Technical Report Documentation Page

1. Report No. FHWA/TX-94/1244-9	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle PROCEDURE FOR CLASSIFICATION OF COARSE AGGREGATES BASED ON PROPERTIES AFFECTING PERFORMANCE	5. Report Date November 1994
	6. Performing Organization Code
7. Author(s) Srikrishna Peapully, Dan G. Zollinger and B. Frank McCullough	8. Performing Organization Report No. Research Report 1244-9
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Study no. 0-1244
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Interim: September 1992 - August 1994
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Study Title: Evaluation of the Performance of Texas Pavement Made with Different Coarse Aggregates.

16. Abstract

Coarse aggregate is the major constituent of both Portland cement concrete and asphalt concrete and is therefore widely used for construction purposes. A classification system for coarse aggregates would provide a systematic means for the identification of aggregates which could be used in the selection of aggregates for different construction activities.

The objectives of this research were as follows: (1) to characterize the aggregates based on their properties, (2) to develop a framework for an Aggregate Classification System (ACS), (3) to provide the basis for the implementation of ACS, and (4) to recommend test procedures and equipment needed to carry out tests on aggregates as required by the ACS.

The classification system is developed in two stages: (1) comprehensive aggregate classification system incorporating all significant aggregate properties affecting pavement performance, and (2) simplified version of the comprehensive aggregate classification system. The ACS is recommended for implementation at three levels: (1) identification of aggregates, (2) simplified aggregate evaluation, and (3) detailed aggregate evaluation to supplement (1) and (2) as needed.

This report also discusses the basic tests recommended for aggregate evaluation and lists the required equipment for these tests. Aggregate properties and their respective performance indicators are tabulated. Various areas of further research are identified and recommendations are made for the implementation of the proposed classification system.

17. Key Words Coarse Aggregates, Pavements, Aggregate Classification System, Evaluation of Aggregates, Properties of Aggregates, Testing, Equipment	18. Distribution Statement No Restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 129	22. Price

PROCEDURE FOR CLASSIFICATION OF COARSE AGGREGATES BASED ON PROPERTIES AFFECTING PERFORMANCE

by

Srikrishna Peapully
Graduate Research Assistant
Texas Transportation Institute

Dan G. Zollinger
Assistant Research Engineer
Texas Transportation Institute

and

B. Frank McCullough
Director, Center for Transportation Research
University of Texas at Austin

Research Report 1244-9
Research Study Number 0-1244
Research Study Title: Evaluation of the Performance of Texas
Pavements Made with Different Coarse Aggregates

Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

November 1994

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

The classification system discussed in this report will assist in evaluating the performance of coarse aggregates prior to their use in the field. Performance assessment of aggregates will provide information regarding the necessity of blending of aggregates for arriving at equal performance with different aggregates. Using different aggregates can lead to better material selection and, thus, better performance of pavements and other structures in which coarse aggregates are used. Implementation of the proposed aggregate classification system can result in direct cost benefits to the Texas Department of Transportation.

DISCLAIMER

The contents of the report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENT

Research findings presented in this report are a result of joint efforts between the Texas Transportation Institute, Texas A&M University, and the Center for Transportation Research, University of Texas at Austin. The Authors would like to thank the staff of the Texas Department of Transportation for their support throughout this study as well as the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

SUMMARY

Coarse aggregates are the major constituents of concrete or asphalt mixtures and are widely used for various construction purposes. A classification system for these aggregates would provide a systematic means of aggregate identification which could be used in the selection of aggregates for different construction activities. The objectives of this research were as follows: (1) to characterize the aggregates based on their properties, (2) to develop a framework for an Aggregate Classification System, (3) to provide basis for implementation of the classification system, and (4) to recommend and list test procedures and equipment needed to carry out the tests on aggregates.

Researchers have conducted extensive field and laboratory investigations to study the performance of pavements made with different types of coarse aggregates and the properties which affected the performance have been incorporated in the aggregate classification system. The framework for the classification system is developed based on various physical, chemical, mechanical, and thermal properties of aggregates.

The classification system is developed in two stages: (1) a comprehensive system of aggregate classification incorporating all significant aggregate properties affecting performance and (2) a simplified version arrived at from the first stage classification system.

The classification system is recommended for implementation at three levels. The first level of implementation consists of aggregate identification, and the second level provides simplified aggregate evaluation. The third level should supplement the findings of the first two levels by providing a detailed evaluation of aggregates as needed.

This report discusses the basic tests recommended for aggregate evaluation and lists the required equipment for these tests. Aggregate properties and respective performance indicators are tabulated. Various areas of further research were identified and recommendations are made for implementation of the proposed classification system.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

American Society for Testing and Materials (ASTM) specification D-8 defines aggregate as "a granular material of mineral composition such as sand, shale, slag, gravel, or crushed stone, used with a cementing medium to form mortars or concrete, or alone as in base courses, rail road ballasts etc" (1). Aggregates consist of coarse and fine portions and as per ASTM C 125, " the portion of an aggregate retained on the 4.75-mm (No.4) sieve" is defined as coarse aggregate (2). Coarse aggregates are the major components of asphalt and portland cement concrete, which are the most common materials used in the construction of pavements and other structural systems. The characteristics of these coarse aggregates influence the performance of the structures in which they are used. Witczak et al. (3) carried out investigations on the potential availability of aggregates in 48 states in the United States of America and rated the availability of aggregates under four different levels: (a) abundant to adequate, (b) adequate to limited, (c) limited to problem, and (d) severe problem. These four rating levels of the availability of quality aggregates are represented in Figure 1.1. From Figure 1.1, it can be inferred that not all states have abundant quality aggregate sources. Different types of coarse aggregates that are being used in the construction of concrete and asphalt pavements fall under one of the four aggregate rating levels and these coarse aggregates have been found to influence the performance of various structures in different ways. The concrete properties such as modulus of elasticity, drying shrinkage, and various thermal properties depend on the type of coarse aggregate used (4). In spite of its significance, coarse aggregate type is not directly considered as a design variable in the concrete pavement design. Similarly, inappropriate selection of aggregates has been found to affect the rutting potential of asphalt concrete (5). Past research has concluded that coarse aggregate type significantly affects the performance of highway pavements (PCC and Asphalt) and various other structures (4). The characteristics of coarse aggregates affecting the performance of pavement structures differ for each aggregate type and depend upon various physical, chemical, mechanical and thermal properties exhibited by each aggregate type. A

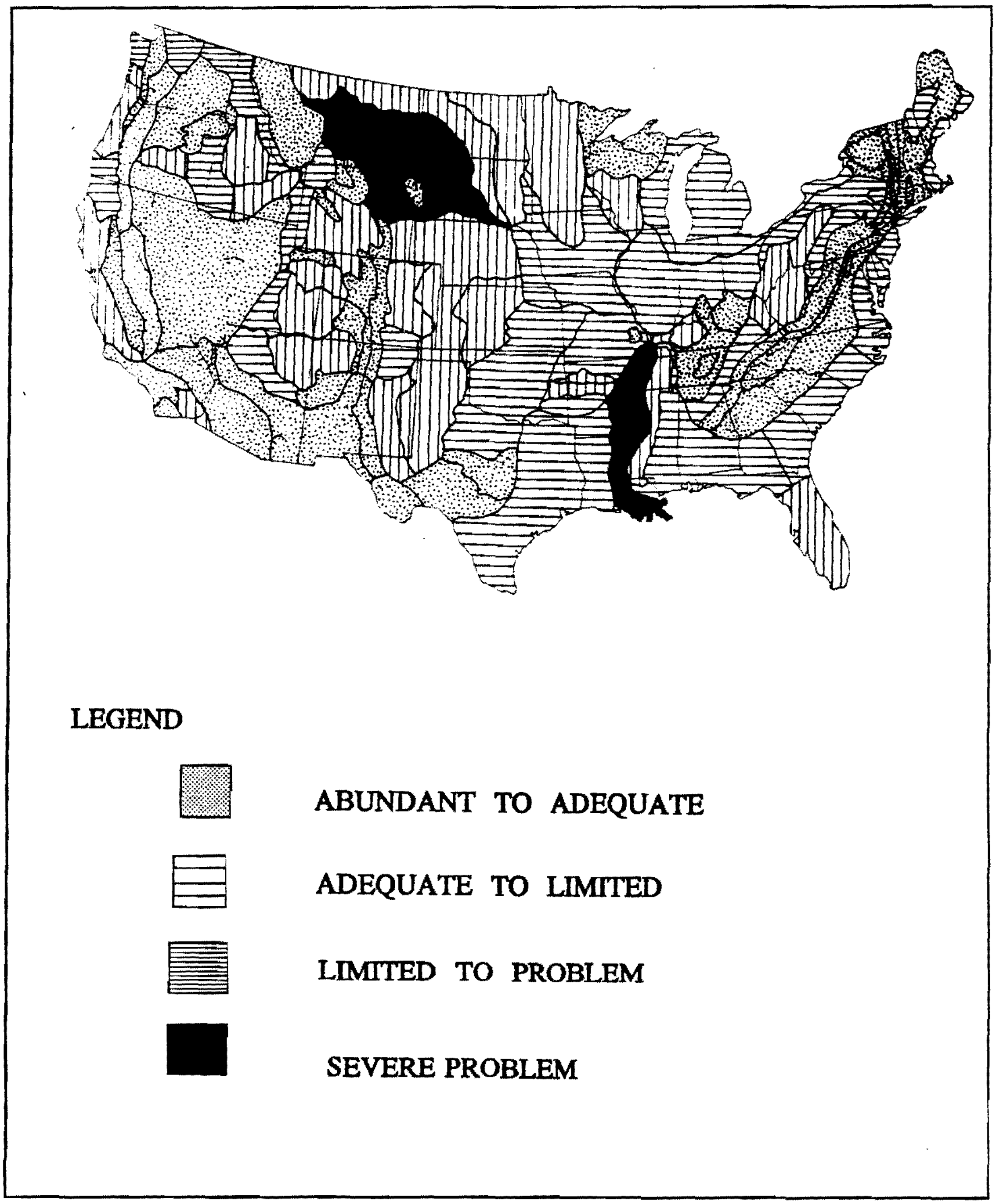


Figure 1.1. Availability of Quality Aggregate Sources in 48 States in United States (After 3).

substantial amount of research has been done in the past correlating various properties of aggregates with the performance of structures in which they are used. Researchers have been investigating the performance standards of aggregates in various ways (4, 6).

Natural aggregates consist of minerals and rocks and a system of classification for these aggregates would be of great assistance for engineers in identifying a suitable type of aggregate for use under given conditions. It also helps in predicting the behavior of different types of aggregates used in the construction of highways and other structures containing notable quantities of aggregates. This would result in minimizing aggregate related failures in these structures. In view of the benefits an aggregate classification system could provide, an effort has been made to develop a comprehensive system of aggregate classification, presented in Chapter IV. A simplified form of this classification system is also discussed in the same chapter. This simplified format is recommended for implementation.

1.2 PURPOSE AND SCOPE

The main objective of this research study was to evaluate the influence of various types of coarse aggregates on the performance characteristics of asphalt and concrete pavements. The aim of this part of the project was to identify the important characteristics of aggregates in terms of their physical, chemical, mechanical and thermal properties and to develop a framework for an aggregate classification system (ACS) which will provide a pattern for considering the behavior and performance of pavements or other concrete structures made with different coarse aggregates. In other words, the objectives of this part of the research are as follows:

- Identify and characterize the coarse aggregates based on their properties,
- Develop a framework for an aggregate classification system,
- Point out the performance related implications regarding the selection of various types of aggregates,
- Develop guidelines for the implementation of the aggregate classification system, and
- Recommend and list the test procedures and equipment needed to carry out these tests on aggregates.

1.3 IMPORTANCE OF CLASSIFICATION SYSTEMS

The reason for any classification system is to group individual units in an organized manner so as to understand the properties of those objects. It provides the user with a systematic means of identifying and predicting the properties and characteristics of the objects which are classified. A classification system for any group of complex objects or units provides an effective means of communication among experts to share their knowledge of the object with one another. Often, it reduces the burden of detailed descriptions and analyses (7). A well-devised system of classification will reflect known information regarding the subject.

Naturally occurring objects which are subjected to seasonal variations and other environmental factors are very complex in nature and difficult to characterize under a systematic classification scheme. But such objects, if classified systematically, would greatly augment the knowledge of practitioners and could provide impetus for further research in related areas. For example, soil, which is a natural body consisting of various constituents in different proportions and has a complicated physical and chemical makeup, has been characterized by uniform classification systems. This has greatly helped in the study of soil materials (7). Currently, more than one system of soil classification is available and each has addressed the needs of soil investigators and researchers in the fields of soil sciences, civil engineering, agriculture, etc. (8). Similarly, rocks, which are also natural bodies, have been classified and rock classification has been useful in assessing geotechnical rock characteristics. Rock classification systems have been used in geotechnical investigations carried out for design and construction of various civil engineering projects. Thus, soil and rock classification systems greatly exemplify the importance of material characterization. A detailed overview of different soil and rock classification systems proposed and published is given in Chapter II of this report.

1.4 REQUIREMENTS OF A CLASSIFICATION SYSTEM

The foremost requirement of any classification system is that it should be simple and should be based only on distinct characteristics of the objects being classified. It should be based on a logical sequence which can be easily remembered and serve an "all in one" reference substituting the use of other references, charts and tables (7). A good classification scheme is one which can be used by both experts and novices with equal ease. In any classification system, there should be meaningful grouping and the number of classes should be held to a minimum such that they address the required engineering characteristics. Various criteria used to distinguish the objects under consideration should be consistent throughout the classification. Any classification scheme consists of "categories" which are usually referred to as "taxons" and these should be mutually exclusive (9).

Other major requirements for a good classification system include the use of appropriate symbols where ever necessary, should consist of easily understood terminology. The classification system so formulated should be practical in its usage in the field and the users should be able to apply it over a wide range of phenomena. Laboratory tests, if needed to distinguish various attributes, should be simple and economical. Finally, the classification system should be easy to apply for both field and laboratory purposes (10, 11).

CHAPTER 2: OVERVIEW OF EXISTING CLASSIFICATION SYSTEMS

2.1 SOIL CLASSIFICATION SYSTEMS

There are three soil classification systems which are currently widely used in the geotechnical and transportation areas of Civil Engineering. They are as follows:

1. AASHTO Classification System,
2. Unified (ASTM) Soil Classification System, and
3. FAA Soil Classification System.

There are other soil classification systems which are currently being used world over but the above mentioned ones are used most often in this part of the world. An overview of each of these classification systems will help in understanding the characteristics the soil and its behavior.

AASHTO Classification System

American Association of State Highway and Transportation Officials, commonly known as AASHTO, developed a system of soil classification which is recognized world over. This system essentially evaluates and classifies engineering properties of soils based on the field performance of highways. This system was originally put forth by the Public Roads Administration in 1931 and was revised by the Highway Research Board in 1945. It became a standard "AASHO M145" in 1945 and subsequently as "AASHTO M145" (9).

In this classification system, soils which were in the same range of load carrying capacity were classified into seven basic groups and were designated from A-1 to A-7. Soils classified under group A-1 were designated as the best soils for subgrades under highways and group A-7 soils constituted the poorest. In order to arrive at specific group evaluations, a group index was developed wherein the index ranged from 0 for the best to 20 for the poorest. In 1966, this was further revised and a relation was developed. This relation is reproduced below for the purposes of clarity and better understanding (10):

$$\text{Group Index (GI)} = (F-35)[0.2+0.005(LL-40)]+0.01(F-15)(PI-10)$$

where,

F= % passing No.200 sieve,

LL = Liquid Limit,

PI = Plasticity Index.

The critical values for the percent passing the No.200 sieve, liquid limit and the plasticity index were arrived at by various highway organizations after a careful evaluation of various subgrade, subbase and base course materials. The AASHTO classification chart lists the significant constituent materials in each soil group and also rates the subgrade from "Excellent" to "Poor" (9). AASHTO classification system does not have a provision of identifying organic soils (7).

Unified (ASTM) Classification System

The unified soil classification system is based on the classification system originally developed by Dr. Arthur Casagrande of Harvard University for the U.S Army Corps of Engineers. This was later revised and it is now a standard of ASTM D 2487. Currently, this system finds its application in the evaluation of suitable soils for the construction of roads, airfields, foundations and embankments (9).

In this system, soils are classified based on their performance as engineering construction materials. The texture and plasticity are critical in identifying soils in accordance with this system. Soils, as per this system, were broadly classified into coarse grained, fine grained and organic soils. This is done based on the percent of soil passing or retained in a No.200 sieve. Soils which contained 50% particles retained in a No.200 sieve were classified as coarse grained soils and soils which contained more than 50% of the particles passing the No.200 sieve were classified as fine grained. Organic soils were identified by their dark color and odor. Soils were further classified into gravels, sands, silts and clays. Gravels and sands are classified based on their percent passing or retained in No.4 sieve. The coarse grained soils, whose percent retained in a No.4 sieve is more than 50 percent, were classified as Gravels and those whose percent passing a No.4 sieve is more than 50 percent as Sands (9).

Fine grained soils were classified into silts and clays based on their liquid limit and plasticity index. The fine grained soils were classified as silts and clays depending on their liquid limit and the plasticity index. The differentiating characteristic was the A-line, which is an arbitrarily drawn line on the plasticity chart. The plasticity chart is a plot between the liquid limit and the plasticity index and all those fine grained soils whose liquid limit and plasticity index fall below the A-line on the plasticity charts were classified as silts and those which fall above as clays. One of the notable features of this system is that it has given designations for each of the divisions and subdivisions which are called "Group Symbols". For example, well graded gravels are given a group symbol "GW" and poorly graded gravels "GP". Organic soils like peat, muck were identified by "PT" (9).

FAA Soil Classification System

The Federal Aviation Administration (FAA) currently adopts the ASTM classification system. But prior to the adoption of the ASTM system, the FAA followed its own system of soil classification which was based on the mechanical (gradation) analysis and the plasticity characteristics which included the liquid limit and the plasticity index.

Mechanical analysis was used as a basis to separate the soils into granular and fine grained. The soils were divided into 13 groups and were designated from E-1 to E-13. They were arranged based on their liquid limit and the plasticity index. Soil group E-1 had the least values for the liquid limit and the plasticity index, whereas the soil group E-13 had the highest values for the same. The soils with less than 35 percent silt and clay combined were classified as granular soils. The sand, silt and clay fractions were determined only for those soils passing a No.10 sieve because these were considered critical with respect to variations in moisture levels and climatic effects (10).

With this system of classification, soils under the E-1 group included well graded, coarse, and granular soils which are stable even under poor drainage conditions. Similarly, the soils classified under groups E-2 to E-4 contained less coarser soils, i.e., more than 45 percent of which are retained in a No.10 sieve. The stability of these soils under poor drainage conditions is less than that of the soils grouped under E-1. Soils under groups E-5 to E-12 are essentially fine grained soils with increasing values of liquid limit and plasticity indices. Group E-13 soils are characterized as organic soils having low stability, low density and high moisture content (10).

The subgrade soil classification is based on the performance of soils as subgrades under flexible and rigid pavements under varying conditions of frost and drainage. Thus, soils classified under group E-1 were expected to provide adequate support except under extreme frost heave conditions. The performance of soil as a road subgrade decreases as we move from E-1 to E-12 in the table. Organic soils were reported unsuitable for subgrades (10).

Other Soil Classification Systems

There are various other classification systems developed by countries like Russia, Canada and England. The AASHTO, ASTM and the FAA soil classification systems were developed to be applied to subgrade soils under pavements, based on the USDA classification system developed by U.S Department of Agriculture in 1938. The USDA system was a genetic system of soil classification where the soils were divided into three categories, namely, order, suborder and great soil group. It consisted of 36 great soil groups and essentially conveyed information regarding the soil profile, soil environment and other pedogenetic factors (12). Butler et al. (13) observed that the class boundaries were not defined and the differentiating criteria were based on environmental factors rather than soil characteristics. The Canadian system of soil classification consists of two classes, namely, orders and great groups. This system is a hierarchial one based on "The generalization of properties of real bodies of soil" (12). The classes in this system are defined based on the measurable soil properties which indicated soil genesis and other environmental factors.

"Soil Classification for England and Wales" was developed in 1973 and is based on the profile characteristics and does not take into account the factors relating to climate and site (12). Since this classification system was intended to be used for general surveys of cultivated and uncultivated land, it consisted of classes characterized by properties measured in the field and inferred from field measurements. This classification system is divided into three principal categories, namely, major groups, groups, and subgroups. The fourth group consists of "soil series" distinguished by profile characteristics (12).

