Size (USA Standard Series)		Percent Passing	
12.5 mm (½in.)			
9.5 mm (⅜in.)		100	100
4.75 mm (No. 4)	100	90-100	70-90
2.36 mm (No. 8)	90-100	65-90	45-70
1.18 mm (No. 16)	65-90	45-70	28-50
600 μm (No. 30)	40-60	30-50	19-34
300 μm (No. 50)	25-42	18-30	12-25
150 μm (No. 100)	15-30	10-21	7-18
75μm (No. 200)	10-20	5-15	5-15
Residual Asphalt Content, % Weight of dry aggregate	10-16	7.5-13.5	6.5-12
Application Rate, lb/yd^2 (kg/m^2), based on weight of dry aggregate	6-10(3-5.5)	10-15(5-5.8)	15(8) or more

**Recommended by International Slurry Seal Association.*

Slurry seal should not be used with structurally weak pavement unless it is repaired. When applied to the surface of an old pavement, it can be used quite effectively.

4.1.5 Emulsified Asphalt Aggregate Mix

Mixtures of aggregates and emulsified asphalts are finding increasing use for road-base and final pavement construction. The aggregates may range from sandy silts to graded rock for base construction. Construction techniques range from simple mixing-in-place to plant-spread batches of paving mixture. Mixing may be with wet or dry aggregates.

The SS and CSS emulsified asphalts are used where maximum emulsified asphalt stability is required, such as when mixing with soils or dense graded aggregates. These emulsified asphalts are mixed with wet aggregates to prevent coalescence. Emulsified asphalt mixes have several uses as shown in Figure A-22.

There are three major types of emulsified asphalts mixes:

4.1.5.1 Open graded mix: Open-graded mixtures with emulsified asphalts have been used for bases and surfaces for many years. Durability and performance of open-graded mixes have been comparable to other types of asphalt paving. Their flexibility and high void content make them resistant to fatigue and reflection cracking.

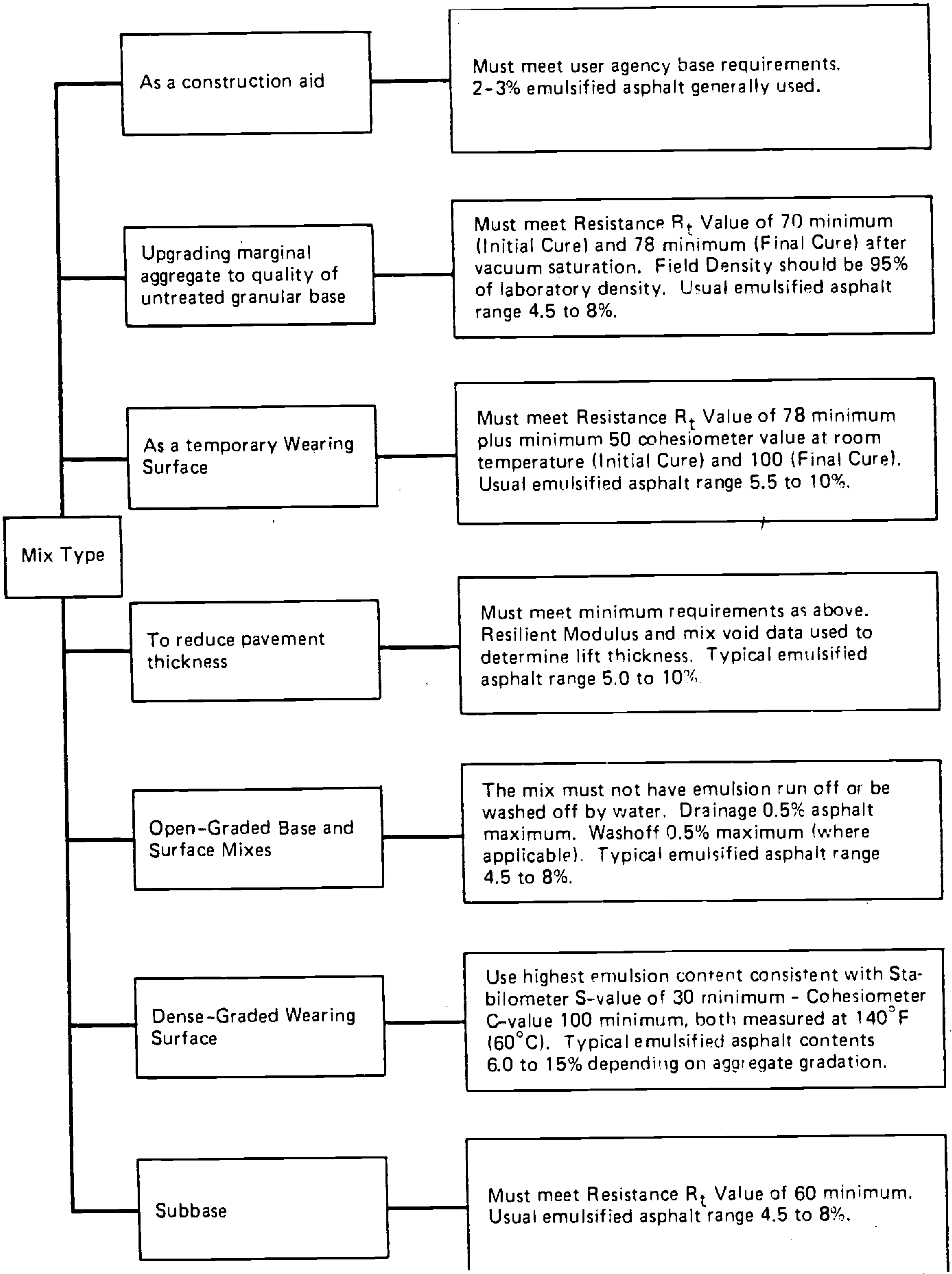

Figure A-22. Major uses of emulsified asphalt mixes. (Courtesy Chevron USA. Inc.)

Open-graded mixes, when used for surface courses, function differently from base courses. Their mix gradings are different and they permit the rapid removal of surface water because of their high permeability which will reduce hydroplaning problems [49]. The gradation of aggregate for open-graded base and surface are shown in Table A-11.

The grade of emulsified asphalt is selected primarily on the basis of its ability to coat the aggregate satisfactorily. This is determined by the coating and stability tests described in ASTM Standard D244. Other factors influencing selection are availability of water and the job site weather conditions during construction, the mixing process, and the curing rate. Cationic emulsified asphalts are generally more effective with a general range of aggregates. However, anionic emulsified asphalts are used if the aggregate has a strong affinity for them. Emulsified asphalts suited for various aspects of work in open-graded pavement are shown in Table A-12 [40].

4.1.5.2 Dense-graded mixes: Dense-graded aggregate mixtures are graded from the maximum size down to and including material passing the 75 μm (No. 200 sieve). They include a wide variety of aggregate types and gradation and can be used for the full range of base and

Table A-11. Aggregates for Open-graded Emulsion Mixes [41].

Sieve Size	Base		Surface
	Coarse	Medium	Fine
38.1 mm (1-1/2 in.)	100		
25.0 mm (1 in.)	95 - 100	100	
19.0 mm (3/4 in.)		90 - 100	
12.5 mm (1/2 in.)	25 - 60		100
9.5 mm (3/8 in.)		20 - 55	85 - 100
4.75 mm (No. 4)	0 - 10	0 - 10	
2.36 mm (No. 8)	0 - 5	0 - 5	0 - 10
1.18 mm (No. 16)			0 - 5
75 μm (No. 200)	0 - 2	0 - 2	0 - 2
Los Angeles Abrasion loss @ 500 Rev. (ASTM C 131)	40 max	40 max	40 max
Percent Crushed Faces	65 min	65 min	65 min
Emulsified Asphalt Grades	MS-2, MS-2h, HFMS-2, HFMS-2h, CMS-2 or CMS-2h		

Table A-12. Types of Emulsified Asphalt [38].