Most Russian soil classification systems are developed based on the genetic properties of the soil. Although all the Russian soil classification systems followed the same basic genetic approach, they can be subgrouped into five categories depending on whether the system was classified based on "the conditions of pedogenesis, the factors governing the pedogenesis, the character of the pedogenetic processes, single process or an evolutionary stage of these processes" (12). The soil classification system developed by Gerasimov and Glazovskaya in 1960 mostly emphasizes the soil dynamics and the pedogenetic functions of the environment. It has a simple structure consisting of three classes, namely, Subtypes, Species and Subspecies (13).

Northcote et al. (14) developed a factual classification system for Australian soils in 1962. This system is a deviation from the conventional soil classification systems which are based on the genetics of the soil. Northcote used a "key" for differentiating soil into various divisions. Soil characteristics such as texture, color and consistence are used for defining soil into different groups, each of which is represented by a key. "Key" is essentially a symbol which aids in grouping of soil into divisions and subdivisions. For example, the first division is based on texture and consists of uniform, gradational and abrupt texture profiles which are represented by keys U, G, and D respectively. Three "divisions" are further classified into 11 "subdivisions". These are subsequently grouped into "Sections", "Classes" and "Principal profile forms" (14). Figure 2.1 shows the basic divisions of this soil classification system and their respective keys.

Other prominent soil classification systems include the FitzPatrick's System developed in 1971, the Kubiena system for the soils of Europe in 1953, "Soil map of the world" developed by Dudal in 1974, the Polar soil classification system by Tedrow in 1977 and "An attempt at a general soil classification" by Ivanova in 1956 (13).

2.2 ROCK CLASSIFICATION SYSTEMS

One of the first rock classification systems was proposed by Terzaghi in 1946 for tunneling with steel supports (15). Since then, many rock mass classifications have been developed which are being used as design aids in the field of Geology, Civil Engineering, Mining and Petroleum Engineering. The prominent engineering rock mass classifications

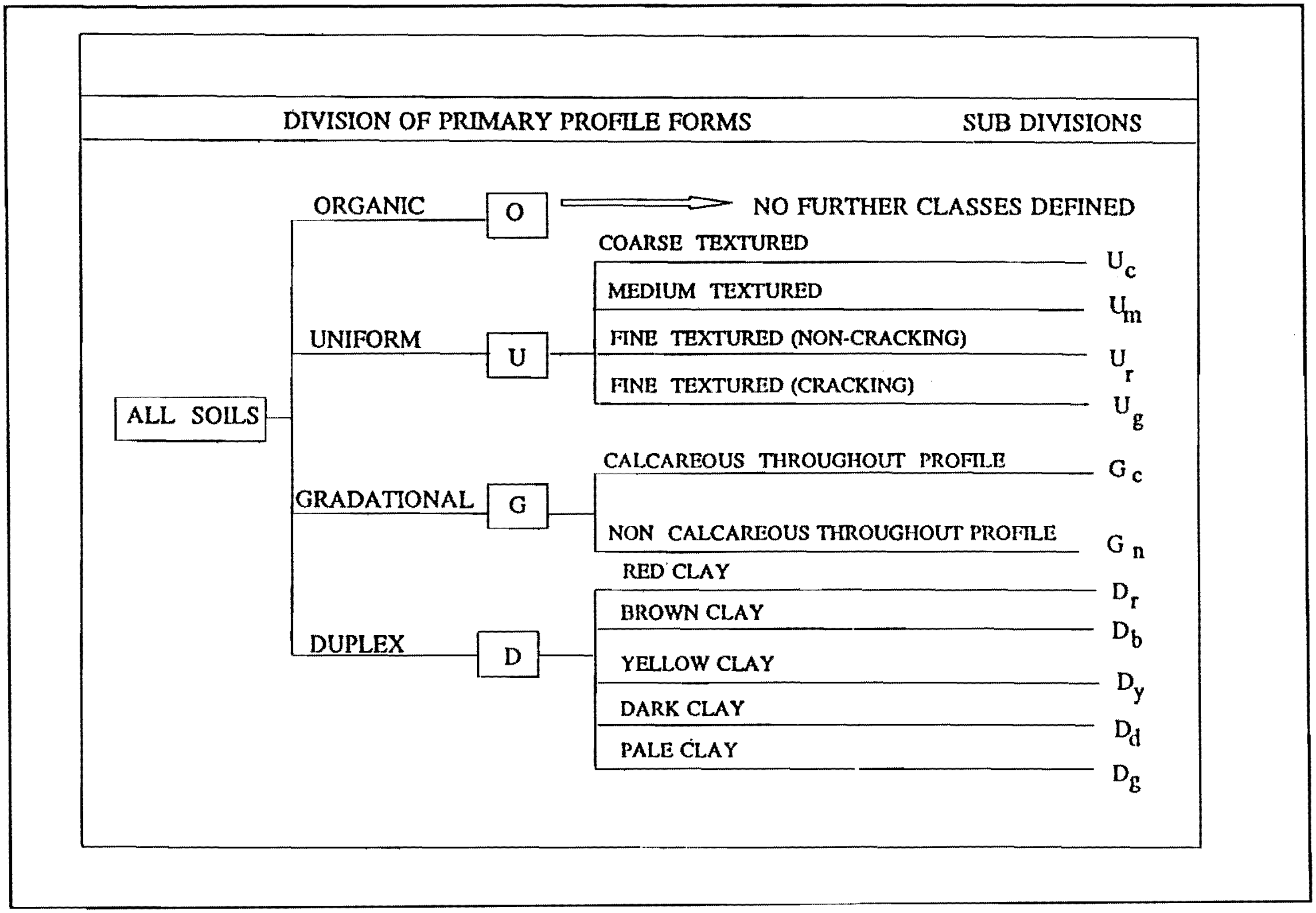


Figure 2.1. Northcote's Key Representing the Basic Divisions and Subdivisions (After 13).

currently in use include the NATM classification system developed by Pacher in 1964, the RQD system by Deere in 1967, the RMR system by Bieniawski in 1973, the Q-system by Barton in 1974 and the Unified Rock Classification System by Williamson in 1959 (15).

Unified Rock Classification System (URCS)

The Unified Rock Classification System, developed by Williamson in 1959 is a simple and concise classification system which assists in the preliminary assessment of rock condition by simple field tests. This classification system is based on the following four fundamental physical properties of rocks (8):

- Weathering,
- Strength,
- Discontinuity, and
- Density.

By evaluating these four basic elements, this classification system provides a reliable estimate of the performance of the rock. The notations, consisting of abbreviated symbols, are clearly indicated in Table 2.1 (8). The equipment required for carrying out field tests are also simple and mostly require a hand lens, 1 lb ball peen hammer, and spring loaded scales (10 lb range). The degree of weathering indicated by this system essentially refers to chemical weathering and is classified into five different types based on the level of oxidation of the rock. The strength of the rock is estimated by using a ball peen hammer and is classified based on the reaction of the rock when struck with a hammer. Planar and linear elements are classified by evaluating the "continuity", "shape" and "relief" of the rock. The fourth element, unit weight, is classified into five categories using the spring-loaded scales. The condition of the rock is represented by letters A through E. Thus, the rock designated by AAAA indicates the good condition of the rock, i.e., the rock that requires least design evaluation, and the rock designated by EEEE indicates the poor quality of the rock (8).

Table 2.1. Notation and Symbols Used in the Unified Rock Classification System (After 7).

Category Symbol	Abbreviation	Meaning
Weathering		
A	MFS	Micro Fresh State
B	VFS	Visual Fresh State
C	STS	Stained State
D	PDS	Partly Decomposed
E	CDS	Completely Decomposed
Strength		
A	RQ	Rebound reaction
B	PQ	Pits with hammer blow
C	DQ	Dents
D	CQ	Craters
E	MBL	Moldable with fingers
Planar and Linear Elements		
A	SRB	Solid w/Random breakage
B	SPB	Solid w/Preferred Breakage
C	LPS	Latent Planes of Separation
D	2-D	Planes of Separation in 2-D
E	3-D	Planes of Separation in 3-D
Unit Weight		
A	>160	lb/ft^3
B	150-160	lb/ft^3
C	140-150	lb/ft^3
D	130-140	lb/ft^3
E	<130	

Size-Strength Classification System for Rocks

A size-strength classification system, developed by Franklin and Louis (16) during 1970-75, is based on the block size and the intact strength of rock mass. This rock classification system has found a variety of applications in Civil Engineering and Mining in the planning and design of underground excavations and ground control systems.

This classification is based on the concept that the rock mass is comprised of discrete intact blocks whose behavior is essentially dependent on a combination of its size and strength. Rock size is measured by observing an exposed rock face and the strength is assessed by using simple hammer and scratch tests. Figure 2.2 shows a plot of the size-strength classification (16).

The values are plotted on a logarithmic scale in the classification chart. A single point on the classification chart explains the uniformity of rock in its size and strength. A variable rock unit results in a "unit plotting zone" which consists of scattered values of the size and strength of the rock. Usually, a weak rock mass plots toward the lower left of the diagram and stronger rock masses plot toward the upper right. This size-strength classification assesses the condition of the rock mass as a function of its size and strength and expresses it as rock quality index.

ISRM Classification System

The International Society for Rock Mechanics developed a rock classification system in 1981. This classification system gives a generic description of rock masses by characterizing various zones that constitute a rock mass. The characteristics which this system recommends for consideration to describe a rock mass are as follows (16):

- Geological description of the rock, explained by its name,
- Layer thickness and discontinuity spacing of the rocks, and
- Uniaxial compressive strength and the angle of friction of the fracture of the rock.

Though this classification is not exhaustive, its importance lies in the fact that it presents intervals and their corresponding descriptions for all the parameters considered in this system. In other words, this system characterizes the rock mass into five intervals based on the respective values of uniaxial compressive strength, discontinuity spacing, and the angle of

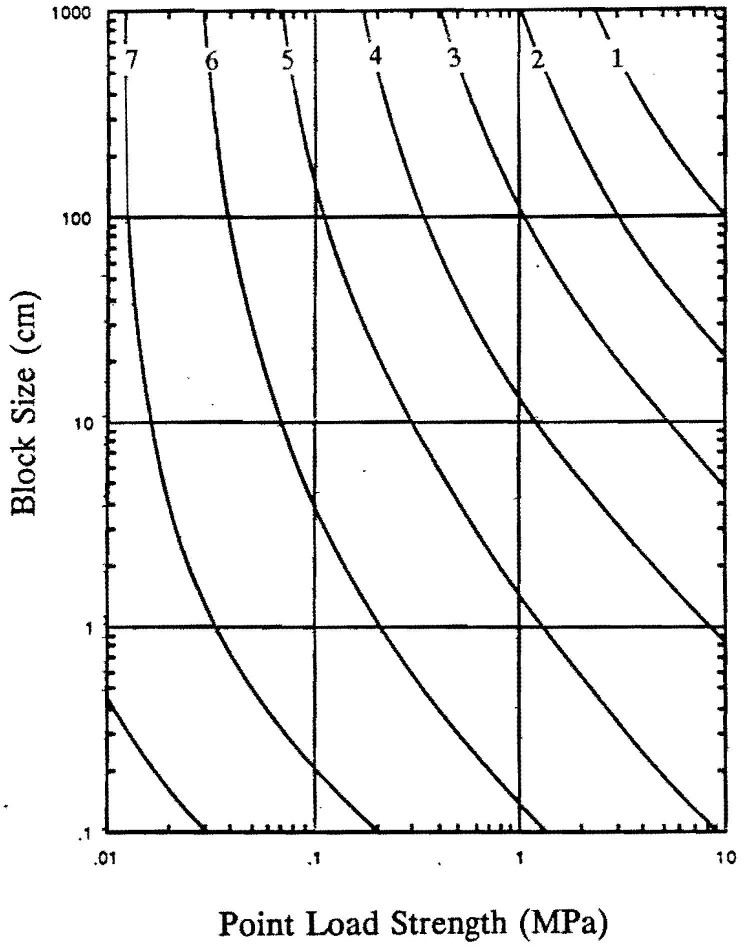


Figure 2.2. Size-Strength Classification Diagram for Rocks (After 16).

friction of the fractures (16). Strength of the intact rock, which has been an important classification criterion in many rock classification systems, has been classified differently by different authors.

There are various other systems of rock classification which are being widely used in engineering projects relating to tunnels, slopes, foundations, and mines. These include the Rock Mass Rating (RMR) classification system proposed by Bieniawski in 1973, the Q-system of rock classification developed by Barton in 1974 in Norway, and the New Austrian Tunneling Method (NATM) developed by Ladislaus in 1965. The RMR classification system proposed by Bieniawski was modified by various persons which contributed to its application in countries like South Africa, Sri Lanka, and India (16).

2.3 PREVIOUS EFFORTS IN DEVELOPING AN AGGREGATE CLASSIFICATION SYSTEM

Aggregates, which are naturally occurring rock materials, have been classified in different ways in the past (17). Some of the approaches for classification of aggregates were based on characteristics such as age, color, grain size, mineralogy, mode of formation, and compressive strength. However, the most common approach is based on the geological classification, which is dependent on the mode of formation of the parent rock.

Geological Classification of Aggregates

Aggregates are broadly classified into three main categories, namely, igneous, sedimentary, and metamorphic rocks. These rock materials are further subdivided on the basis of their texture, mineralogy and chemical composition. The British Standards Institute (17) developed a "Group Classification" of aggregate materials which was later modified as "Petrological Group Classification" because this system grouped all aggregates into their petrological classes such as Basalt, Schist, and Limestone. One of the shortcomings of this system was that it is not designed to predict the suitability of any aggregate for a particular purpose and thus does not convey information regarding the mechanical or physical properties of the aggregate. This standard was withdrawn by the British Standards Institute in 1984.

Weinert et al. (18) has proposed a classification system for aggregate materials used in road construction in southern Africa in 1980 . This classification system categorizes aggregates into nine groups depending on whether the rock material contains quartz or not. The nine rock groups which are identified by this system are acid crystalline, basic crystalline, high-silica, arenaceous, argillaceous, carbonate, diamictites, metalliferous rocks and pedogenetic materials. Though the quartz content was a major criterion in grouping of aggregate materials, some rock groups like diamictites and pedogenic materials were exclusively based on the mode of formation. This lead to lack of consistency in the identification and classification of aggregate materials. It is described in this classification system that the mode of weathering, the durability and the suitability of aggregate material for road construction purposes are inferred from the presence or absence of quartz. Knight et al. (17) proposed a classification system for roadstones which was based on the petrological characteristics of rocks. Lees et al. (17) in 1968 proposed a similar classification system with the exception that this classification system consisted of symbols for each group identified. This classification is shown in Table 2.2 (17).

The Asphalt Institute suggested a general system of classification for mineral aggregates (19). This system of classification stresses the importance of the knowledge of origin of rock from which the mineral aggregates are produced. This system classifies aggregates based on the parent rock of the aggregate material into igneous, sedimentary and metamorphic rocks. These are further subdivided into constituent classes depending on the texture and mineralogy of the rocks. Table 2.3 gives the complete structure of this classification system in which the "Type" and "Family" essentially represent the texture and mineralogy of the aggregates (15).

Grain Size and Particle Size Classification of Aggregates

The next common approach for classification of aggregates is in accordance with two basic parameters, the particle size and the grain size characterizing the aggregate texture. Fookes et al. (17) proposed a classification system for near-shore carbonate sediment rocks in 1975. This system was based on the grain size and "post depositional induration" of rocks. Clarke et al. (17) expanded the system developed by Fookes in 1977 to accommodate non-carbonate sedimentary rocks. Sherman et al. (17) in 1980 proposed a classification of

Table 2.2. Classification of Roadstones Proposed by Lee in 1968 (After 17).

ROCKS					
Igneous		Sedimentary		Metamorphic	
Ic	Coarse Granite Syenite Diorite Gabbro	Sc	Coarse Conglomerate Breccia Gravel Scree	Mc	Coarse Gneiss
Im	Medium Microgranite Microsyenite Microdiorite Dolerite	Sm	Medium Sandstone Sand	Mm	Medium Quartzite
If	Fine Rhyolite Trachyte Andesite Basalt	Sf	Fine Shale Mudstone Clay	Mf	Fine Schist Slate Hornfele
		Sca	Calcareous Limestone Dolomite		
ARTIFICIAL MATERIALS Slag Calcined Bauxite Calcined Flint Crushed Brick Pulverized Fuel Ash Symopal					

Table 2.3. Aggregate Classification Based on Origin of Aggregates (After 19).

Class	Type	Family
Sedimentary	Calcareous	Limestone
		Dolomite
	Siliceous	Shale
		Sandstone
		Chert
		Conglomerate
		Breccia
Igneous	Intrusive (Coarse Grained)	Granite
		Syenite
		Diorite
		Gabbro
		Periodotite
		Pyroxenite
		Hornblendite
	Extrusive (Fine-Grained)	Obsidian
		Pumice
		Tuff
		Ryholite
		Trachyte
		Andesite
		Basalt
		Diabase
Metamorphic	Foliated	Gneiss
		Schist
		Amphibolite
		Slate
	Nonfoliated	Quartzite
		Marble
		Serpentinite

aggregates based on their particle size. The size limits specified in this system conform to the standard values in British Standards, BS 1377:1975. American Society of Testing and Materials (ASTM) standard C-136 specifies size limits for aggregates. Thus, the particle size distribution of aggregates can be determined by carrying out a sieve analysis which essentially separates aggregates when passed through a series of sieves.

Mantuani et al.(15) proposed a "Size Classification of Aggregate particles and Rock Grains" which is similar to that developed by Sherman. Some of the assumptions made by Mantuani are listed below (15):

- Same particle size classification is proposed for unconsolidated rocks like gravels and sands, and consolidated ones crushed to similar sizes,
- On account of limited precision in sieving operations of aggregates, a level of tolerance is specified for particle size distributions,
- Among the consolidated rocks, the crystalline rocks like metamorphic, crystalline sedimentary, and clastic granular sedimentary rocks to be distinguished, and
- Grain size classification is based on the particle size range of the aggregates.

This classification system suggested a uniform range for particle sizes, clast sizes, and grain sizes. The unconsolidated rocks have been classified into Gravel, Sand, Silt, and Clay based on the particle size in millimeters (15). In other words, the particles greater than 4.76 mm were classified as coarse aggregates and the particles less than 4.76 mm were classified as fine aggregates which includes sand, silt and clay.

Based on the grain size, the aggregates are classified into four classes, namely Macrogranular, Mesogranular, Microgranular, and Cryptogranular. Each of these are classified further into coarse, medium and fine particles (15). Table 2.4 represents the proposed classification system. One of the important assumptions that the particle size range can be adopted for grain size classification is indicated clearly in Table 2.4 (15). Based on the particle size range, the grain size of aggregates has been classified further into coarse, medium and fine textures.

Table 2.4. A Proposed Particle Size and Grain Size Classification System for Aggregates by Mantuani (After 15).

Sieve Size (mm)	Aggregate Type	Unconsolidated Rocks	Consolidated Rocks	
			Granular	Crystalline
> 256	Boulder	Rock		
64-256	Gravel	Very Coarse	Macro Granular	Macro Crystalline
32-64		Coarse		
16-32		Medium		
4-16		Fine		
2-4	Sand	Very Coarse	Meso Granular	Meso Crystalline
1-2		Coarse		
0.5-1		Medium		
0.25-0.5		Fine		
0.125-0.25		Very Fine		
0.062-0.125		Extremely Fine		
Size **μm**			Micro Granular	Micro Crystalline
30-62	Silt	Coarse		
16-30		Medium		
8-16		Fine		
4-8		Very Fine		
2-4	Clay	Fine	Crypto Granular	Crypto Crystalline
0.25-2		Very Fine		
< 0.25 μm		Colloidal		

Shape and Texture Classification of Aggregates

Shape and Texture are often described as "Geometric or External" characteristics of an aggregate. These properties have been found to affect the performance of aggregates in the structures in which they are used. Shape has been described under two independent criteria, namely, roundness or angularity and sphericity (15). Surface texture is also called surface roughness of the aggregate and depends on the texture, structure and degree of weathering of the source rock (15). These properties are discussed in detail in Chapter III. A shape classification of aggregates is developed by the British Standards Institute and is specified by their standard BS 812: Part 1: 1975 (20). This classification system is included in Table 2.5. According to this classification system, aggregates have been classified into Rounded, Irregular, Flaky, Angular, Elongated, and Flaky and Elongated shapes. A detailed description of each of these shapes is given in this classification system and is appended in Table 2.5.

British Standards Institute has also developed a textural classification system for aggregates and this is specified by their standard BS 812: Part1: 1975 (20). Textural classification of aggregates in this system is based on the extent to which the particle surfaces are polished. The characteristics of each of these textural classes have been specified in the classification system along with pertinent examples. The textural classification system developed by British Standards Institute is shown in Table 2.6 (20). Collis et al. (17) of the Engineering Working Party of the Geological Society of London have developed a system of classification for aggregate materials in 1985 which was intended to be a replacement for the existing British Standard classification. This system is known by an acronym, CADAM, which stands for "Classification and Description of Aggregate Materials". The objective behind development of this system was to provide a classification system for aggregate materials based on sound geological principles (use of relevant aggregate properties for grouping them into different classes), conceptually simple, and capable for further expansion if necessary. This system also provides full description of the nature of the aggregate material in a form which makes it easily understood and implemented at all levels in the industry for both commercial as well as contractual purposes. The CADAM system groups aggregates into various classes depending on the mineral content of the materials and is independent of the physical properties of the aggregates. This system requires three sets of data in order

Table 2.5. Shape Classification According to BS 812: Part 1: 1975 (After 20).

Classification	Description
Rounded	Fully water-worn or completely shaped by attrition
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges
Flaky	Material whose thickness is small compared to other two dimensions
Angular	Consisting of well defined edges which are formed at the intersection of roughly planar surfaces.
Elongated	Usually angular whose length is larger than other dimensions
Flaky and Elongated	Aggregates whose length is larger than width, and width larger than the thickness

Table 2.6. Classification of Surface Texture of Aggregates Developed by British Standards Institute, BS 812: Part 1: 1975 (After 20).

Group	Surface Texture	Characteristics
1	Glassy	Conchoidal fracture
2	Smooth	Water-worn, Smooth due to laminated rock
3	Granular	Fracture exhibiting uniform grains
4	Rough	Rough fracture consisting of invisible crystalline constituents
5	Crystalline	Consisting of visible crystalline constituents
6	Honeycombed	Containing visible pores and cavities

to classify aggregates listed below (17):

- The "Form" of the aggregate indicating the nature of the material,
- The "Class" of the aggregate indicating the dominant minerals present in them, and
- Age, Grain size, Color and Foliation of the aggregate material.

The authors of the CADAM system have devised a standard data sheet for entering and analyzing the data pertaining to the aggregates. This standard form essentially serves as a data compilation sheet and aids in the description and classification of the aggregate material. The CADAM standard data form is shown in Table 2.7. Thus, based on the "Form", this system classifies aggregates into crushed rock, gravel, sand, land-won or marine-dredged aggregates. "Class" categorizes aggregates into either carbonate, quartz, silicate or other miscellaneous groups. The third data set provides geological assessment of aggregates. It includes information related to the aggregate age, grain size, color and foliation. Apart from the data represented in Table 2.7, this system also requires the location and sampling details of the aggregates in order to assess the extent to which the sample represents the aggregate source.

For a complete engineering assessment regarding the suitability of the aggregates for construction purposes, this system recommends the provision of data related to the physical, chemical and mechanical properties of the aggregates. Depending on the intended usage of the aggregates, this system recommends evaluation of specific properties such as shape, texture, porosity, particle size, hardness, water absorption and extent of contamination of the aggregate material. Similarly, provision of petrological data is added as supplementary information in this system. This data is recommended to be provided only when a possible alkali-silica reactivity is suspected or to identify any potential problems related to aggregates.

2.4 CLASSIFICATION OF SYNTHETIC COARSE AGGREGATES

Synthetic aggregates, which are artificially produced lightweight aggregates, have found their application in construction. These are generally produced by a process of expansion or agglomeration of clay , shale, slate or pulverized ash (21).

Table 2.7. Classification and Description of Aggregate Mateirals (CADAM) Proposed by Collis in 1985 (After 19).

<table>
<tr><td rowspan="3">AGGREGATE FORM</td><td rowspan="3">Crushed Rock</td><td rowspan="3"></td><td rowspan="3">Gravel</td><td>Natural</td><td></td><td rowspan="3">Sand</td><td>Natural</td><td></td><td>Land-Won</td><td></td></tr>
<tr><td>Crushed</td><td></td><td>Crushed</td><td></td><td rowspan="2">Marine</td><td rowspan="2"></td></tr>
<tr><td>Mixed</td><td></td><td>Mixed</td><td></td></tr>
</table>

<table>
<tr><td rowspan="2">CLASS</td><td rowspan="2">Carbonate Class</td><td rowspan="2"></td><td rowspan="2">Quartz Class</td><td rowspan="2"></td><td colspan="6">Silicate Class</td><td rowspan="2">Misc.</td><td rowspan="2"></td></tr>
<tr><td>Igneous</td><td></td><td>S'tary</td><td></td><td>M'morphic</td><td></td></tr>
</table>

Petrological Name	
Geological Age/Color/Grain Size/Fissility	
Comment (if any)	

Ledbetter et al. (22) conducted research on synthetic aggregates for highway use at the Texas Transportation Institute, Texas A&M University, during 1966-69 and have developed a "Synthetic Coarse Aggregate Classification System".

This classification system divides the synthetic coarse aggregates into two classes, namely, Bloated and Non-Bloated. Each of these classes are subdivided into groups A, B, C based on the following recommended tests on the synthetic coarse aggregates (22):

- Dry Loose Unit Weight,
- 100 Minute Saturation,
- Aggregate Freeze-Thaw Loss,
- Pressure Slaking Value, and
- Los Angeles Abrasion Loss.

Based on the classification of synthetic coarse aggregates, Ledbetter et al.(22) suggested a functional grouping for these aggregates. These functional groups indicate the synthetic aggregates suitable for surface treatments, base materials, Asphaltic Concrete surfaces, Portland Cement Concrete structures, etc. Table 2.8 explains the classification of synthetic coarse aggregates. The functional grouping of synthetic coarse aggregates developed by the same authors is shown in Table 2.9 (22). The documented report on the synthetic coarse aggregate classification system also recommends test procedures for evaluating these aggregates.

2.5 COMMENTS ON EXISTING AGGREGATE CLASSIFICATION SYSTEMS

Overview of existing aggregate classification systems suggests that mineral aggregates predominantly have been classified based on various characteristics such as geological origin, particle and grain size, shape, and surface texture. Apart from the CADAM system of classification of aggregates, all other systems of classification were based on a single characteristic of aggregates and hence do not give a complete description of the aggregate material. Particle size and shape can be quantified according to the ASTM standards which serve as equivalents to the British Standards Institute's shape and textural classification systems. Although CADAM system provides a supplementary list of mechanical and

Table 2.8. Recommended Synthetic Coarse Aggregate Classification System by Ledbetter (After 22).

Class	Group	Dry Loose Unit Weight(pcf)		100 Minute Saturation-%Max	Aggregate Freeze-Thaw Loss-% Max	Pressure Slaking Value-% Max	L.A. Abrasion Loss-% Max
		Max	Min				
I Bloated	A	55	35	15	7	6	35
	B	55	35	20	15	6	40
	C	55	35			10	45
II Non Bloated	A		55		7	6	35
	B		55		15	6	40
	C		55			10	45

Table 2.9. Recommended Functional Classification of Synthetic Coarse Aggregates (After 22).

Function	Permissible Aggregate Group
Surface Treatments	IA
Asphaltic Concrete Surfaces	IA, B, IIA
Asphaltic Concrete Bases	IA, B, C, D, IIA, B, C
Exposed Lightweight PCC Structures	IA, B
PCC Pavements	IA, B
Unexposed PCC Bases	IA, B, C, IIA, B
Flexible Base Materials	IA, B, C, D, IIA, B, C

chemical properties for aggregate evaluation, these are not integrated in the main classification system in the sense that they do not provide preliminary information on the mechanical and chemical aspects of the aggregate material. Also, this system of classification does not provide information on the thermal properties such as the thermal coefficient of expansion of aggregates. Keeping in view the need to integrate various physical, chemical, mechanical and thermal characteristics of aggregates into a common system of classification which will assist in the complete classification and description of aggregates for engineering use, a framework for a coarse aggregate classification has been developed as a part of this research and is explained in detail in the subsequent chapters. For the purpose of implementation, a simplified version of the classification system has been developed and is included in Chapter IV. Chapter III explains the properties of mineral aggregates and their significance with respect to aggregate performance in the structures in which they are used.

CHAPTER 3: PROPERTIES OF MINERAL AGGREGATES

Natural aggregates are formed from various types of parent rocks and consist of different types of minerals exhibiting various properties. All properties of aggregates affect the quality and performance of structures in which they are used. However, there are perceptible differences in their effect which depends on the intended purpose, type of construction, and environment in which they are used. Thus, natural aggregates can be described based on different types of properties exhibited by them.

3.1 CHARACTERIZATION OF NATURAL AGGREGATES

Aggregates can be broadly characterized based on four different classes of properties which include physical, chemical, mechanical and thermal properties. These properties represent the physical condition, chemical composition, mechanical strength, and thermal stability of the aggregates, respectively. Physical properties are inherent physical characteristics of the material such as maximum size, shape, texture, porosity, and specific gravity. Chemical properties of aggregates essentially constitute the composition of aggregates and represent the level of reactivity of the aggregates. They provide chemical identification of aggregate particles and indicate their response to various chemical processes. Similarly, mechanical properties of aggregates are a measure of material response to external forces such as impact and compressive loads, dynamic stresses and evaluate the resistance of aggregates (23). Lastly, thermal properties of aggregates describe the thermal expansion, conductivity and volume stability of aggregates. The subsequent sections of this chapter explain various characterization procedures that have been followed and the significance of aggregate properties on performance.

Physical Properties

Characterization of aggregates based on their physical properties can be done by following standard test procedures established for the same. Maximum particle size of the aggregates is the size of the sieve opening through which 100% of the aggregate material passes and is determined by performing a sieve analysis. Sieves are metallic plates consisting of uniformly spaced openings (6). Characterization of particle size is important in that the coarse aggregates which are deficient in any size fraction are usually undesirable. The maximum size of the aggregate can be characterized by performing the mechanical sieve analysis on a sample of aggregates. Excessively larger size of aggregate fractions, if present in the gradation, will cause segregation during stockpiling and handling. On the other hand, higher percentages of finer portions of aggregate would present problems in obtaining desired workability (6). Thus, separation of aggregates into various sizes and determination of optimum percentages of coarse and fine portions of aggregate is essential in achieving the required gradation.

Shape and surface texture are attributes of coarse aggregates that describe their geometry and they have been found to influence the performance of portland cement, asphalt concrete, bases, and subbases under pavements and various other structures in which they find their application (4, 5). Hence, characterization of aggregate shape and surface texture holds significance in determining the available surface area of aggregates, interfacial bond between aggregate surface and a binder, if present. Particle shape and texture have been characterized in various ways in the past and play major roles in the mix design, and workability of Portland Cement Concrete or Asphalt Concrete and thus affect their performance. ASTM D 3398 describes a procedure for characterization of aggregate shape and surface texture wherein a numerical index is determined for aggregate shape and texture based on the weighted average void content of specified aggregate sizes at a certain level of compaction. The original percent of voids is initially determined and the final void percentage is determined after subjecting the sample to two compactive efforts. The particle index is expressed as a function of original percentage of voids and the change in the percent of voids measured after compaction (24).

Folk et al. (6) characterized aggregates based on a form and a shape factor, respectively. Both form and shape factors are a measure of axial proportions of the three axes of an aggregate particle. Characterization of shape by form factor is shown in Figure 3.1. Sphericity is represented by ψ in the figure. This figure illustrates various particle shapes within the triangle and categorizes aggregates into compact, platy, bladed and elongated

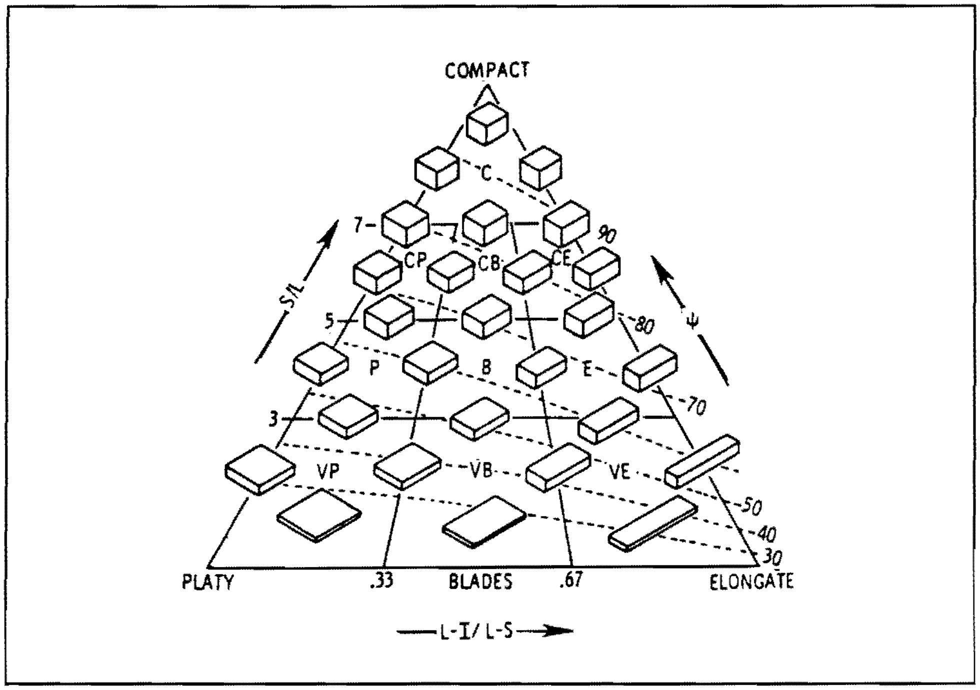


Figure 3.1. Characterization of Aggregate Shape Based on Form Factor Proposed by Folk (After 6).

shapes. The method for shape classification adopted by the British Standards Institute is discussed in Chapter II. Zingg et al. (6) defined aggregate shape based on the ratio of the intermediate to the long axis and the ratio of the short to the intermediate axis of an aggregate particle.

The four shape categories described by Zingg are shown in Figure 3.2. Burke et al. (6) adopted the technique of projection of silhouettes of aggregate particles on a grid and calculated the maximum sphericity of projected silhouettes. A similar method was adopted by Heigold et al. (6) who measured the intercepts of silhouettes of aggregate particles and compared it with the reference data containing geometrical standards using a computer. Krumbein et al. (25) used roughness of aggregate in terms of average deviation of actual surface from the surface mean as basis for characterizing the particle shape of aggregates. Fractal characterization of aggregate shape and surface texture is a novel technique that has been used in the recent past. Li et al. (26) carried quantitative analysis of aggregate shape based on fractal technique and have characterized shape and texture of aggregates. Fractal Dimension is the defining characteristic of fractals and essentially describes the level of

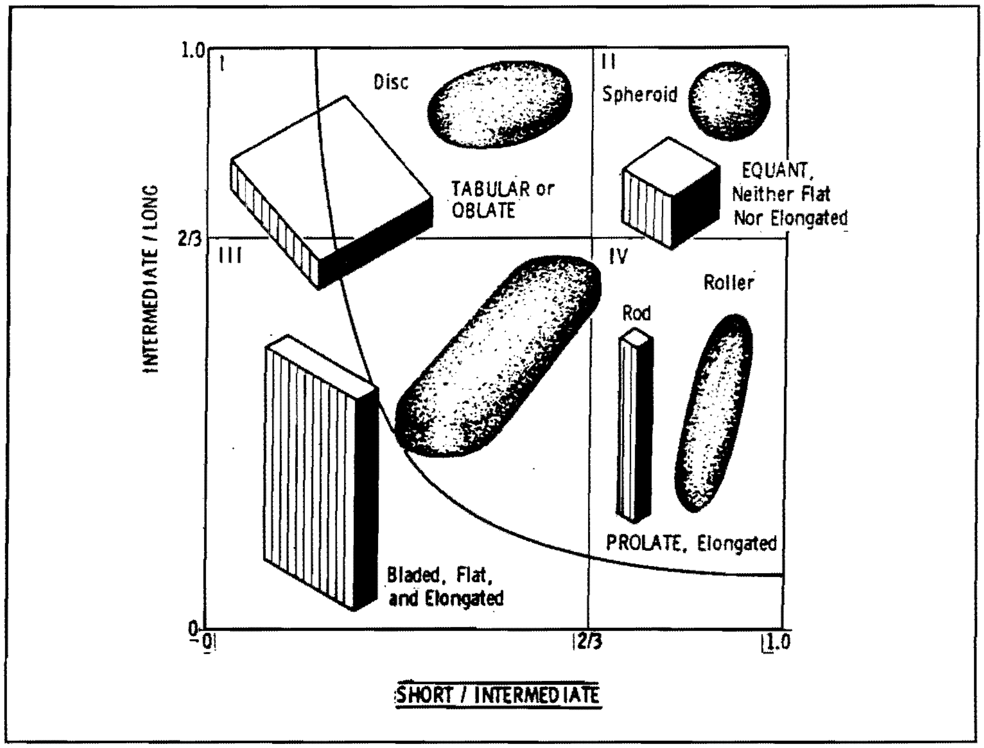


Figure 3.2. Four Shape Categories as Described by Zingg (After 6).

roughness of a surface. The major steps involved in fractal characterization will be discussed at greater length in Chapter VI.

The technique of numerical evaluation of roughness profile of aggregate surface is used by Wright et al. (6). This technique consists of determination of roughness value by either measuring the average height and depth from a mean surface line or by using root mean square average to identify peak to valley heights on a surface profile. The roughness value is used as a measure of surface texture of aggregates. Tons et al. (6) presented an approach where the aggregate texture is related to its bulk packing behavior. Kummer et al. (27) described the aggregate depth of texture as smooth, fine and coarse and the sharpness of texture into smooth, rounded and, gritty textures as shown in Figure 3.3.

Other important physical properties of aggregates, which can be readily characterized based on the available standard ASTM specifications, are the specific gravity, unit weight and absorption. Unit weight can be determined according to ASTM C-29 and the specific gravity and absorption of aggregates can be arrived at by following the ASTM standard C-127 or

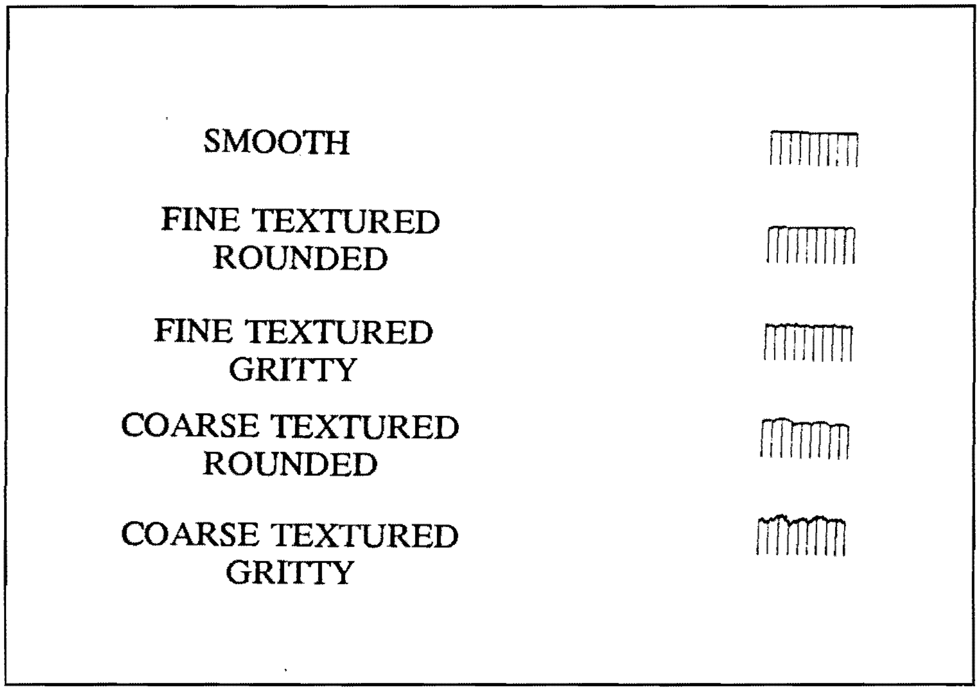


Figure 3.3. Surface Texture Characterization Proposed by Kummer (After 27).