EMULSIFIED[3] ASPHALT USE	ASTM D 977 OR AASHTO M 140 (Anionic)					ASTM D 2397 OR AASHTO M 208 (Cationic)			
	MS-1, HFMS-1	MS-2, HFMS-2	MS-2h, HFMS-2h	SS-1	SS-1h	CMS-2	CMS-2h	CSS-1	CSS
Open-graded plant mix		X	X			X	X		
Prime coat				X[2]	X[2]			X[2]	X
Tack coat	X[1]			X[2]	X[2]			X[2]	X

[1]Diluted with water by manufacturer.

[2]Diluted with water.

[3]Emulsified asphalts shown are ASTM and American Association of State Highway and Transportation Officials (AASHTO) grades and may include all grades produced in all geographical areas.

surface pavement types. Locally available, unprocessed aggregates can be utilized on lightly travelled roads and bases for heavy-duty pavements. Recommended aggregate gradation and quality requirements for dense-graded mixes are shown in Table A-13. SS-1, SS-1h, CSS-1 or CSS-1h emulsified asphalts are used for dense-graded mixes.

4.1.5.3 Sand mixes: Sand mixes, like dense graded mix, can be used for base or surface construction. The addition of one or two percent of Portland cement will aid in the development of early initial strength. Table A-14 shows a recommended sand gradation which has been used successfully.

The emulsified asphalt content normally varies within a range of 6 to 15 percent. Types SS-1, SS-1h, CSS-1, or CSS-1h may be used.

Emulsified asphalt can be used for several other purposes. It can be used for crack filling, soil stabilization, upgrading mrginal aggregate and reducing overall pavement thickness.

4.2 Industrial Applications

The adhesive, waterproof, and inert character of asphalt has prompted the development of a wide variety of emulsified asphalt products for the construction, manufacturing and mining industries. The major uses of emulsified asphalt are:

Table A-13. Aggregates for Emulsified Asphalt Mixtures [41].

Sieve Size USA Standard	Sieve Size Alternative	Semi-Processed Crusher, Pit or Bank Run	Processed Dense-Graded Asphalt Mixtures					
Gradation Percent Passing by Weight								
50 mm	(2 in.)	–	100	–	–	–	–
38.1 mm	(1-1/2 in.)	100	90-100	100	–	–	–
25.0 mm	(1 in.)	80-100	–	90-100	100	–	–
19.0 mm	(3/4 in.)	–	60-80	–	90-100	100	–
12.5 mm	(1/2 in.)	–	–	60-80	–	90-100	100
9.5 mm	(3/8 in.)	–	–	–	60-80	–	90-100
4.75 mm	(No. 4)	–	20-55	25-60	35-65	45-70	60-80
2.36 mm	(No. 8)	25-85	10-40	15-45	20-50	25-55	35-65
1.18 mm	(No. 16)	–	–	–	–	–	–
600 μm	(No. 30)	–	–	–	–	–	–
300 μm	(No. 50)	–	2-16	3-18	3-20	5-20	6-25
150 μm	(No. 100)	–	–	–	–	–	–
75 μm	(No. 200)	3-15	0-5	1-7	2-8	2-9	2-10
Sand Equivalent, Percent		30 min.	35 min.	35 min.	35 min.	35 min.	35 min.
Los Angeles Rattler @ 500 Revolutions		–	40 max.	40 max.	40 max.	40 max.	40 max.
Percent Crushed Faces		–	65 min.	65 min.	65 min.	65 min.	65 min.
Emulsified Asphalt		SS or CSS grade	SS or CSS grade	SS or CSS grade	SS or CSS grade	SS or CSS grade	SS or CSS grade

Table A-14. Sand-emulsion Mixes [41].

Sieve Size	Total Percent Passing		
	Poorly-Graded	Well-Graded	Silty Sands
12.5mm (1/2 in.)	100	100	100
4.75mm (No. 4)	75 - 100	75 - 100	75 - 100
300μm (No. 50)	–	15 - 30	–
150μm (No. 100)	–	–	15 - 65
75μm (No. 200)	0 - 12	5 - 12	12- 20
Sand Equivalent, percent	30 min.	30 min.	30 min.
Plasticity Index	NP	NP	NP

- o Roof and surfacing coatings include:
  - filled coatings
  - combinations with polymers
- o Paper and building-board sizes
- o Adhesives
- o Metal coating uses
- o Applications in mineral industry
- o Concrete additives
- o Oil well treatment.