C-128, depending on whether the sample consists of coarse or fine aggregates. Determination of specific gravity will not only be useful in converting weights to solid volumes for the purposes of proportioning but also serves as criteria for identification and acceptance. Determination of unit weight of aggregates will aid in classifying them into normal weight, light weight and heavy weight aggregates. Table 3.1 describes the unit weight classification of aggregates where the unit weight range is specified by various ASTM or PCA test procedures. Porosity is the ratio of volume of the voids to the bulk volume and different methods have been used for its determination. Porosity can be determined by using either pycnometric methods or with a McLeod gage porosimeter. ASTM standard C 457 can be used for microscopic determination of air voids in concrete. Though this method has reportedly been used on aggregates, its accuracy is limited on account of the low resolution of the microscope. Another method which has been used for determining the pore size distribution of solids is the mercury porosimetry method whose application to aggregates has been reported (6).

Table 3.1. Unit Weight Classification of Aggregates (After 6).

Aggregate Classification	Unit Weight Range (kg/m^3)
Light Weight	880-1120 (55-70 lb/ft^3)
Normal Weight	1200-1760 (75-110 lb/ft^3)
Heavy Weight	1760-4640 (110-290 lb/ft^3)

Chemical Properties

Characterization of aggregates based on chemical properties provides an engineer with a means of estimating the reactivity of aggregates and its effect on the performance. Some of the important chemical properties of aggregates which affect their performance in the field are their mineralogy, oxide content, alkali-silica reactivity and alkali-carbonate reactivity. Characterization of mineral composition of aggregates is crucial in determining the deleterious minerals present in the aggregates which adversely affect their quality. Mineral composition of aggregates can be determined based on the geological origin of the aggregates or by other methods such as X-ray diffraction or by petrographic examination of aggregates according to ASTM standard C-295. Classification of aggregates based on the mineral composition and geological origin is dealt with in detail in Chapter II. Dossey et al. (4) carried out chemical analysis on aggregates by (a) mineral composition test, and (b) oxide content test. The mineral composition of aggregates has been determined by X-ray diffraction which helped in the identification of the most abundant minerals in a specified aggregate sample. The oxide content of the aggregates was determined by using an atomic emission spectroscopy technique which provided a valuable description of various oxides present in the aggregates. The data from this chemical characterization study was used to develop PC based computer programs, CHEM 1 and CHEM 2. These programs use oxide percentages as user inputs in order to estimate various concrete properties such as the compressive strength, tensile strength, elastic modulus and drying shrinkage. Graves et al. (28) performed Petrographic and X-ray diffraction analyses to determine the mineral composition and texture of coarse aggregate samples. Microscopic petrographic examination was carried out on aggregates to determine the shape, texture, fossil fragments, pore spaces, and detectable minerals. X-ray diffraction analysis was used to confirm the minerals detected by petrographic examination (28).

Other chemical properties, such as the alkali-silica reactivity and alkali-carbonate reactivity, can be determined by the ASTM test procedures. ASTM C-289 is a quick chemical method for determination of alkali-silica reactivity and ASTM C-227 is a mortar bar method for identifying the potential silica reactivity. Similarly, ASTM C-586 can be followed to determine the potential carbonate reactivity.

Petrographic examination of aggregates provides a comprehensive means of aggregate evaluation which includes the determination of mineral composition, chemical activity such as the solubility, oxidation, hydration, alkali-silica reactivity, alkali-carbonate reactivity, and identification of any deleterious substances (6).

Mechanical Properties

Abrasion resistance, strength, soundness, elastic modulus, polish value, and toughness constitute some of the important mechanical properties of aggregates. Characterization of aggregates based on mechanical properties helps in assessing the resistance of aggregates to mechanical forces and localized impacts and thus assists in the evaluation and selection of aggregates for various purposes.

Abrasion resistance can be determined by using standard test procedures ASTM C-131 and ASTM C-535 for small size and large size aggregates, respectively. All aggregates larger than 1-1/2 inches can be evaluated for abrasion loss by ASTM C-535. ASTM C-88, a test for soundness of aggregates by use of sodium or magnesium sulphate, is widely used for evaluating the overall quality of aggregates. Soundness testing aids in characterizing the resistance of aggregates to disintegration by saturated solutions of sodium or magnesium sulphate. Another similar test that is carried out to evaluate the skid resistance of aggregates used in wearing surfaces in highway pavements is the accelerated polish value test. This test can be carried out as per ASTM D 3319 and E 303 and Texas Department of Transportation follows a modified version (Tex-438-A) of these ASTM tests.

Elastic properties of aggregates such as the modulus of elasticity and Poisson's ratio can be characterized by testing concrete mixtures containing different types of aggregates. There are no ASTM specified test procedures for characterization of elastic properties of aggregates directly. Similarly, no standard test procedure is available for characterization of strength of aggregates directly. Though there are test methods available for evaluating the strength of rock specimens, they do not, however, provide information on the mechanical bond strength of aggregates, which is a crucial factor for mechanical characterization of aggregates. Graves et al. (28) studied the interfacial bonding properties of different aggregates using a polarized light microscope (PLM) and scanning electron microscope on the concrete specimens obtained from different parts of the state of Florida. The micrographs obtained from these tests showed the textural characteristics of the aggregates and this information was used to interpret the mechanical bonding properties and thus the bond strength of the aggregates. Evaluation of fracture toughness parameters is made by using the RILEM test procedure to provide information on the fracture energy of concrete which could be used to estimate the bond strength of aggregates (29).

Thermal Properties

Thermal coefficient of expansion of aggregates is one of the important thermal characteristics of aggregates which was found to influence their performance in the structures in which they are used. Other important properties which need special mention are the thermal conductivity and specific heat of aggregates. Several methods have been developed to evaluate the thermal coefficient of coarse aggregate and they are based on the linear expansion of the aggregates over a certain temperature range. One such method was proposed by Willis and DeReus (6). The Corps of Engineers developed another method for evaluating the linear expansion of coarse aggregates which a SR-4 strain gage is attached to a coarse aggregate specimen and readings are noted over a temperature range (30). Another method adopted by Bureau of Reclamation consists of 25.4 to 76.2 mm deep specimens which are coated with wax and are held in fulcrum-type extensometer frames. Electromagnetic strain gages are used for recording the measurements while the specimen is immersed in a solution of ethylene glycol (6). Thermal conductivity can be determined directly by ASTM test C 177 for steady state thermal transmission properties by means of a guarded hot plate. Specific heat of aggregates can be determined by a procedure developed by the Corps of Engineers which is also known as the method of mixtures. It is a calorimetric method which measures the net heat required to raise the temperature of a specimen whose weight is known (6).

3.2 SIGNIFICANCE AND EFFECTS OF AGGREGATE PROPERTIES ON PERFORMANCE

Natural aggregates exhibit different physical, chemical, mechanical and thermal properties and each of these are important in affecting the quality and performance of structures in which they are used. Physical properties such as particle shape and surface texture affect the workability, strength and the bond between the aggregate particles and the binder. Various studies on particle shape have indicated that the equidimensional particles produce high density and higher strength of concrete, whereas flat and elongated particles pack poorly with the binder and decrease workability. Crushed aggregate particles such as limestone are angular and rough textured and hence provide a good bond with the binder. Rounded and smooth textured aggregates, such as siliceous river gravels, are easy to work with and provide good lubrication with less binder. Smooth particles, on account of less bonding area, affect the bond between the aggregate surface and the binder. Also, past research studies have shown that the shape of the aggregate affects the strength of concrete. A concrete specimen, in a compressive strength test, is most likely to crack and subsequently fail around smooth aggregate particles. However, the concrete specimens made with angular aggregates have resulted in cracks through them. These results show that the failure at the binder-aggregate interface in the concrete specimen made with smooth aggregate is due to the low bond between the binder and aggregate (6, 15, 21).

Button et al. (5) investigated the influence of aggregate characteristics on rutting of asphalt concrete and concluded that an increase in percent crushed coarse aggregate increases the stability of asphalt concrete and improves the resistance to creep of the mixture. Kaplan et al. (6) studied the effects of texture on the strength of Portland Cement Concrete and concluded that texture greatly influences the compressive strength of concrete. Some of the factors which cause rough textured aggregates resulting in higher strength are the mechanical interlock, available surface area for bonding and shape of the aggregate. Porosity of aggregates is an important aggregate property which influences the surface texture and thus the interfacial bond, abrasion resistance, and other elastic properties such as modulus of elasticity and Poisson's ratio. It influences the absorption characteristics of aggregates and pore spaces alter the volume of solids in the bulk volume of aggregates.

Mineral composition, oxide content and alkali-aggregate reactivity constitute principal chemical properties which affect the performance. Natural aggregates consist of different types of rocks and minerals, some of which significantly affect the quality of concrete. Mineral composition identifies the most abundant minerals present in the aggregates in question. A clear understanding of the mineralogy may prevent incompatibilities with the binder. Deleterious mineral constituents present in an aggregate, if undetected, may cause a serious deterioration of the quality of the aggregates, affecting the performance of the structure in which they are used. Aggregates containing minerals such as quartzites and other siliceous minerals may exhibit higher values of thermal expansion than limestone aggregates.

Aggregates derived from sedimentary and metamorphic rocks such as shales, slates, phyllites and schists often consist of objectionable fabric, a fan-like form caused by the coarse micaceous grains, which cause splitting and low bonding in these aggregates. Aggregates containing chert and clay minerals which consist of sodium, potassium, calcium or magnesium as "exchangeable cations" have been found to be susceptible to D-cracking in pavements and other slabs on grade. On the other hand, aggregates of igneous origin, such as granites and diorite, have not been associated with similar kinds of distress (31). Oxide based chemical models have been developed by Dossey et al. (4) for predicting the material properties of the hardened concrete. These studies have shown that various oxides present in aggregates can be successfully used for preliminary assessment of aggregates prior to greater in-depth laboratory testing.

The chemical characteristic of aggregates which has been investigated extensively is alkali-aggregate reactivity. Alkali reactive aggregates cause expansion which results in various types of distresses in concrete structural elements in which they are used. Among the distresses that are caused by such aggregates include pattern or wavy cracking, popouts in concrete pavements, and dislocation of structures. Alkali reactions cause changes in the original composition of the aggregates, alter the texture and initiate microcracks. Though petrographic examination of aggregates for reactive minerals and prediction of their effect on the performance is very complex, it helps in the identification of reactive constituents of aggregates (15).

The predominant reactive groups that occur in aggregates are the silica group and the carbonate group, each of which influence the reactivity of aggregates in a different manner (15). Some of the minerals and rocks which have caused alkali-silica reactivity are opal, chalcedony, chert, flint, siltstones, and argillites. Similarly, some of the alkali reactive carbonate rocks which have been identified are dolomite, calcitic dolostones, and quartz bearing argillaceous rocks. Determination of calcite-to-dolomite ratio is one of the significant parameters for identifying carbonate aggregates. Both silicate and carbonate aggregates have caused extensive damage in the form of severe cracking, expansion, and loss of strength which lead to deterioration and failure of existing structures (6).

The mechanical properties which play a significant role in the evaluation and selection of aggregates are the hardness, abrasion resistance, polish value, soundness and strength. The Texas Department of Transportation's Aggregate Quality Management Program (AQMP) requires evaluation of three mechanical properties on all aggregate samples submitted by the aggregate producers. These are the "Abrasion of Coarse Aggregate by Use of the Los Angeles Machine", "Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate", and "Accelerated Polish Test for Coarse Aggregate" which provide information regarding the percent loss due to abrasion, resistance to disintegration, and extent to which aggregate polishes under moving traffic respectively (32). The significance of these properties is that they provide adequate information by which poor quality aggregates can be eliminated in the aggregate selection process.

Dumas et al. (32) have carried out extensive investigation on the effects of aggregate blends on the properties of portland cement concrete and have concluded that blending of aggregates is a viable option for meeting the performance specifications of aggregates to be used in pavements. One of the other mechanical properties which is critical in evaluating the quality of aggregates is their bond strength. Past studies on bond strength have stressed more on the chemical aspects of the bond than the mechanical aspects of it. Another notable aspect of bond strength is the surface area provided by each aggregate for bonding. Thus, the surface area and surface roughness of aggregates can impact the bond strength of the concrete and characterization of mechanical bond strength could improve the performance evaluation of aggregates used in various structures (33).

Thermal characteristics of aggregates, such as the coefficient of thermal expansion, thermal conductivity and specific heat of aggregates, influence various temperature related distresses such as cracking and curling in pavements and other massive structures. Thermal coefficient of expansion of aggregates is the most significant thermal property which affects the durability of concrete, especially under severe exposure and extreme temperature changes. Walker et al.(6) showed that the concretes containing aggregates with higher thermal coefficients of expansion are less resistant to temperature changes than the aggregates with lower coefficients of expansion. Typical range of values of thermal coefficient of expansion of limestone and siliceous river gravel are 1-3 X 10^{-6} in/in/°C and 6.0-13.0 X 10^{-6} in/in/°C, respectively (6).

Thermal conductivity of normal weight aggregates is largely influenced by their mineral composition, whereas it is influenced by the moisture content in light weight aggregates. Concrete made with limestone aggregates have a typical thermal conductivity of 10 Btu.in./h.ft^2 and for moist concrete made with sandstone it is 20 Btu.in./h/ft^2. The specific heat of aggregates influence the specific heat of concrete and its determination is important in the control of concrete placement temperatures and thermal volume change of mass concrete (6).

The format of the coarse aggregate classification system is outlined and its stage wise development is explained in detail in Chapter IV. The list of properties which are included in the format of the proposed classification system are based on the understanding obtained as a result of the thorough evaluation of the significance and affect of aggregate properties on performance.

CHAPTER 4: DEVELOPMENT OF AGGREGATE CLASSIFICATION SYSTEM

4.1 FORMAT OF THE PROPOSED CLASSIFICATION SYSTEM

The format of this classification system is developed based on some significant properties of coarse aggregates which affect performance. The ultimate goal of this work is to develop a classification system which can be used as a tool to understand the behavior of coarse aggregates commonly used in construction of concrete or asphalt pavements and other concrete structures. Hence, several properties of aggregates which have affected the performance of pavements and other structures have been investigated for developing a list of properties to be incorporated in the classification system. All the properties which were studied for this purpose are included in Table 4.1.

The main objective of the evaluation of aggregates was to identify important characteristics which affect the performance of structures in which they are used. The idea behind the development of this classification system was to keep it simple, i.e., which consists of material properties which can be easily evaluated in the laboratory and also to convey more information regarding the aggregate being evaluated. To be consistent with this idea, a careful investigation of the above listed properties of aggregates was carried out and standard test procedures were evaluated for determining the type of equipment required, duration of the test, and the level of pertinent information provided by each test. This evaluation revealed that some of the tests needed extensive laboratory equipment, expertise, and longer duration to obtain required results. As there are no standard tests for determination of hardness, elastic modulus and thermal diffusivity of aggregates, they were excluded from the format of the classification system. However, alternative evaluation methods for these properties are suggested in the later part of this report. In order to facilitate a quick evaluation of coarse aggregates in the field, visual examination of aggregates is proposed in the classification system.

Table 4.1. Various Properties of Aggregates Evaluated for Developing the Format of the Classification System.

Physical Properties	Chemical Properties	Mechanical Properties	Thermal Properties
Particle Size	Mineralogy	Hardness	Coefficient of Thermal Expansion
Surface Texture	Oxide Content	Abrasion Resistance	Thermal Conductivity
Shape/ Sphericity	Alkali-Silica Reactivity	Elastic Modulus	Specific Heat
Specific Gravity	Alkali-Carbonate Reactivity	Bond Strength (K_{IF})	Thermal Diffusivity
Geologic Origin	Impurities	Soundness	
Porosity		Accelerated Polish Value	

4.2 BASIC CLASSIFICATION GROUPS

The coarse aggregates have been broadly classified into two basic groups:

(a) Visual examination of aggregates in the field, and

(b) Laboratory evaluation of coarse aggregates.

These basic classification groups have been given group designations. They are V and L respectively. The basic classification of aggregates is shown in Figure 4.1. Visual examination of coarse aggregates is expected to provide preliminary information on aggregates such as its color, nominal size, origin, surface type and presence of any obvious impurities.

Laboratory evaluation refers to the detailed investigation of coarse aggregates. This is expected to provide in-depth information on various properties of aggregates and also help in predicting the specific behavior of the aggregates when used in concrete or asphalt.

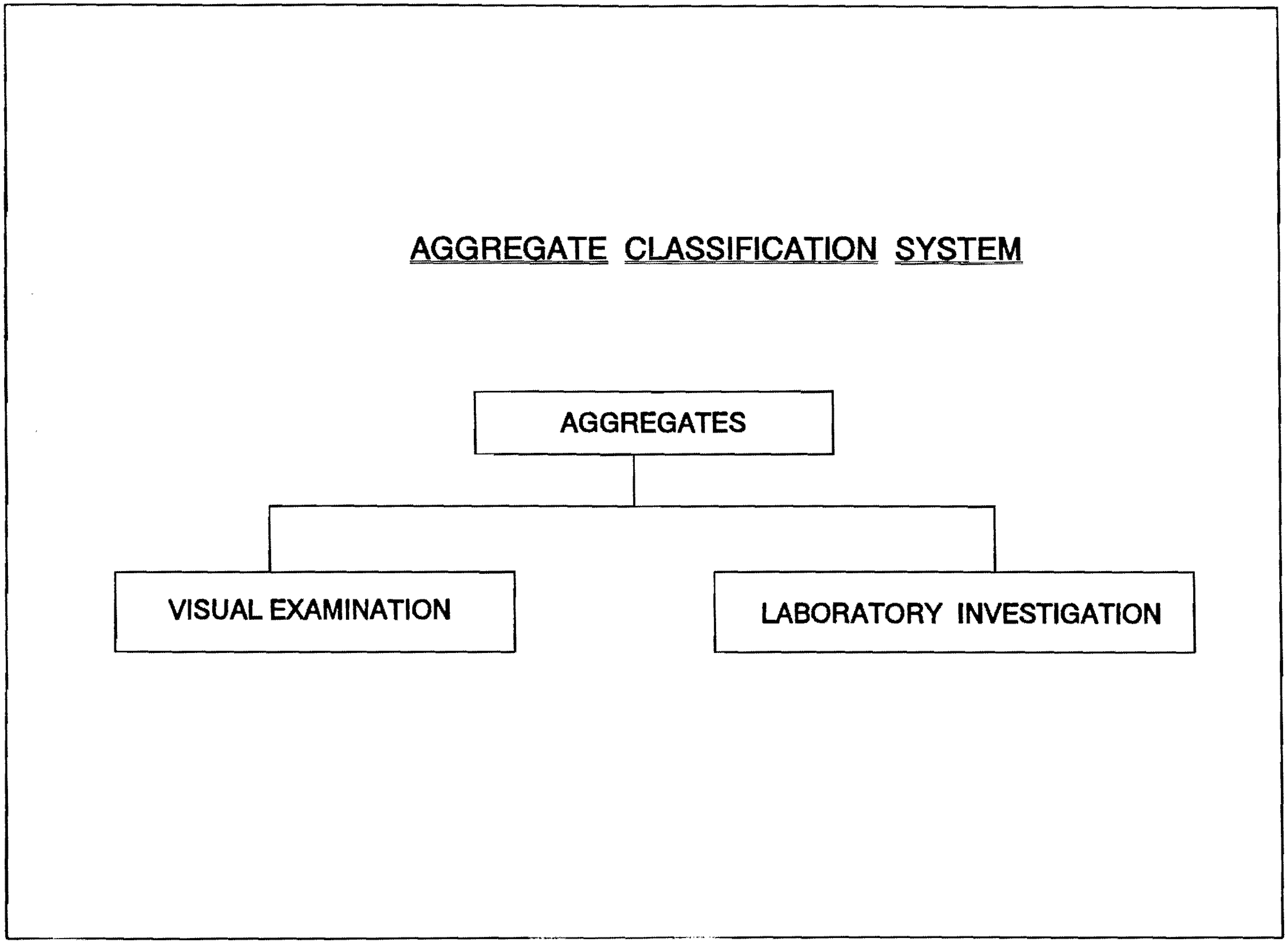


Figure 4.1. Basic Classification of Coarse Aggregates.