4.3 Agricultural and Water-Conservation Uses

The low cost and versatility of emulsified asphalt makes it a useful material for soil coatings, sealants, and soil stabilizers that can be used for environmental improvement. Emulsified asphalt can be used as:

- o Agricultural mulches:
  - Emulsified asphalt spray mulch
  - Emulsified asphalt mulch-tie-down
- o Soil-erosion control
- o Canal and reservoir sealants
- o Water harvesting (rainfall collection)
- o Underground sealing of sandy fields
- o Climate modification
- o Fertilizer component

5.0 ADVANTAGES AND DISADVANTAGES

The use of emulsified asphalts has several advantages as follows:

1) Use of emulsified asphalt eliminates the need for petroleum distillates that are used in cutback asphalts. Cutback asphalts average about 35 percent distillate which is either naptha (gasoline), kerosene, or diesel fuel. In addition, emulsified asphalt also helps in energy conservation because the high heating requirements of other asphalt mixtures are not necessary for emulsified asphalts. It requires about 5.43 liters (2 U.S. gal.) of fuel to dry the aggregates used for normal conditions to produce one ton of hot mix [48]. The saving is in vital hydrocarbons that can be diverted to other uses.

2) The reduction or elimination of petroleum distillates in emulsions also contributes to the reduction of air pollutants. When asphalt mixtures that contain distillates begin to cure, the fumes from these distillates do add to the pollution.

3) The production of hot asphalt mix requires the heating of both the aggregate and the asphalt cement to temperatures of approximately 300°F (149°C). This heating process is the cause of considerable amount of pollution in the form of dust and asphalt vapor. If

pollution is to be avoided, pollution control devices, which are quite costly, should be used.

4) Asphalts mixed with distillates must be heated for application. Even with careful handling there is a danger of fire. Also, the hot liquid causes handling problems and danger to workers. The comparatively low application temperatures of emulsified asphalts poses no danger of burns [44].

5) Versatility in mixing methods and equipment are inherent in the use of emulsified asphalt emulsions. Mixtures can be produced in a central mixing plant, in travel plants or in place at low costs. They can be applied in a wide range of ambient temperatures and climatic coditions. Emulsified asphalts need little or no heating and can be applied to damp sands or aggregates.

6) With emulsified asphalts, locally available and in-place aggregate can often be used and thereby reduce the requirements on the type and amount of base aggregate needed. Marginal grade aggregates can be upgraded to (or even above) the quality of crushed rock [34, 40].

7) Emulsified asphalts will provide cohesion to sands and granular bases. Tensile strength provided to the base material minimizes degradation and segregation during placement. Base compaction is aided by treatment of the base aggregate with emulsion.

8) By upgrading marginal base materials, it is often possible to reduce the pavement thickness significantly by using emulsified asphalt. Use of the emulsion helps retard moisture absorption to reduce freeze-thaw damage, and the tensile strength increases the load-bearing quality of the base [34, 40, 44].

9) The fast-cure characteristics of emulsified asphalt, when used in surfaced mixes, reduces the possibility of traffic damage such as shoving. It also reduces the paving surface tendency to soften because of high ambient temperatures and prolonged curing time. Moreover, open-graded emulsified asphalt mixes provide a safe, skid-resistant surface with the ability to rapidly drain water, minimize hydroplaning, reduce road spray and improve nighttime visibility.

10) Emulsified asphalts have excellent wetting ability (coating). This wetting action of emulsified asphalt raises the asphalt level high on the stone. The opposing electrical charges between the stone and emulsified asphalt form a strong bond. When the emulsified asphalt breaks, aggregate material is held firmly in place. Moreover, the availability of a greater number of emulsified asphalt types, coupled with improved laboratory procedures, to satisfy design and construction requirements.

5.2 Disadvantages

Emulsified asphalts also have disadvantages, which are:

1) Emulsified asphalts have one characteristic that can create an environmental hazard. Because the asphalt is suspended in water, the emulsified asphalt is susceptible to being washed off of aggregates or a road surface by rain if the emulsified asphalt is not sufficiently cured. Some unbroken emulsified asphalt may be carried into streams, lakes, springs, etc., causing contamination of the water.