4.3 CLASSIFICATION OF AGGREGATES BASED ON VISUAL EXAMINATION

Visual examination of aggregates is an indispensable first step in evaluating concrete aggregates and helps in the preliminary assessment of quality and thus the suitability of aggregates for different construction purposes. Information pertaining to the geological features of aggregates can be obtained by a careful examination of their color, texture and mineral content (34). Knowledge of the physical geology and origin of rock type of aggregates is helpful in identifying some deleterious minerals present in the aggregates. The presence of fractures and cracks present in the aggregates can be determined by the visual examination of aggregates. Also, the nominal size of the aggregate can be estimated by a visual examination of a sample of aggregates from a stock pile.

Visual examination of aggregates is further classified into three subgroups. Each subgroup has been given a designation. The subgroups and their group designations are shown in Table 4.2.

Surface Type Classification (V-1)

This classification is expected to group the aggregate based on whether the surface of aggregate is crushed or uncrushed. The identification of cracks and fractures in natural aggregates is important in assessing their suitability for use in concrete (33). This information is also expected to be obtained by the surface type classification of aggregates. Figure 4.2 represents the visual examination and its subgroup classification.

Table 4.2. Subgroups and Respective Designations under Visual Examination of the Classification System.

Classification Subgroup	Subgroup Designation
Classification by Nominal Maximum Size	V-1
Aggregate Type Classification	V-2
Surface Type Classification	V-3

Nominal Maximum Size (V-2)

As the name indicates, nominal maximum size of the aggregates can be obtained by a visual examination of a sample of aggregates. Thus, size distribution of aggregates can be arrived at by this classification. This classification of aggregates is expected to provide a quick estimate of the size of the aggregate.

Aggregate Type Classification (V-3)

"Aggregate type" essentially refers to the geologic origin of the aggregates under investigation. Visual examination of the color, texture and mineral content of the aggregate is helpful in identifying the origin or the rock type of the aggregate. For example, igneous rocks can be identified based on their interlocking of mineral grains, as intrusive or extrusive rocks. Color also provides a valuable means of identification of rock type based on the silica content of the rock. Igneous rocks contain silicic and mafic rocks and they are identified based on their color. Siliceous rocks, which normally contain quartz and feldspar, are light colored whereas mafic rocks, which contain iron and magnesium, are dark colored (34). Though this classification of aggregate type calls for experience, it is believed that this identification provides a means for assessing the quality of aggregates.

4.4 CLASSIFICATION OF AGGREGATES BASED ON LABORATORY INVESTIGATION

Laboratory investigation of coarse aggregates is the second basic classification group proposed in the aggregate classification system. An attempt has been made to characterize coarse aggregates based on their properties. Almost all properties of aggregates were found to affect the performance and characterization of aggregates based on their properties would serve in providing the engineer with a complete description of the aggregate material. Thus, laboratory investigation of aggregates is classified into four subgroups. Each subgroup has been given a designation. The subgroups and their designations are shown in Table 4.3. Based on the preliminary evaluation of the significance of various properties of aggregates, each of the above subgroups have been classified further into their constituent properties.

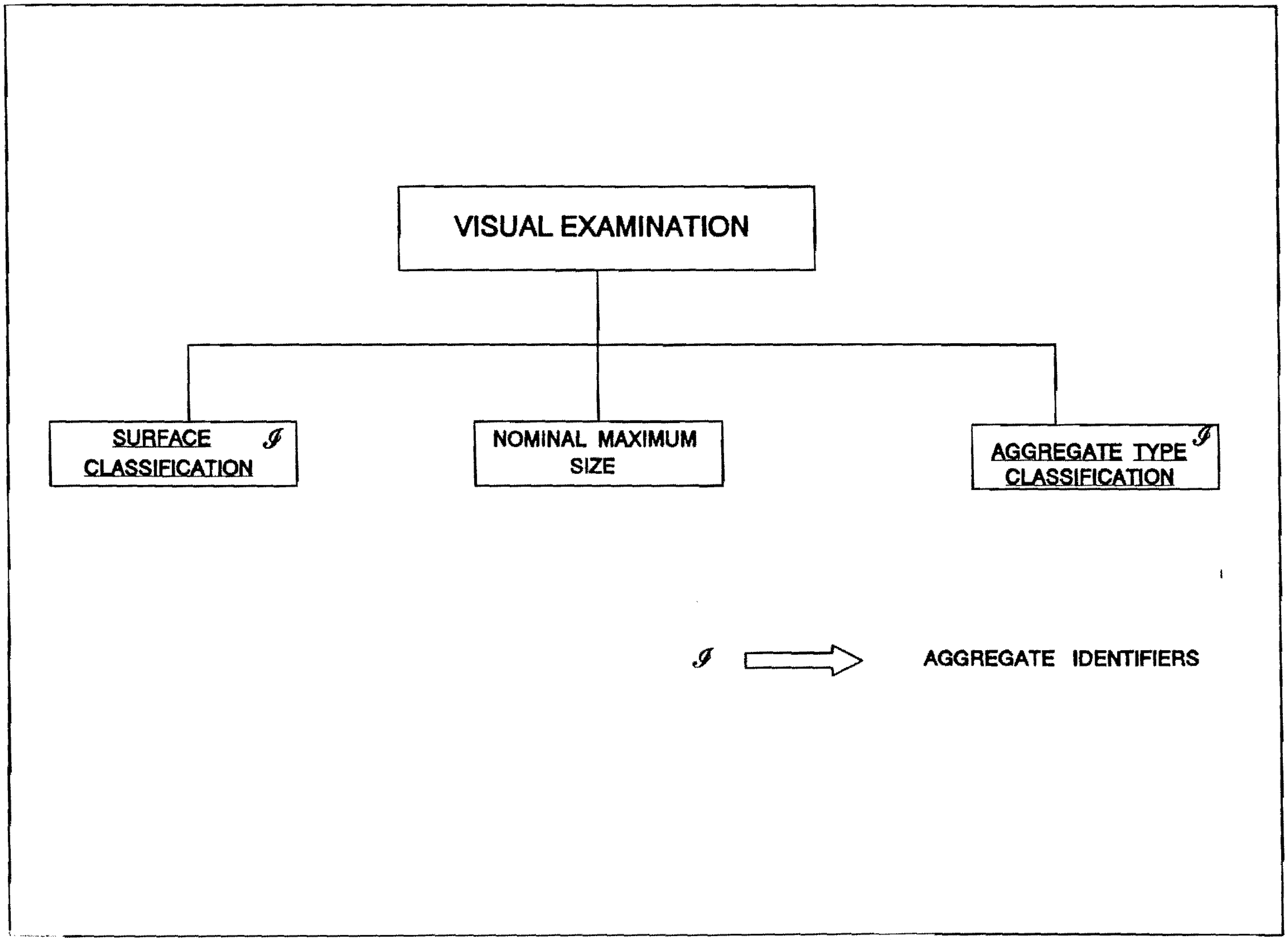


Figure 4.2. Classification of Aggregates Based on Visual Examination.

Table 4.3. Subgroups and Respective Designations under Laboratory Examination.

Subgroup	Designation
Physical Properties	LP
Chemical Properties	LC
Mechanical Properties	LM
Thermal Properties	LT

Physical Properties

Physical properties of coarse aggregates are proposed to be evaluated by classifying them based on the:

- Size Distribution,
- Textural Characteristic,
- Shape Classification,
- Specific Gravity, and
- Porosity.

These subgroups have been designated from LP-1 to LP-5. These properties are expected to provide comprehensive evaluation of the physical aspects of coarse aggregates.

Chemical Properties

Chemical properties of coarse aggregates are classified further based on the:

- Mineral Composition,
- Oxide Content,
- Alkali-Silica Reactivity, and
- Alkali-Carbonate Reactivity.

Evaluation of these properties would help in assessing the chemical composition, mineralogy and presence of any deleterious chemical compounds in coarse aggregates and is thus expected to provide a good understanding of the chemical behavior of the aggregates. These subgroups have been designated from LC-1 to LC-4.

Mechanical Properties

Mechanical properties of coarse aggregates can be further classified based on the:

- Abrasion Resistance,
- Accelerated Polish Value,
- Fracture Toughness (stress intensity factor, K_{IF}), and
- Sulfate Soundness.

Evaluation of mechanical properties of aggregates is crucial for assessing the key characteristics like strength, soundness, skid resistance, impact resistance and bond strength of the aggregates. These properties have been designated from LM-1 to LM-4.

Thermal Properties

Coarse aggregates can be further classified based on their thermal properties, namely:

- Thermal Coefficient of Expansion,
- Specific Heat, and
- Thermal Conductivity.

These are expected to provide an understanding of the effects of the thermal properties of aggregates on the performance of concrete. These subgroups have been designated from LT-1 to LT-3. Figure 4.3 shows the classification of coarse aggregates based on their laboratory evaluation. Some of the properties have been represented by a superscript and are the properties into which the classification system narrows down ultimately.

Keeping in view the complexity of the suggested classification of aggregates, which is not only exhaustive but also time consuming, the properties listed in the classification system are divided into three major categories:

- Aggregate Identifiers,
- Basic Test Parameters, and
- Inferred Parameters.

The rationale behind this division can be explained by the following points:

1. To keep the classification system simple,
2. To suggest tests which are less time consuming but more informative, and
3. To differentiate between the properties which help in aggregate identification and the properties which provide information for predicting their behavior.

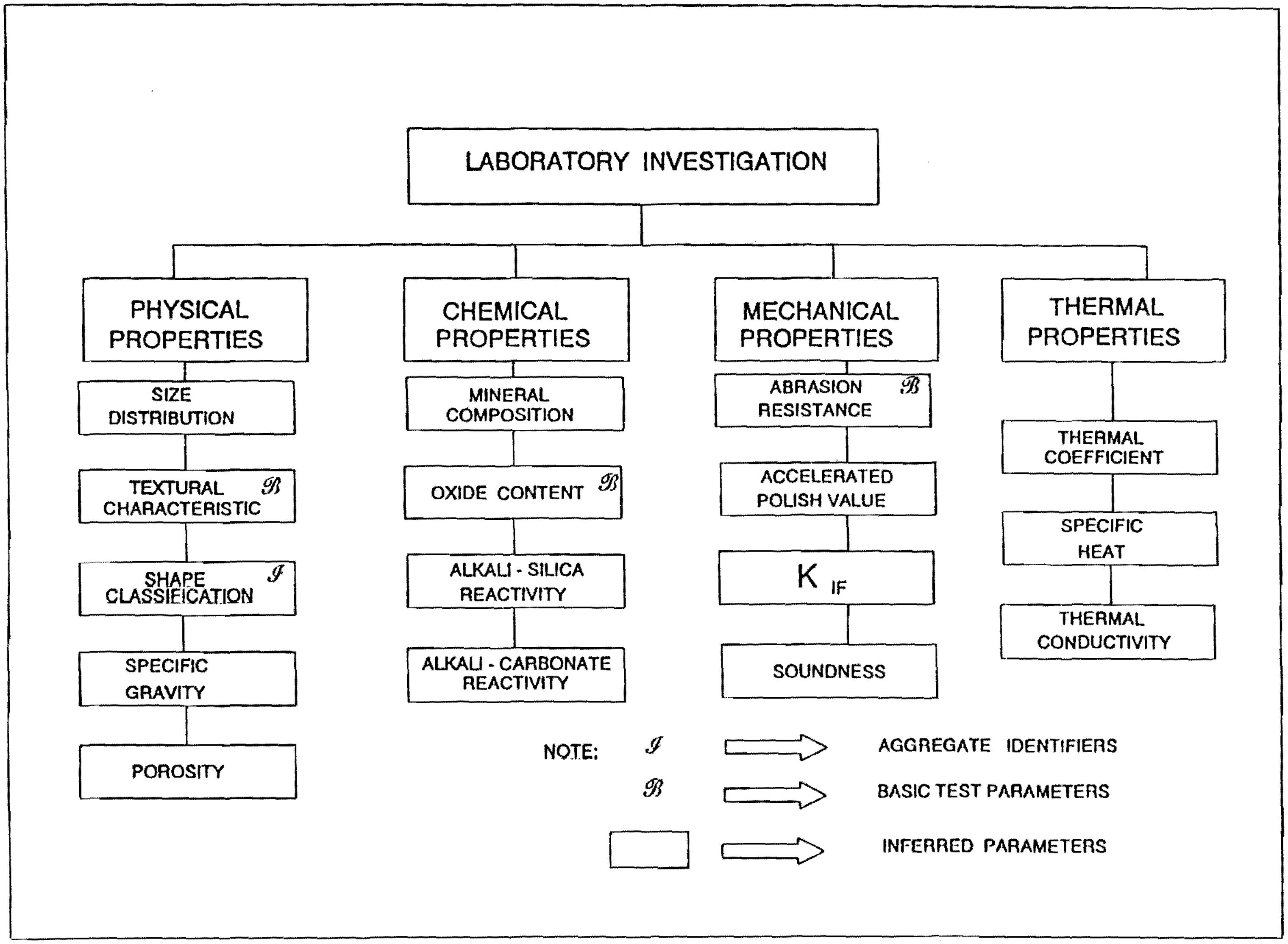


Figure 4.3. Classification of Aggregates Based on Laboratory Examination.

Aggregate Identifiers

Aggregate identifiers can be defined "as those aggregate parameters which identify the aggregate". These are the parameters which provide the ultimate classification of the coarse aggregates based on this classification system. Hence, these are referred to as "Designators". The properties which are classified under this category are:

- Shape Classification,
- Aggregate Type Classification, and
- Surface Type Classification.

Classification of aggregate identifiers is shown in Figure 4.4. The above mentioned properties correspond to the subgroup designations LP-3, V-3, and V-2, respectively.

Based on shape, aggregates are further classified into standard shapes of aggregates, namely, Cubic, Disc, Bladed and Rod. Shape classification identifiers are designated C, D, B, R respectively.

Aggregate type classification helps in identifying the geologic origin of the aggregates. It is further classified into Igneous, Sedimentary and Metamorphic rock types. These are designated by I, S and M respectively.

Surface type classification essentially helps in identifying the aggregate based on whether the aggregate is crushed or uncrushed. These identifiers are designated as C and U, respectively. A typical classification of aggregate based on this classification system is "DSC", where D corresponds to the Disc shape of the aggregate, S refers to the sedimentary origin of the aggregate and C suggests that the aggregate in question is crushed. This classification is represented more explicitly in the attached appendix.

Basic Test Parameters

Basic test parameters can be defined as the "aggregate parameters which provide detailed information with regard to the properties of the aggregate which may be correlated to the performance of the aggregate under a given set of conditions" These are referred to as "Modifiers". The properties which have been classified under this category are as follows:

- Textural Characteristic,
- Oxide Content, and
- Abrasion Resistance.

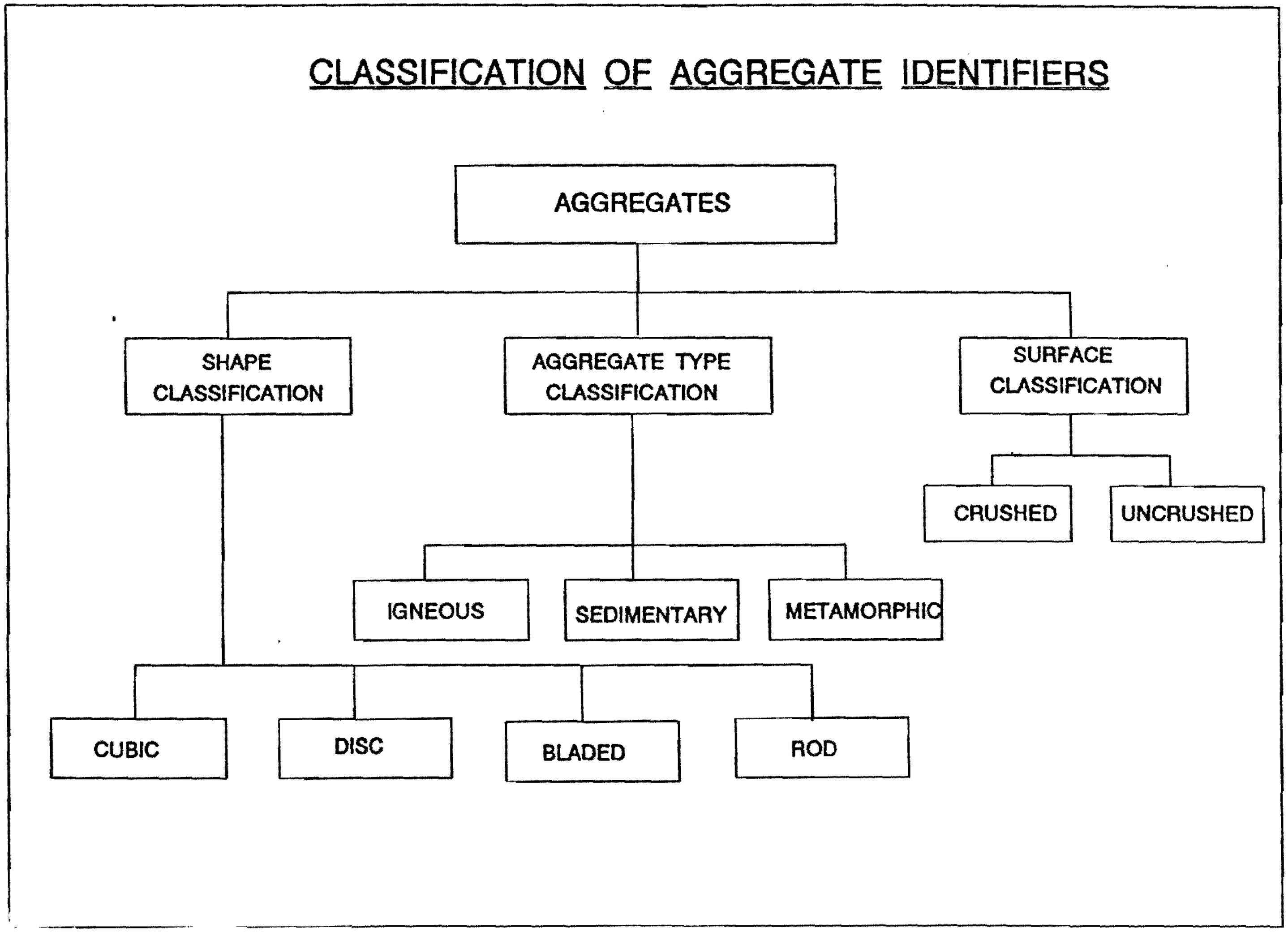


Figure 4.4. Classification of Aggregate Identifiers.

The classification of basic test parameters is shown in Figure 4.5. These properties correspond to the subgroups designated by LP-2, LC-2, and LM-1. Fractal Dimension analysis can be carried out on aggregates and their textural characteristics can be classified as smooth, medium or rough. Chemical analysis of aggregate samples can be performed by using the technique of atomic emission spectroscopy, from which the percents of various oxides can be quantitatively determined. Since the concrete properties are more influenced by the mineralogy of the aggregate, by using stoichiometric analysis, the original mineral composition can be back calculated from the determined oxide contents present in the aggregates. CHEM 2 a computer model, has been developed by Dossey et al. (35) at the Center for Transportation Research at the University of Texas at Austin, which does the back calculation of mineral composition. The abrasion resistance of coarse aggregates can be determined by using the L.A abrasion machine and the results can be used to classify the abrasion resistance of aggregates as high, medium and low. Test procedures and equipment required for performing these basic tests are dealt within Chapter VI.

Inferred Parameters

These are the properties which were not classified under either of the above two categories. They can be defined as the "properties which are a part of the aggregate classification system, but are inferred from the designated basic tests." This category consists of all the tests on aggregates which are very exhaustive to run and are time consuming. For example, alkali-silica reactivity (ASR) and alkali-carbonate reactivity (ACR) are significant chemical characteristics, but these tests require extensive setup time and need more time to be carried out. It is anticipated that these characteristics may be inferred from the basic test on oxide content, which is not only simple, but also provides information regarding the presence of silica and carbonates in the aggregates. If this test determines that excess quantities of silica or carbonates are present, based on need, either standard tests on ASR and ACR can be carried out on the aggregates.

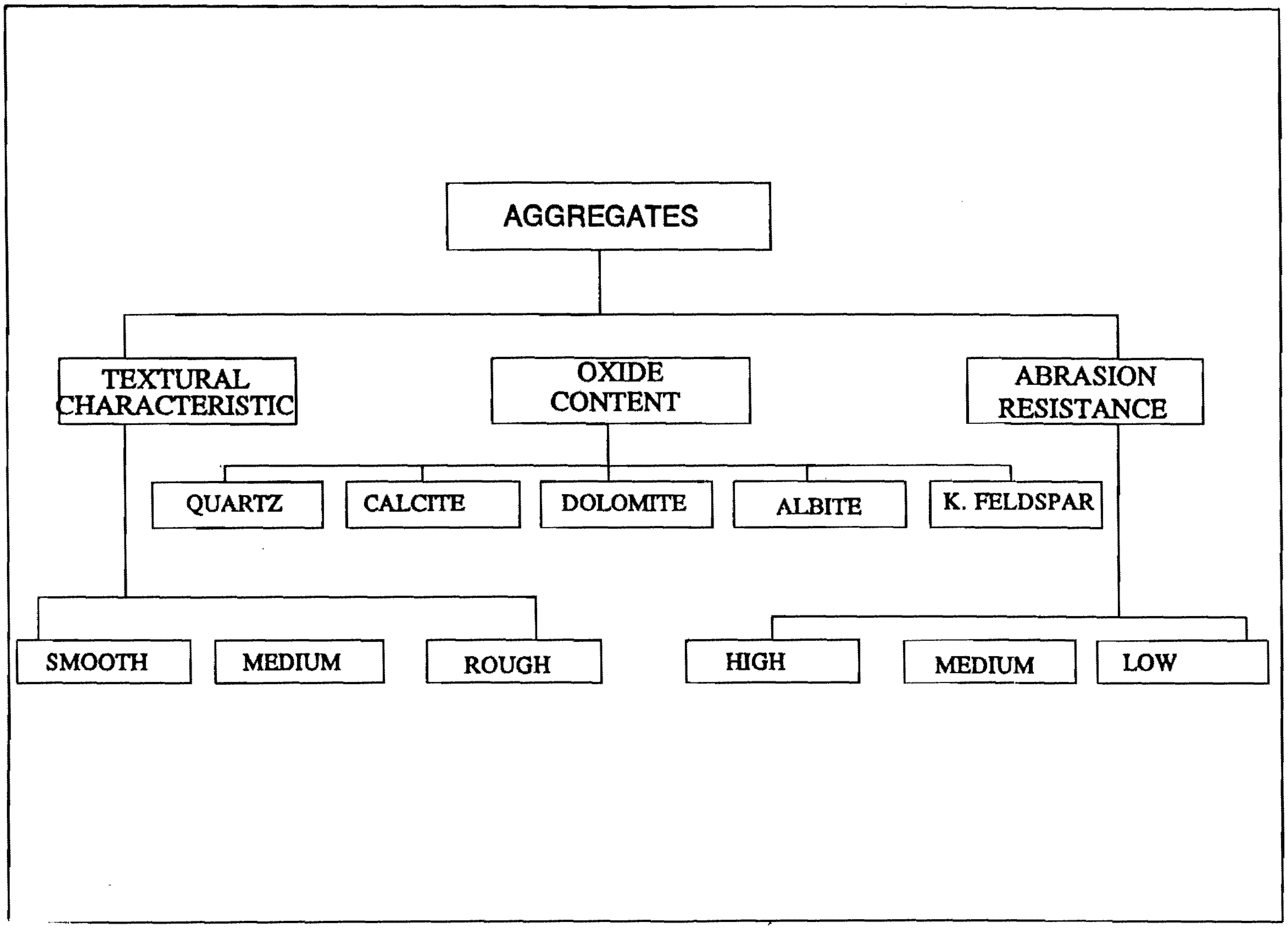


Figure 4.5. Classification of Basic Test Parameters.

4.5 SIMPLIFIED FORMAT OF THE AGGREGATE CLASSIFICATION SYSTEM

As the classification system presented in the previous pages is not only complex but also impractical for implementation, a simplified format of the classification system is suggested. This version of the classification system consists of 6 essential tests to be carried out on aggregates. These tests are simple and provide the required information quickly, thus making the classification system more implementable. Figure 4.6 shows the aggregate identifiers and basic test parameters and the suggested test methods for their evaluation. These properties represent the most important parameters in evaluating the performance of the aggregates to be used in the construction of highway pavements. Aggregate type and surface type can be evaluated by visual examination of the aggregates and a knowledge of physical geology. Shape and texture analysis of aggregates can be performed using the technique of fractal analysis. The suggested test for oxide content evaluation of the aggregates is based on the technique of atomic emission spectroscopy. The simplified version of the aggregate classification system is expected to provide guidelines for studying the behavior of aggregates when used in highway pavements or other structures. This system is also expected to assist in both field and laboratory evaluation of coarse aggregates. The major steps involved in the aggregate evaluation, based on the proposed aggregate classification system, are shown in Figure 4.7.

The other significant characteristics of this classification system are: the level of difficulty in carrying out the tests in the laboratory increases from (a) left to right and (b) top to bottom. This can be more explicitly understood from Figure 4.8. The level of difficulty increases from V-1 to V-3 under visual examination, i.e., examination of subgroup V-1, which is nominal maximum size, is relatively easier than subgroup V-2 (surface type), which is easier than V-3 (aggregate type). Similarly, under laboratory investigation, evaluation of all subgroups follow the same trend. Also, as we move from left to right, the level of difficulty increases, i.e., from visual examination to laboratory examination. The level of difficulty is gauged based on (a) duration of the test; (b) type of equipment required; and (c) complexity of the test.

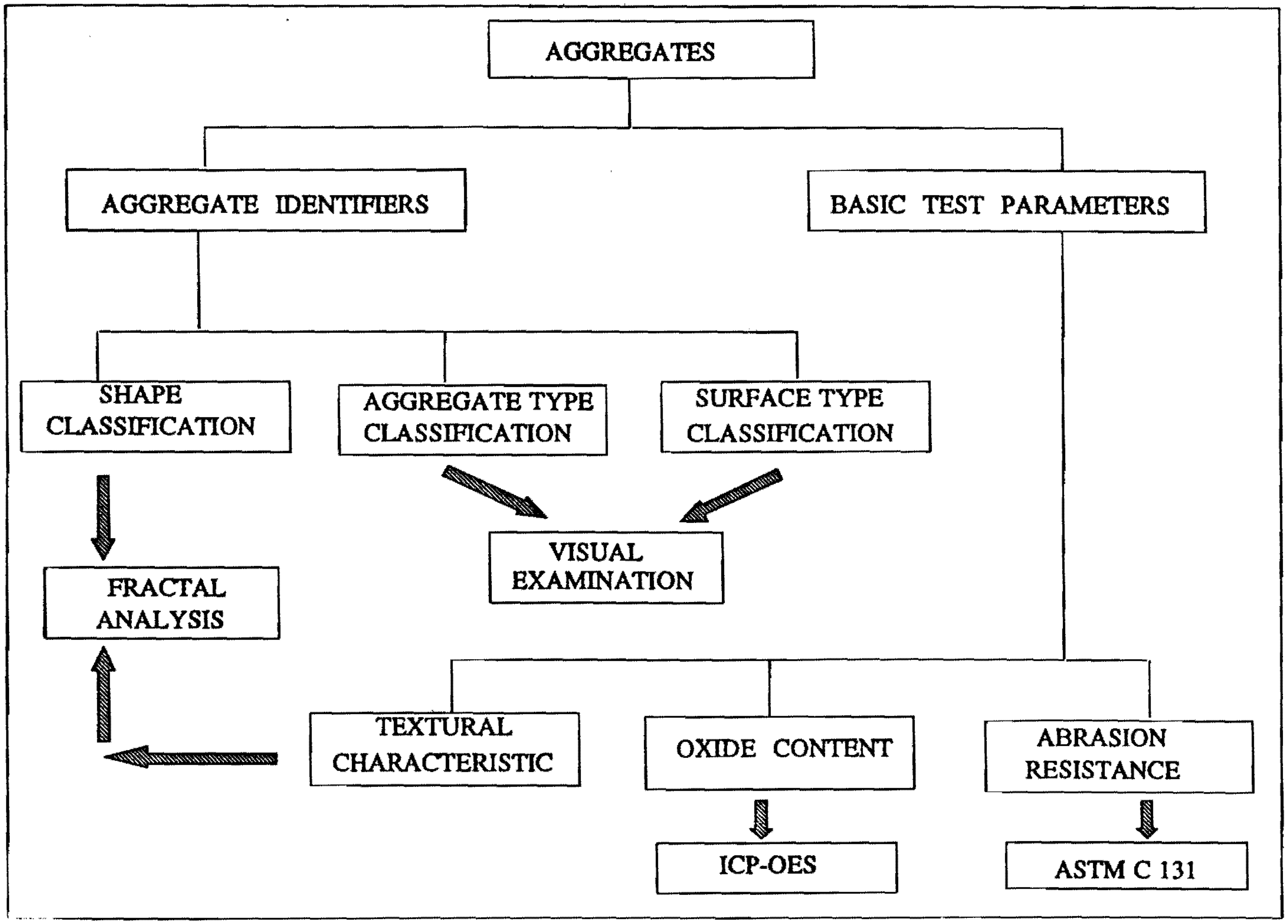


Figure 4.6. Simplified Format of the Aggregate Classification System.

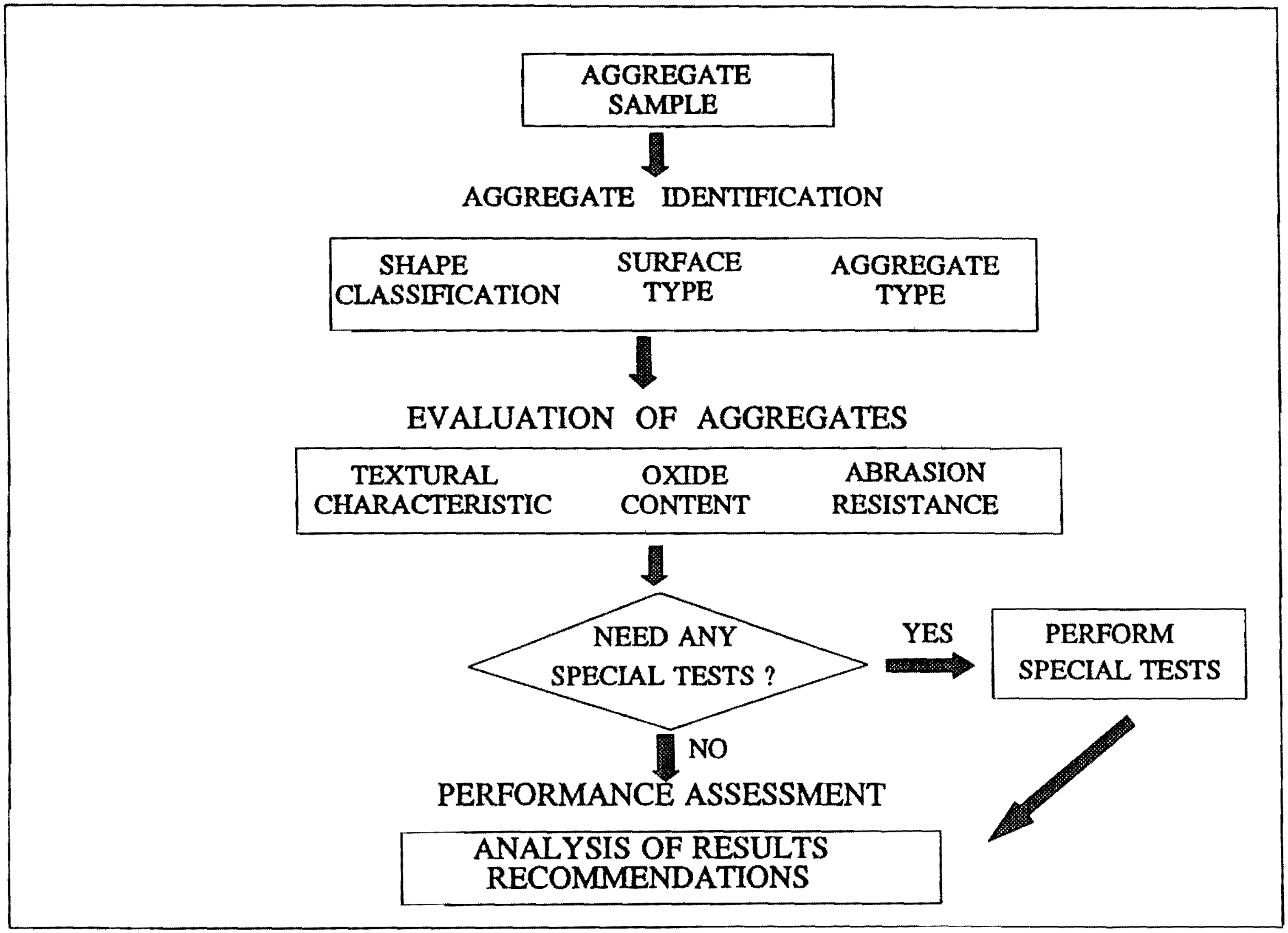


Figure 4.7. Major Steps Involved in the Performance Assessment of Coarse Aggregates Based on the Aggregate Classification System.

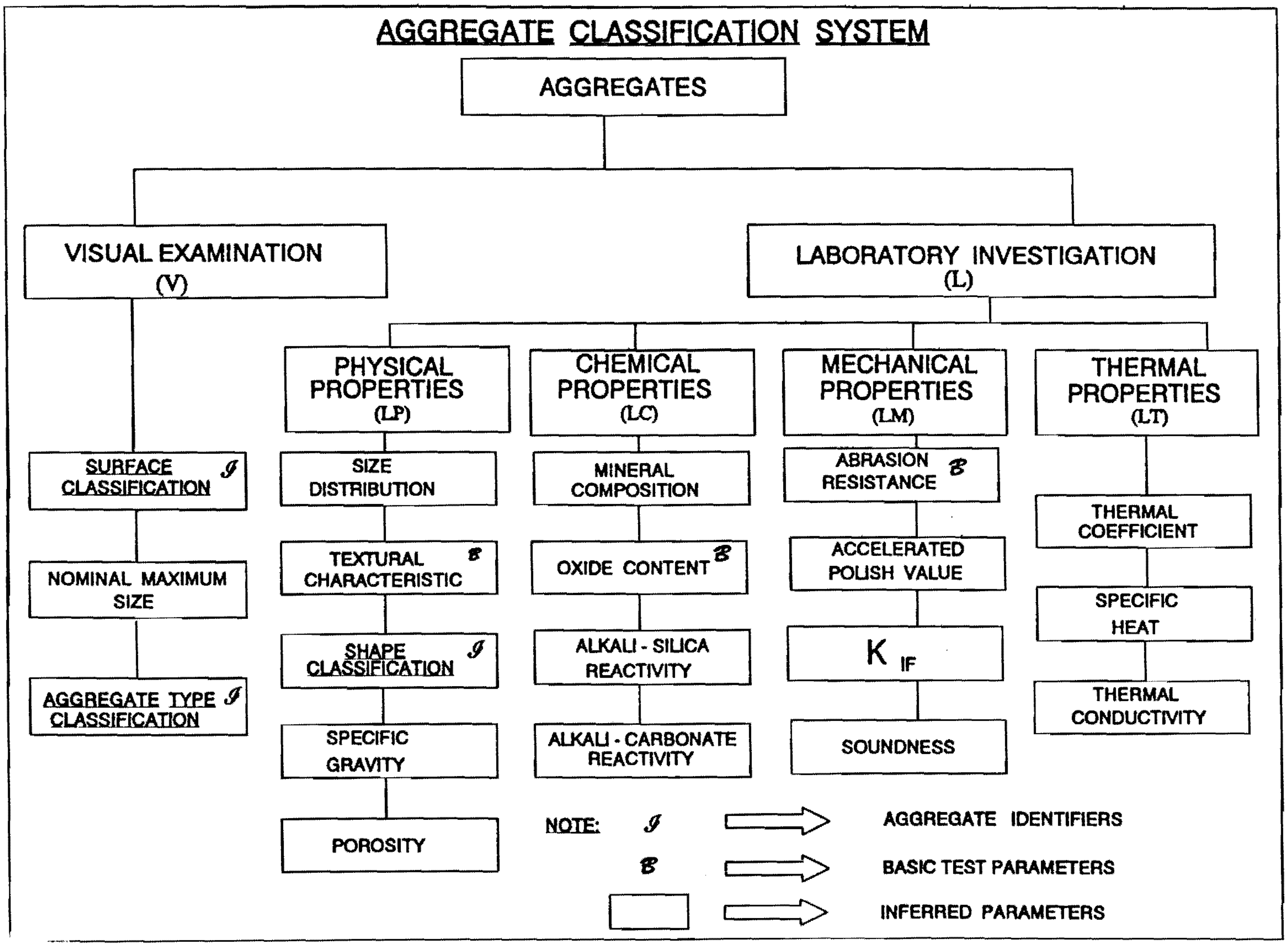


Figure 4.8. Complete Structure of the Proposed Coarse Aggregate Classification System.

CHAPTER 5 : BASIS OF AGGREGATE CLASSIFICATION SYSTEM IMPLEMENTATION

Various field and laboratory studies which have been carried to evaluate the influence of aggregate type on the performance have been discussed in this chapter. Based on the results of these studies, an effort has been made to develop guidelines for the implementation of the proposed aggregate classification system which are presented in the later part of this chapter.

5.1 FIELD INVESTIGATIONS

As a part of this research project, various field studies have been conducted in the form of concrete pavement test sections at different locations in the state of Texas. These test sections were primarily aimed at studying the factors that affect the performance of pavements. The first field investigation was carried out on FM 559, Texarkana, Texas, where a jointed plain concrete pavement section of 13 inches thickness was constructed in the month of October, 1991. Among other factors, the effects of aggregate type and gradation on the behavior of jointed concrete pavement were investigated and the results documented. The five different mix designs which were used in that field study are presented in Table 5.1.

The aggregate types in the above table are represented by "SRG" and "LS" for siliceous river gravel and limestone aggregate, respectively. The aggregate type, percent, and size for each mix design are shown in Table 5.1. Mix design 1 was the control mix and did not contain any intermediate (medium size particles) aggregate. In all other mixes, buckshot was added as an intermediate aggregate to the aggregate gradation. The main purpose of addition of intermediate aggregate is to fill the "gaps", which are essentially the voids between coarse aggregates in the mix. These aggregates, on account of their medium size, can occupy these spaces between coarse aggregates and thus decrease the volume of voids in the concrete. The effect of addition of intermediate aggregate was studied by evaluating the cored specimens from the pavement sections of different mix designs. The elongation and spacing of air pockets were measured by linear traversing and the level of honey combing was identified for

Table 5.1. Different Mix Designs Used in Texarkana Test Section (36).

Mix Design No.	Coarse Aggregate	
	Type	Size
1 (Control Mix)	SRG(100%)	1-1/2"
2	LS (50%) SRG (50%)	1-1/2" 3/4"
3	SRG (100%)	1-1/2"
4	SRG (100%)	3/4"
5	LS(100%)	1-1/2"

each cored specimen. The cored specimens containing intermediate aggregate showed lower percentages of air pockets indicating the low severity of honey combing. Also, it was reported that placement of concrete was relatively easier with the mix containing intermediate aggregate, which can probably be attributed to the improved workability caused by the intermediate aggregate. Mix design 2 was used to examine the effect of aggregate blending on the properties of concrete. Siliceous river gravel of different sizes were used in mixes 3 (aggregate size: 1 1/2") and 4 (aggregate size: 3/4") and limestone aggregate was used in mix 5. Thus, these mix designs were developed to evaluate the effect of aggregate size, type, and blending on the crack development in the pavement. Both conventional and early-aged saw cutting techniques were used for studying the crack development at longitudinal and transverse joints. The depth used for early-aged sawcut was 1 inch, whereas the conventional technique used a depth of D/4 or about 3 inches. Crack surveys were done to observe the pattern of crack formation at the desired locations (i.e., sawcut locations) and at any other locations. The surveys showed that the sections with river gravel coarse aggregates showed higher likelihood of crack formation at the sawcut locations than the sections with limestone aggregates (36).