2) Emulsified asphalts have difficulty in withstanding freezing temperatures while in storage. It is necessary that stored emulsions be able to withstand a certain amount of freezing [23, 32].

3) Emulsified asphalts form a protective skin upon the air-emulsified asphalt interface when stored for any length of period which prevents separation of oil and water. Agitation of the emulsified asphalts will break the skin into pieces which will clog lines and spray bars, therefore agitation should be avoided [29, 40].

4) Emulsified asphalts require the presence of water for proper mixing and compaction. This is a problem in areas where water is scarce [44].

6.0 SUMMARY OF LITERATURE REVIEW

Emulsified asphalts which are used widely in road construction and maintenance, agriculture and industry may be defined as a homogeneous mixture of minute asphalt droplets suspended in a continuous water phase. The droplets are held in suspension by use of suitable emulsifiers.

There are three classes of emulsions, cationic emulsified asphalts which adhere better to electronegative aggregate, anionic emulsified asphalts that adhere better to electropositive aggregate, and nonionic emulsified asphalts which are neutral. Cationic emulsified asphalts are more versatile in construction due to the wide range of aggregate they can coat.

Depending on the type and amount of emulsifying agent, there are three types of emulsified asphalt: Rapid Setting (RS), Medium Setting (MS), and Slow Setting (SS). The choice of emulsified asphalt class and type depends upon the intended use of emulsion.

There are many advantages in the use of emulsified asphalts, such as:

- Low storage and application temperatures
- Construction versatility
- Reduce energy requirement
- Reduce air pollution

- o High mix production rate
- o High adhesion to the aggregate

On the other hand, emulsified asphalts have some problems, such as:

- o Susceptibility of uncured emulsion to water wash
- o Difficulty in withstanding freezing temperatures
- o Formation of protective skin upon the air-emulsion interface
- o Water is required for proper mixing and compaction.

APPENDIX B. SUMMARY OF MIX DESIGN AND MIX PROPERTY TEST RESULTS

Table B-1. Equations for Calculating Tensile Properties (75,69)

(1) Tensile strength S_t, psi $= \frac{P_{fail}}{h} * 0.156$

(2) Tensile strain $\varepsilon_t = X_t \left(\frac{.03896 + \mu * 0.1185}{.0673 + \mu * 0.2494}\right)$

(3) Compressive strain $\varepsilon_c = Y_t \left(\frac{-.1185 - \mu * 0.03896}{-.8914 + \mu * 0.0156}\right)$

(4) Inst. res. Poisson's ratio = μ

$$= \frac{\frac{V_{ri}}{H_{ri}} * (.0673) - .8914}{\frac{V_{ri}}{H_{ri}} * (-.2494) - .0156}$$

(5) Inst. res. Modulus, psi $= \frac{P * (.2692 + \mu * .9974)}{H_{ri} * h}$

(6) Indirect comp. stress $\sigma c = 0.47 * \frac{P}{h}$

(7) Bending modulus of elasticity of asphaltic beam (after Barksdale and Miller)

$$E_b = \frac{C}{4*I} \left(\frac{(P*\rho)^{4/3}}{k^{1/3}} \right)$$, where:

P_{fail}	= total load at failure.
P	= repeated load, lb.
h	= specimen height, in.
X_t	= total horizontal deformation, in.
Y_t	= total vertical deformation, in.
H_{ri}, V_{ri}	= inst. resilient horizontal and vertical deformations, in.
ρ	= radius of curvature of beam = $D/(2*\varepsilon_t)$.
k	= modulus of subgrade reaction, pci.
I	= beam moment of intertia = $BD^3/12$.
C	= correction factor.
D	= Beam depth, in.

Table B-2. Relation Between Tensile Strain and Poisson's Ratio

	Material	
$\varepsilon_t \cdot 10^{-6}$	Dune Sand Emulsion	Marl Emulsion
10	.28*	
15		.23
20	.3	
25	.32	.27
40	.34	.32
50		.35
60	.36	.37
80	.37	.38
100	.36	.38

* Numbers are averages of three values

Table B-3. Results of Split Tensile Strength Test, psi.