Concrete properties such as compressive strength, flexural strength, and fracture toughness were tested for beam specimens that were prepared in the field. These tests were conducted to investigate the effect of different coarse aggregate characteristics on the behavior of concrete. The average flexural strength and compressive strength for all the mixes at the age of seven days and the fracture parameters for mixes 3, 4, and 5 at 1-day concrete age are tabulated in Table 5.2 (36). From Table 5.2, it can be observed that the mix with 100 % crushed limestone (mix 5) showed higher flexural and compressive strength than mixes 3, 4, and 5. On the other hand, mix design 2, which consisted of 50% river gravel and 50% limestone, exhibited higher compressive strength but lower flexural strength than mix 5. Although mixes 3 and 4 had same the intermediate and fine aggregate, mix 3 showed higher compressive strength and flexural strength than mix 4. This can probably be attributed to the larger size of coarse aggregate used in mix 3. However, the compressive strength of mix 4, which contained smaller size river gravel (3/4") than mix 1 (1-1/2"), was higher than that of mix 1. The higher compressive strength of mix 4 may have been a result of improved gradation by the addition of intermediate aggregate. The coefficient of variation for flexural strength was found to be in the range of 3.8 to 6 % and for compressive strength, it was in the range of 0.6-5.9 %. The variation of compressive strength of different mixes with age is shown in Figure 5.1.

Table 5.2. Various Concrete Properties of Specimens Prepared with Different Mix Designs at Texarkana Test Section (36).

Mix Design No.	Average Flexural Strength @ 7 Days (psi)	Average Compressive Strength @ 7 Days (psi)	Fracture Toughness Parameter ($psi\sqrt{in}$)
1	662	4235	-
2	805	5945	-
3	693	5155	717
4	662	4380	687
5	841	5685	827

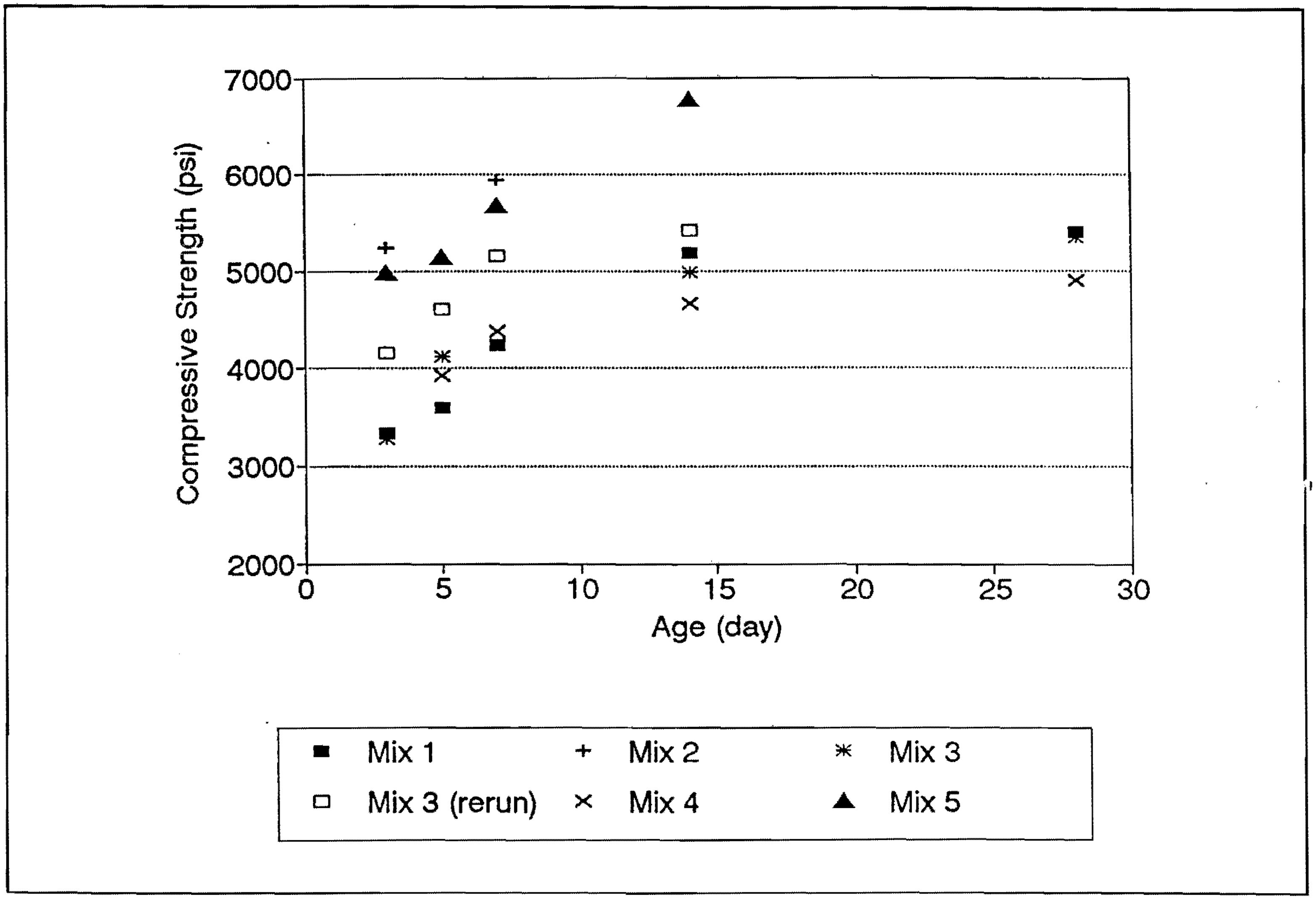


Figure 5.1. Compressive Strengths of Concrete Specimens at Texarkana Test Section.

Fracture toughness was measured by determining fracture parameters based on a nonlinear fracture model for concrete (size effect law), which suggests that fracture occurs in concrete in a nonlinear fashion. Three point bending tests were carried out on beam specimens of 1-day age and two fracture parameters, K_{If} - critical stress intensity factor and C_f -effective critical crack increase, were determined. As shown in Table 5.2, the critical stress intensity factor for mix 5 was the highest and was lowest for mix 4. The mix containing crushed limestone showed a higher K_{If} value than specimens made with different sizes of river gravel aggregate (36). Thus, it can be reasonably concluded from these results that the aggregate type, size and gradation affect the concrete material properties such as compressive strength, flexural strength and fracture toughness.

The variations in concrete material properties caused by different aggregate types can be attributed to the chemical composition of the aggregate, its shape and texture, and the bond of the aggregate. Characterization of these properties could provide additional information to observe the variation in these properties caused by different aggregates and would provide for a better understanding of the crack propagation in concrete pavements.

While the Texarkana test section was constructed in cool weather (November 1991; average temperature: 70°F), the next field study was conducted in summer (August 1992; average temperature 95°F) in Cypress, Texas, on Highway 290. The layout of this test section is shown Figure 5.2. The primary aim of this field study was to examine the factors that affect the cracking behavior of Continuously Reinforced Concrete (CRC) pavement and to develop some guidelines for concrete pavement construction under hot weather conditions. Four different mix designs were used in Part I-A and Part II of this test section, shown in Figure 5.2. Specimens were prepared from these different mixes and were tested for compressive strength and flexural strength. The four mix designs and their corresponding values of concrete properties at 28-day age are summarized in Table 5.3. It can be seen from Table 5.3 that the flexural strength of concrete made with 100% river gravel shows higher flexural strength than one made with 100% limestone. However, the compressive strength is highest for the concrete specimen made with 100% limestone.

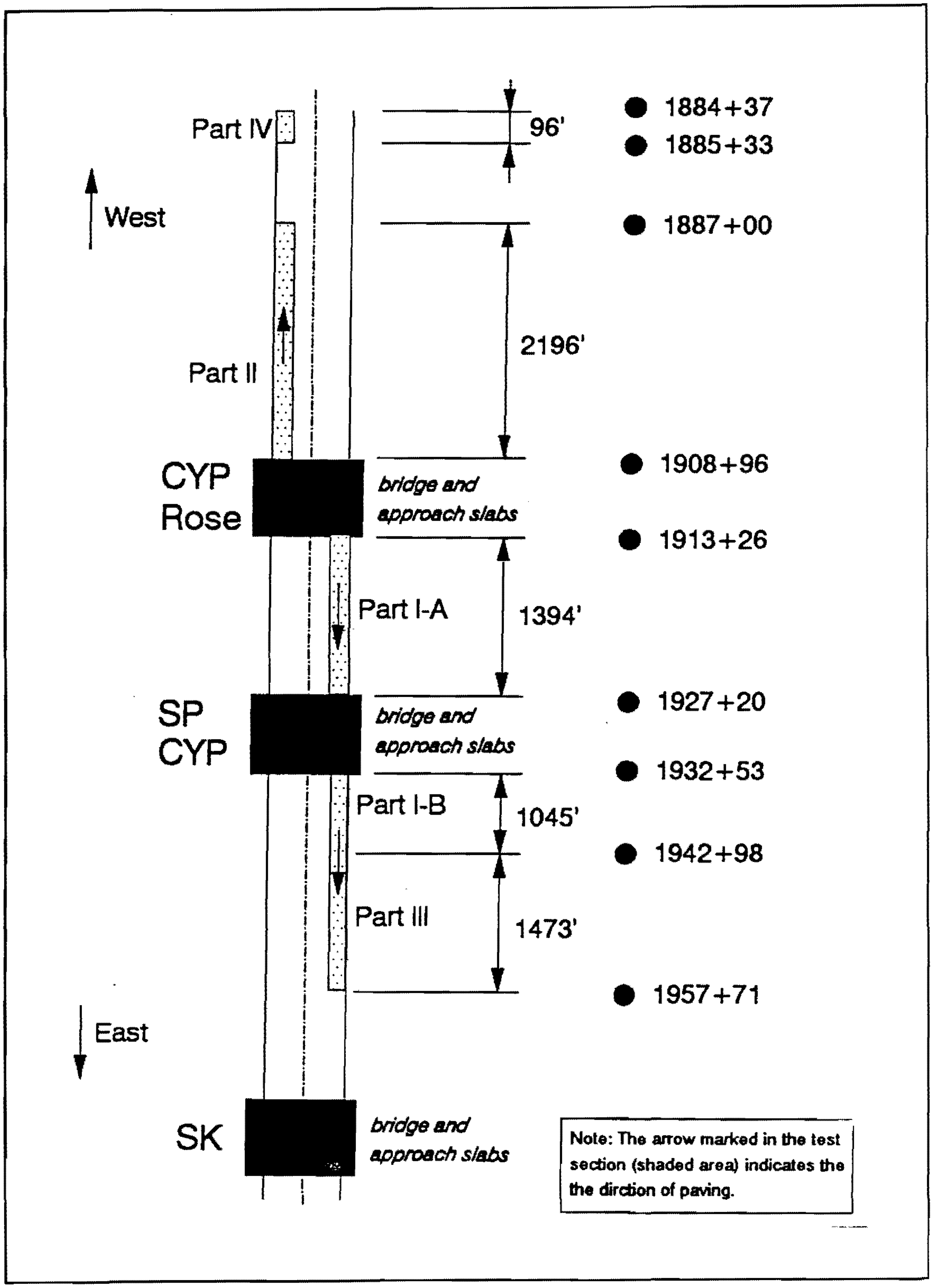


Figure 5.2. Layout of Cypress Test Section.

Table 5.3. Observed Material Properties at Cypress Test Section.

Mix Design	Aggregate Type	Flexural Strength @ 28 days (psi)	Compressive Strength @ 28 days (psi)
1	100% LS	799	6790
2	67% LS, 33% SRG	818	5625
3	33% LS, 67% SRG	769	5395
4	100% SRG	843	6005

Concrete specimens made with aggregate blends showed different results than the ones made with single aggregate. This can be better explained with the aid of Figure 5.3, where the variation of flexural strength of concrete made with different proportions of river gravel and limestone aggregates with age is illustrated. This figure indicates that mix 3, which contained a higher percentage of river gravel, showed higher initial strength but a low final strength, whereas mix 2, containing about 33% river gravel, showed a consistent increase in strength with age. This suggests the importance of further research on aggregate blends on the performance of concrete pavements.

An extensive crack survey was carried out to investigate the influence of aggregate type on crack initiation and subsequent growth in the pavement. The study revealed that the section which had concrete made with a higher percentage of river gravel had less uniformly distributed cracks and the average crack spacing was found to be smaller than the pavement section where a relatively higher percentage of limestone was used. This is illustrated in Figure 5.4. Also, the siliceous river gravel sections had higher average crack width than corresponding limestone sections. The crack development pattern of the siliceous gravel sections could probably be attributed to their higher thermal coefficient than the limestone coarse aggregate (35). Figure 5.5 shows the variation of average crack density with percent of river gravel coarse aggregate in concrete used in two parts of the test section. The regression fits of the average crack density values show the linear variation with the increase

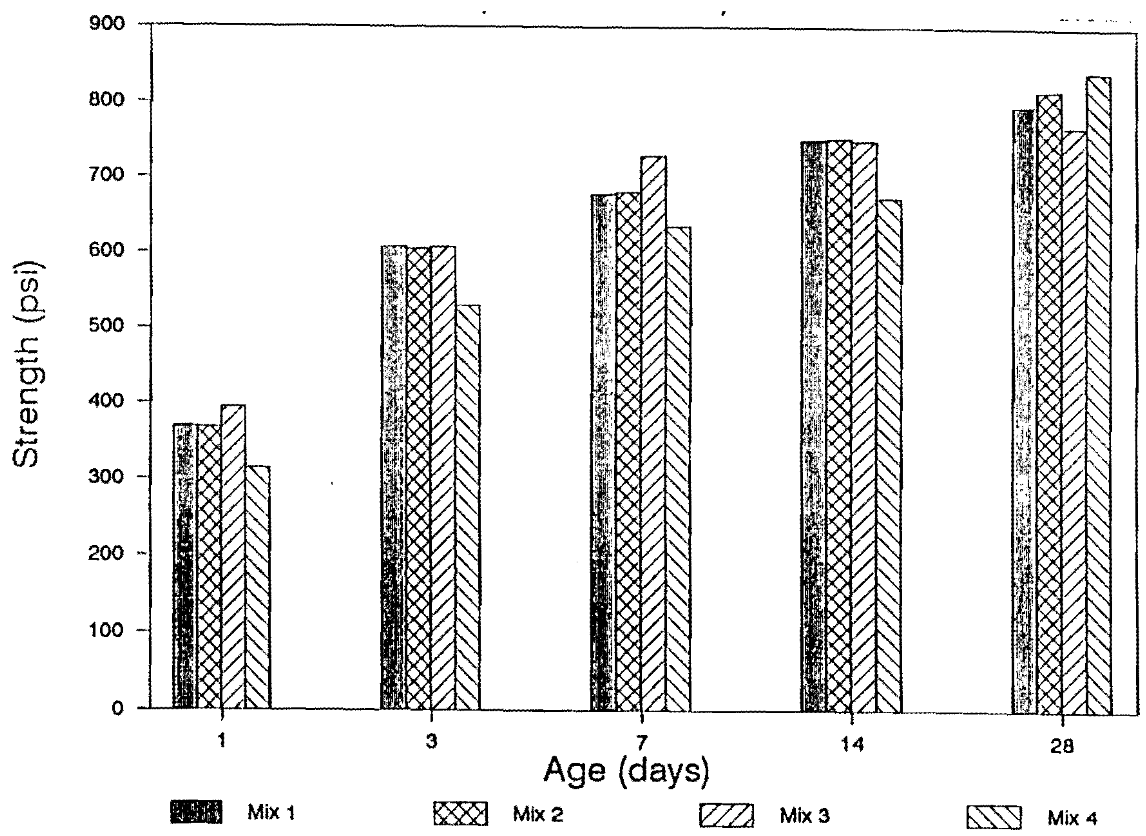


Figure 5.3. Flexural Strength vs. Age of Concrete for Different Mix Designs Used in Cypress Test Section.

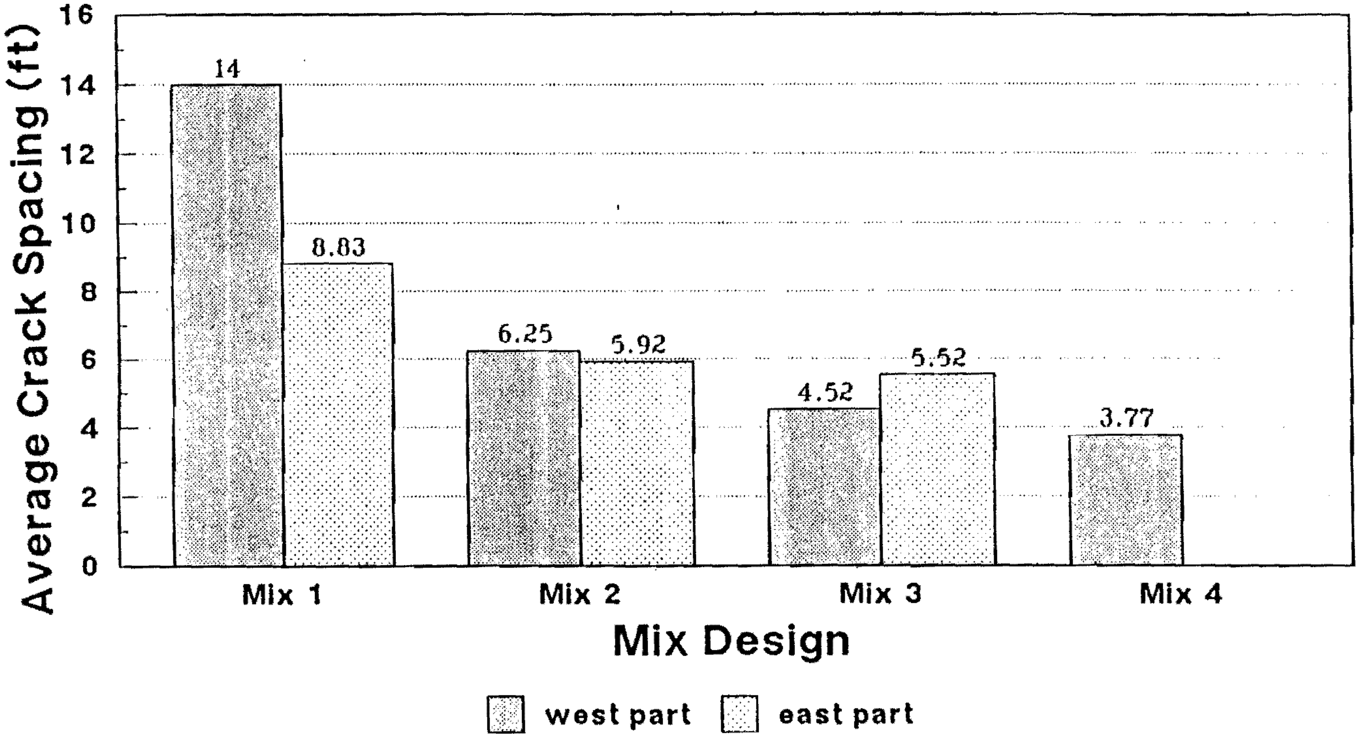


Figure 5.4. Variation of Average Crack Spacing for Different Mix Designs Used in Cypress Test Section.