	Material					
	Dune Sand		Marl			
						Chev
	2	5	1	2	5	5
Temp. ^{o}C	(% Cement)			(% Cement)		
10	127*	165				
25	44	74	55	59	83	86
40	14	18		45	60	65
55				30	40	40

* Numbers are averages of three values

Table B-4. Marshall Stability Dry and Vacuum Soaked Dune Sand Emulsion

% Water	Dry/Soaked	Dune Sand + 2% Cement				
		6	8	10 (% Asphalt)	12	14
1	Dry	2300*	1870	2320	2500	21600
	Soaked	2070	1600	2230	2310	2110
2	Dry			3200		
	Soaked			2650		
3	Dry	2550	2330	2880	2120	
	Soaked	2016	2160	2570	2030	
4	Dry			2250		
	Soaked			2100		
5	Dry	2150	1970	2050		
	Soaked	2100	1900	1880		

* Numbers are averages of three values

Table B-5. Modulus of Resilience for Dune Sand Emulsion (10^5 psi)

$\varepsilon_t \cdot 10^{-6}$	Dune Sand + 2% Cement			Dune Sand + 5% Cement		
	10	25 (Temp. °C)	40	10	25 (Temp. °C)	40
20	10.5*	5.3	3.8	14.5	10.1	9.8
40	10.3	4.2	3.2	14.0	9.0	8.6
60	10.0	3.0	2.4	13.6	8.4	8.1
70				13.1		
80	9.5					
100	9.0					

* Numbers are averages of three values

Table B-6. Fatigue Life for Dune Sand Emulsion "Diametral Fatigue Test"

$\varepsilon_t \cdot 10^{-6}$	2% Cement			5% Cement		
	10	25 (Temp. °C)	40	10	25 (Temp. °C)	40
20		2.0E4	3.0E3			1.8E4
40		1.2E4	9.8E2		8.0E4	
60	1.0E5*	2.8E3	6.5E2	3.0E5	8.0E3	5.5E2
70				4.0E4		
80	2.0E4			5.0E3		
100	5.0E3				6.0E2	5.5E1

* Numbers are averages of three values

Table B-7. Beam Bending Modulus (10^5 psi), for Dune Sand Emulsion Beam (Beam Equation)

$\varepsilon_t \cdot 10^{-6}$	5% Cement			2% Cement
	10	25	40	25
	(Temp. °C)			(Temp. °C)
20				16.0
60				14.0
80		27.0		10.5
100		23.3	18.8	8.8
150			13.0	
200	43.0*	18.3	11.0	
300	36.0	16.6		
350	35.0			

* Numbers are averages of three values

Table B-8. Beam Bending Modulus (10^5 psi), For Dune Sand Emulsion Beam (Finite Element Technique)

$\varepsilon_t \cdot 10^{-6}$	5% Cement			2% Cement
	10	25	40	25
	(Temp. °C)			(Temp. °C)
20				13.0
60				12.2
80		16.5		10.6
100		16.0	14.5	8.9
150			12.0	
200	25.6*	14.0	10.5	
300	16.5	13.5		
250	15.0			

* Numbers are averages of three values

Table B-9. Fatigue Life for Dune Sand Beam

$\epsilon_t \cdot 10^{-6}$	2% Cement	5% Cement		
	25 (Temp. °C)	10	25 (Temp. °C)	40
20	5.0E4*			
60	2.0E4			
80	1.3E4		2.9E5	
100	1.0E4		7.0E4	6.0E4
150				8.0E3
200		4.0E4	6.5E2	2.0E3
300		2.5E3	2.5E2	
365		6.5E2		

* Numbers are averages of three values

Table B-10. Marshall Stability (lb), Dry and Vacuum Soaked Marl

		Marl + 30% Dune Sand + 2% Cement									
Residual Asp. %	Dry/ Soaked	5.5	7.5	9.5	10.5	11.5	13.5	15.5	17.5	19.5	21.5
		(Total Water, %)									
3.0	Dry				2900						
	Soaked				1300						
4.5	Dry				3990						
	Soaked				1540						
6.5	Dry			3200	3470						
	Soaked			1800	1800						
8.5	Dry	2130*	2550	2800	3700	2540	2450	2070	2000	1534	1550
	Soaked	1000	1600	2000	1940	1950	1650	1608	1435	1300	1160
10.0	Dry				3550	3550					
	Soaked				1800	1800					
11.0	Dry				3200						
	Soaked				1650						

* Numbers are averages of three values

Table B-11. Modulus of Resilience For Marl Emulsion (10^5 psi)

	2% Cement			5% Cement			
$\varepsilon_t \cdot 10^{-6}$	25	40 (Temp. °C)	55	25	40 (Temp. °C)	55	Chev 25
40						7.2	
50		5.0	4.5				
60		4.7	3.5	8.0	7.4	6.5	
70	5.5*	3.8	2.7				
80	5.1			7.5	6.7	6.2	8.9
90	4.5			7.2			8.3
100					6.0		7.3
125				6.6			
130							5.2

* Numbers are averages of three values

Table B-12. Fatigue Life of Marl Emulsion Mixes, "Diametral Fatigue Test"

	2% Cement			5% Cement			
$\varepsilon_t \cdot 10^{-6}$	25	40 (Temp. °C)	55	25	40 (Temp. °C)	55	Chev 25
40						5.0E5	
50		3.0E4	1.0E4			2.8E4	
60		1.2E4	9.0E3		2.2E5	1.1E4	
70	8.0E4*	3.5E3	5.0E2				
80	2.2E4			2.5E5	3.0E4	1.6E3	1.0E5
90	5.0E3			1.8E4			2.9E4
100				2.2E3	2.0E3		7.0E3
120				7.0E2			
130							7.5E2
150					6.0E1		
200							

* Numbers are averages of three values

Table B-13. Bending Modulus of Beam (10^5 psi), For Marl and O. G. Mix (Beam Equation)

	Marl Emulsion				O. G. Emulsion
$\varepsilon_t \cdot 10^{-6}$	25	40 (Temp. ^oC)	55	Chev 25	25 (Temp. ^oC)
100		7.0	5.2		
150		5.8	4.3		
200	13.7*	4.7	4.1	14.0	
350	7.3			8.0	
500	5.9			7.2	
700					1.78
1000					1.24
1500					1.24
2000					1.0

* Numbers are averages of three values

Table B-14. Bending Modulus of Beam (10^5 psi), For Marl and O. G. Mix (Finite Element Technique)

	Marl Emulsion				O. G. Emulsion
$\varepsilon_t \cdot 10^{-6}$	25	40 (Temp. °C)	55	Chev 25	25 (Temp. °C)
100		7.5	6.0		
150		6.5	5.0		
200	12.0*	5.5	4.85	12.0	
350	8.0			8.8	
500	6.5			7.9	
700					2.6
1000					2.25
1500					1.9
2000					1.6

* Numbers are averages of three values

Table B-15. Fatigue Life For Marl and O. G. Emulsion Beams @ 6 psi Confining Pressure

	Marl Emulsion				O. G. Emulsion
$\varepsilon_t \cdot 10^{-6}$	25	40 (Temp. °C)	55	Chev 25	25 (Temp. °C)
100		6.3E5	3.3E5		
150		1.3E4	5.0E3		
200	1.4E4*	7.2E2	2.5E2	7.8E3	
300					
350	6.5E2			2.0E3	
500	2.3E2			4.0E2	
700					1.9E5
1000					4.0E4
1500					1.1E4
2000					3.0E3

* Numbers are averages of three values

Table B-16. Modulus of Resilience for O. G. Emulsion (10^5 psi) @ 6 psi Confining Pressure

$\varepsilon_t \cdot 10^{-6}$	O. G. Mix		
	10	25	40
		(Temp. ^oC)	
20	8.8*	4.2	3.0
40	8.0	3.5	2.5
60	7.0	3.0	2.0
80	6.9		
100	6.8	2.8	1.9

* Numbers are averages of three values