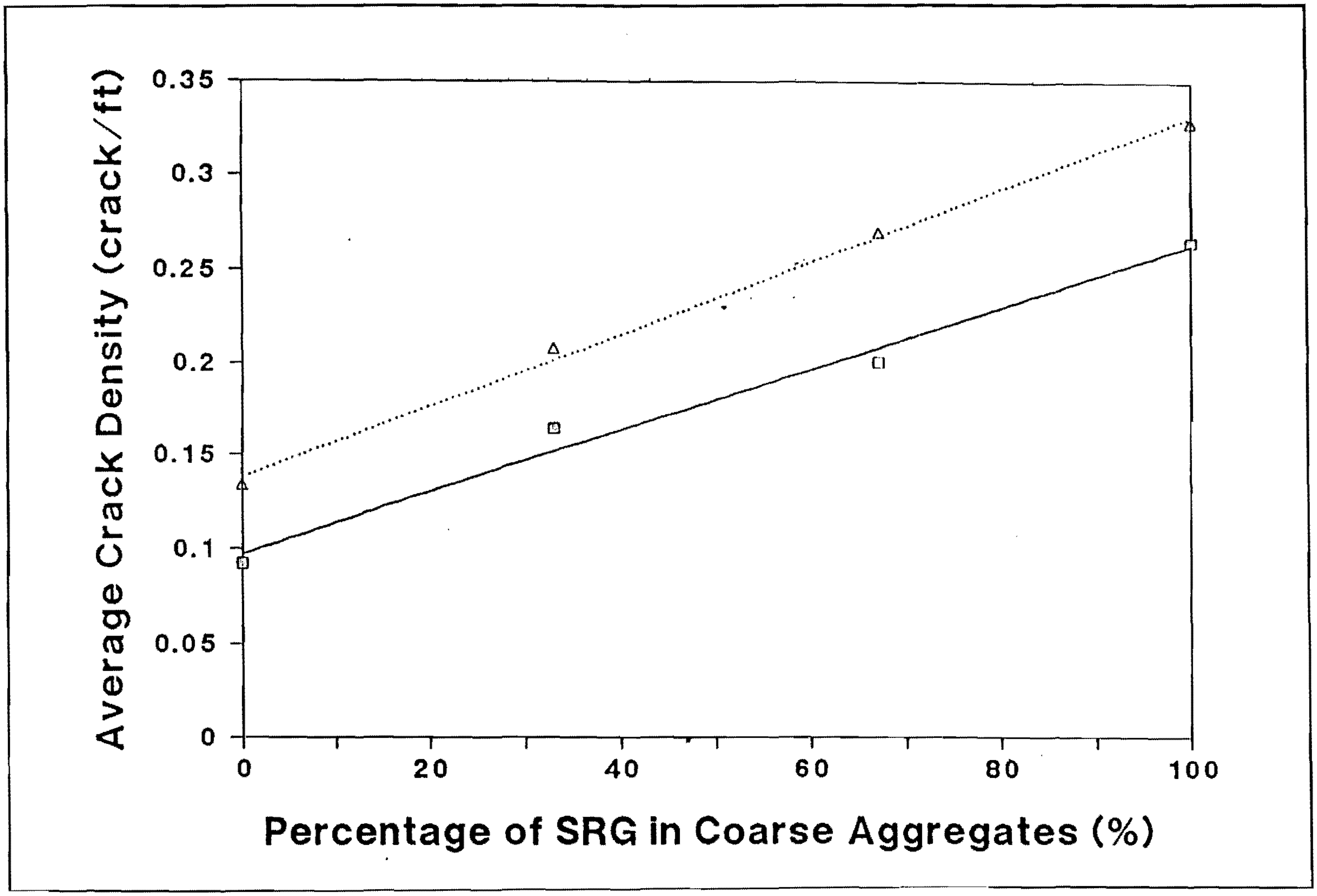


Figure 5.5. Average Crack Density (crack/ft) vs. Percent of River Gravel in Coarse Aggregates Used in Cypress Test Section.

in the percent of river gravel coarse aggregate. This can be explained by the fact that the higher river gravel content causes higher thermal expansion, resulting in the development of cracks under high temperatures, such as 90°F, prevalent at the time of construction of the Cypress test section. This figure explains the importance of characterization of aggregate type for developing effective crack control guidelines.

5.2 LABORATORY STUDIES

A part of this research study, conducted at the Center of Transportation Research, University of Texas at Austin, concentrated on the laboratory evaluation of the effects of aggregate blends on the properties of Portland Cement Concrete. Specimens made with blended aggregate and single aggregate were tested for compressive strength, modulus of elasticity, splitting tensile strength, and linear shrinkage. The comparison of results showed a linear relationship between concretes made with single and blended aggregates (32). This study suggested that the properties of concrete made with blends of aggregates would vary depending on the aggregate type and proportion.

Dossey et al. (35) have performed extensive chemical composition studies on aggregates which include determination of principal mineral composition by X-ray diffraction and oxide residue analysis. Oxide based models were developed with the results obtained from this project. A computer program, CHEM 1, was developed which required the percent by weight of four oxides, namely, CaO, MgO, Al_2O_3, and Fe_2O_3 as inputs to predict the tensile strength, compressive strength, modulus of elasticity and drying shrinkage of concrete. The idea behind this model was to provide the user with a rough prediction of material properties of concrete made with a particular type of aggregate. The ultimate purpose was to use these concrete material properties to determine design parameters such as the bar size, and steel percent using another computer program, CRCP, so as to obtain the desired level of performance.

As the oxide contents in aggregates are proportional to various minerals, these models were further modified so as to develop models that are directly based on mineral composition. Stoichiometric analysis was used to back-calculate the mineral composition from the determined oxide contents. A modified version of the CHEM 1 program has been developed which requires percent by weight of minerals, namely, Quartz, Calcite, Dolomite, Albite and

Potassium Feldspar. Regression models that were developed for various concrete material properties are listed below (35).

$$f_c \text{ (psi)} = e^{8.943} * (\text{Calcite})^{-0.086} * (\text{Quartz})^{-0.072} * (\text{Dolomite})^{-0.021} * (\text{FS})^{-0.033}$$

$$f_t \text{ (psi)} = 1298-8.87 * (\text{Calcite}) - 8.089 * (\text{Quartz})-7.45 * (\text{Dolomite})-49.8 * (\text{PF}) + 16.6 * (\text{Albite})$$

$$E(\text{psi, millions}) = e^{1.115} * (\text{Calcite})^{-0.0087} * (\text{Quartz})^{0.021} * (\text{Dolomite})^{0.088} * (\text{FS})^{-0.101}$$

The CHEM 2 program also predicts the thermal coefficient of expansion and the regression model for thermal coefficient was (35):

$$\alpha_c = e^{1.098} * (\text{Quartz})^{0.486} * (\text{Calcite})^{-0.106} * (\text{Dolomite})^{0.415} * (\text{PF})^{-2.37} * (\text{Albite})^{1.635}$$

These models were used in computer program CHEM 2 to predict the material properties of concrete. The oxide content test is a quick test and the results obtained from this test can be conveniently used to predict the performance of aggregates prior to their use in the field (35).

Another important characteristic of coarse aggregates which needs to be evaluated before their selection is the chemical reactivity. Presence of deleterious minerals in aggregates can cause alkali-aggregate reactivity in concrete. Extensive studies have been carried out to study the causes of alkali-silica reactivity and alkali-carbonate reactivity. It has been determined that the existing test procedures (ASTM C-289 and ASTM C-227) for detecting deleterious aggregates have often been ambiguous in the sense that slow reactive aggregates such as quartzites, gneisses, and schists, which have been found to be innocuous in the laboratory tests, have caused failures due to alkali-silica reactivity in field structures (37).

Various research studies conducted under the Strategic Highway Research Program (SHRP) reflected that the existing test procedures are not only time consuming but also very permissive in identification of "deleterious" or "innocuous" aggregates. For example, aggregates such as quartz, quarried granite, quarried granite, chert, quartzite were classified as "slow reacting" when tested as per ASTM C-289 but these aggregates were found to be associated with alkali-silica reactivity when used in concrete structures. Conversely, aggregates which have been found to be susceptible to deleterious reactivity did not indicate development of alkali-silica reactivity. This can be attributed to the low alkali cement that may have been used which impedes its development. Similar results were reported when these tests were reported as per ASTM C-227. Thus, these studies stressed the need for development of a quick and a reliable test method for identifying deleteriously reactive aggregates (37).

A rapid immersion test, originally developed in South Africa, was found to be a suitable test procedure to identify aggregates based on the measured expansion of mortar bars after 14 days of testing. This test procedure essentially consists of mortar bar preparation as per ASTM C 227, immersion of these bars in water at 80 °C for 1 day and then in 1N NaOH solution for 14 days, and measurement of comparator readings (37). The other form of alkali-aggregate reactivity is the alkali-carbonate reactivity, but this is reported to be less frequent than the alkali-silica reactivity. The reaction mechanism is similar to that of alkali-silica reactivity. The aggregates which are rich in minerals such as dolomite, calcite and illite are susceptible for causing this carbonate reactivity. This can be determined as per ASTM C-586 test procedure (38).

Thus, these test procedures evaluate the deleterious nature of the aggregates based on which recommendations can be given for the use of low alkali cement which inhibits the development of alkali-silica reactivity or alkali-carbonate reactivity in the field.

5.3 GUIDELINES FOR IMPLEMENTATION OF CLASSIFICATION SYSTEM

The guidelines for implementation have been drawn based on the laboratory and field studies conducted as a part of this research study and other studies conducted to determine the reactive aggregates.

As explained in Chapter IV, different types of physical, chemical, mechanical and thermal properties that make up the classification system are divided into three categories, namely, Aggregate identifiers, Basic test parameters, and Inferred parameters. These were categorized in view of the difficulty in implementing an exhaustive aggregate classification system. It is recommended that the proposed classification system be implemented at three levels based on the type of information required on the aggregate and required level of accuracy. Before implementing the classification system, based on the location of the project, functional importance and type of structure, the potential problems associated with the aggregates should be determined. Based on this assessment which assists in arriving at a specific level of accuracy of information required, the implementation of the classification system should be carried out accordingly.

The first level of implementation consists of evaluation of aggregate properties and physical geology as identified and grouped under "Aggregate Identifiers". This includes a qualitative appraisal of aggregates with respect to their Shape, Aggregate Type and the Surface Type. These properties will serve to identify the aggregate and would provide information regarding the parent rock of the aggregate being evaluated. The information obtained from this evaluation could be used to understand other properties of aggregates and the performance level can be specified. Evaluation of these properties is expected to provide a precise identification of the aggregates. This would be the first level at which the aggregate classification system could be implemented, which essentially consists of visual examination of the aggregates from a stock pile. Knowledge of physical geology for aggregates can be supplemented by use of reference 44.

The next level of suggested implementation of the aggregate classification system would involve a more detailed investigation of the aggregates. It entails laboratory evaluation of aggregates so as to predict their performance. The tests which need to be carried out for this evaluation include the oxide content, abrasion resistance and the texture of the aggregates. The oxide content test is expected to provide a thorough chemical analysis of the aggregates. Various oxides present in the aggregates can be determined from this test and the dominant minerals present in the aggregates can be back calculated using stoichiometric analysis. This information would assist in predicting the thermal expansion of the aggregates. The abrasion resistance would provide information pertaining to the hardness or toughness of the aggregates and the textural characteristic would furnish the roughness of the aggregate. The surface texture can be used as a basis to interpret the skid resistance of the aggregates. Though this level of implementation is more time consuming than the first level, the suggested tests are quick and provide necessary information and would greatly assist in the performance assessment of the aggregates.

The first two levels of aggregate classification system not only render a comprehensive identification and evaluation of the aggregates but also provide the highway engineers with a tool for effective selection of suitable aggregates for various projects. A third level of implementation of the classification system is suggested only if aggregate evaluation of greater detail and accuracy is warranted. This level would essentially involve evaluation of only those properties which require a detailed investigation. For example, if the basic tests which are included in the second level of implementation suggest presence of some deleterious minerals which would promote Alkali-Silica reactivity in the aggregate being investigated, a more detailed evaluation of Alkali-Silica reactivity can be done based on the suggested test procedure in the basic structure of the classification. These tests would be specific, more time consuming, involve higher costs and would need more complex equipment.

The first two levels of implementation of these recommendations should be carried out in a phased manner and effort should be made to study the aggregate properties in the first two levels carefully and develop patterns by which more complex aggregate properties can be inferred from these properties. Though the third level is not easily implementable, it does assist in either confirming or negating the results obtained from the first two levels.

5.4 RELATION OF AGGREGATE PROPERTIES TO PERFORMANCE

This section is intended to summarize the aggregate test parameters as they relate to the performance. The test parameters included in the classification system relate to the performance in the sense that the information provided by these tests would help the engineers using this system in arriving at definite conclusions regarding the performance of aggregates in the field. Trial field implementation would help in correlating the performance of different aggregate types to the overall performance of the pavements or other structural systems.

The Texarkana test section provided some interesting results relating to the contribution of aggregates to the performance of pavement and these results are used for an explicit explanation of the relation of aggregate tests to performance. FWD testing was conducted on various joints and cracks to evaluate the load transfer efficiency across joints and cracks in sections made with different coarse aggregates. The results showed that the concrete made with river gravel aggregates caused higher LTE values and effective stiffness, indicating high load transfer across those joints. This information directly relates the aggregate properties to performance. The better load transfer of river gravel concrete joints can be understood by studying the fracture behavior of concrete made with different aggregate types. The fracture toughness of river gravel concrete was higher than that of limestone concrete which indicates that river gravel is hard (36). Figure 5.6 shows the variation of load transfer efficiency versus type of mix design. The examination of fracture toughness specimens of concrete made with river gravel aggregate showed that the fracture surface progresses around a river gravel aggregate. Better aggregate interlock was provided by the river gravel aggregate, which improves the joint performance under moving loads. However, river gravel sections resulted in higher average crack density than that of limestone sections. Thus, identification of aggregate type is crucial in understanding its field performance. The oxide content test, which is one of the recommended basic aggregate tests, would provide information regarding the different oxide contents present in aggregates which can be used for back calculating the most abundant mineral present in the aggregate. Knowledge of mineral composition of the aggregate assists in identifying the aggregate type (such as siliceous or dolomitic) which could be used to infer other aggregate parameters such as thermal coefficient of expansion, strength, and fracture toughness which are characteristic of the minerals present in the aggregates (35). Identification of aggregate with a high thermal coefficient suggests more closely spaced cracks and higher average crack density. The joint spacing and sawcut timing could be varied accordingly so as to expect controlled crack formation at designated sawcut locations.

Shape and surface texture of aggregates indicate the permanent deformation characteristics of an asphalt pavement and porosity of aggregates determine the available pore spaces and their water retention capacity. Thermal characteristics, such as thermal coefficient and thermal conductivity, cause volume changes (causing water in the voids and pore spaces to expand) in the aggregate which causes microcracking and popouts. Chemical properties, such as alkali-silica reactivity and alkali-carbonate reactivity, are related to the distresses such as map and longitudinal cracking in pavements and other bridge columns and indicate the surface deterioration of pavements (37). Mechanical properties such as abrasion resistance, polish value, fracture toughness, and soundness indicate the resistance to degradation under loads and extent of polish of the wearing surface.

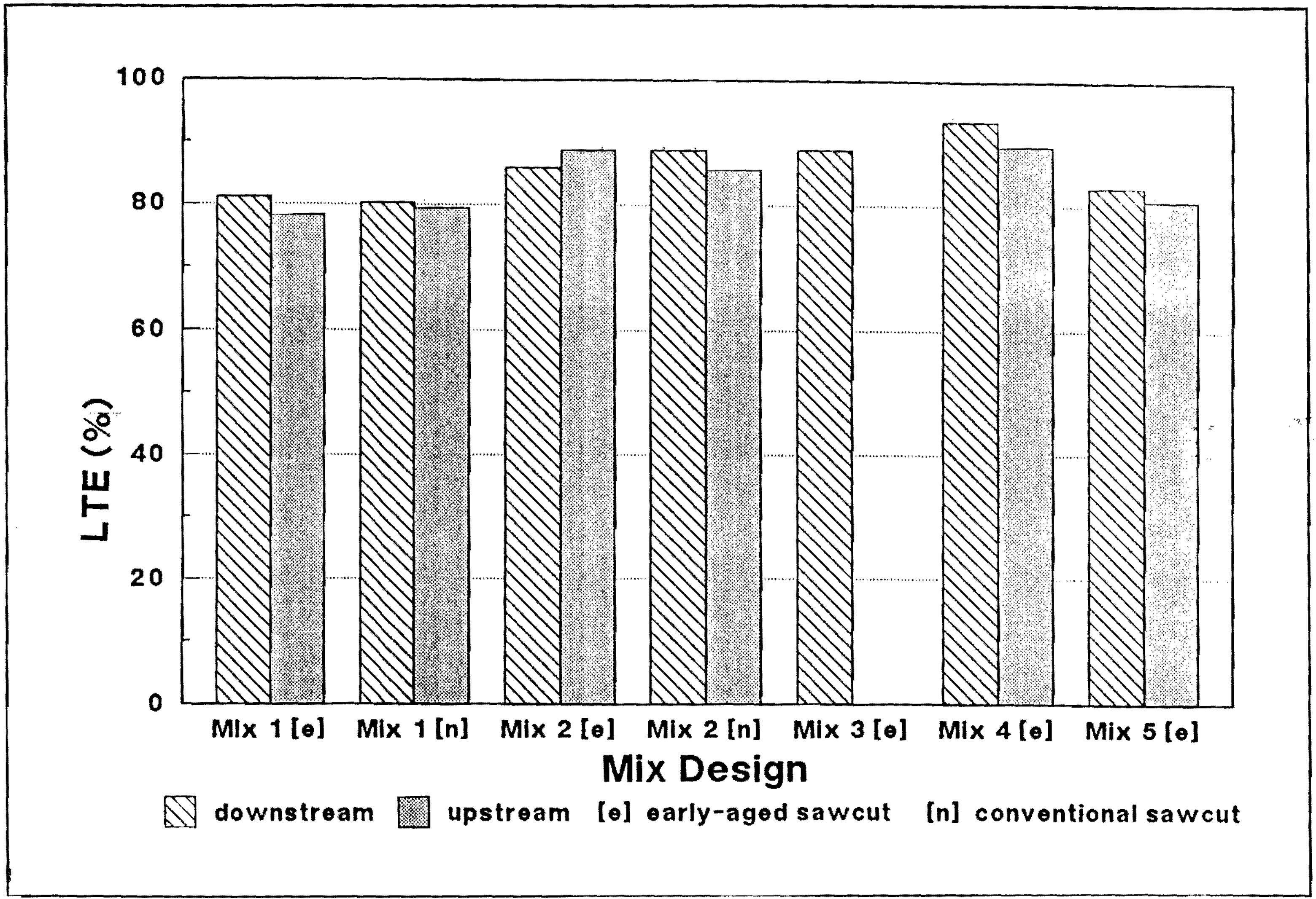


Figure 5.6. Load Transfer Efficiency vs. Mix Design.

Different aggregate parameters are indicative of different performance characteristics. Aggregate properties and respective performance indicators are summarized in Table 5.4. From the table, it can be seen that evaluation of material properties of aggregates provide an indication of their performance. Also, it can be seen that some aggregate characteristics can be inferred from other aggregate parameters. For example, physical properties, such as shape and texture, provide information not only on the geometry of the aggregate but also on its physical stability. Similarly, chemical properties, such as such as oxide content, provide information regarding the mineral composition, chemical reactivity and thermal coefficient of expansion. The Texas Department of Transportation used the Los Angeles abrasion test as a primary test to evaluate the wear of aggregates and soundness of aggregates is inferred from this test (31).

As explained in the previous section, three basic test parameters, namely, textural characteristic, oxide content, and abrasion resistance are included in the second level implementation of the classification system and serve as performance indicators with respect to the physical stability, chemical as well as thermal characteristics, and mechanical wear of aggregates.

Table 5.4. Aggregate Test Parameters and Relative Performance Indicators (15).

Property Type	Aggregate Characteristic	Performance Indicator
Physical Properties	Particle Size Shape Surface Texture Porosity Specific Gravity	Uniform distribution of surface loads; Aggregate interlock; Rutting in HMA pavements; Durability of pavements
Chemical Properties	Mineralogy Oxide Content Alkali-Silica reactivity Alkali-Carbonate Reactivity	Expansion characteristics of structures; Reactivity with the binder; Distress in pavements and bridge columns; Surface deterioration of structures
Mechanical Properties	Abrasion Resistance Accelerated Polish Value Fracture Toughness (k_{IF}) Soundness	Resistance to degradation due to vehicle loads; Skid resistance; Extent of polish of wearing surface;
Thermal Properties	Coefficient of Thermal Expansion Specific Heat Thermal Conductivity	Thermal distresses such as curling, warping and microcracking

CHAPTER 6: TESTS AND EQUIPMENT FOR AGGREGATE EVALUATION

The basic tests which are recommended for aggregate evaluation are discussed in detail in this chapter. Table 6.1 lists the tests required for aggregate identification and evaluation. The test procedures listed in Table 6.1 are explained in the subsequent sections of this chapter. The equipment required for carrying out these tests on the aggregates are listed and figures are appended where necessary. Other special tests such as Mineralogy, Fracture toughness, which constitute the third level of the aggregate classification system and their recommended test procedures, are also listed in this chapter.

Table 6.1. Basic Tests and Recommended Test Procedures.

Aggregate Property	Test procedure
Aggregate Type	Visual Examination
Surface Type	
Shape Classification	Fractal Dimension Analysis
Textural Characteristic	
Oxide Content	Atomic Emission Spectroscopy
Abrasion Resistance	ASTM C 131 / C 535

6.1 AGGREGATE TYPE CLASSIFICATION

Aggregate type classification refers to the geological origin of the aggregates. This essentially consists of identifying the parent rock of the aggregate material which can be either an Igneous, Sedimentary, or Metamorphic rock. This is recommended to be carried out by visual examination of aggregates in the field or from a stockpile. The characteristics which are used to for "aggregate type" classification are (39):

- Texture,
- Mineral composition, and
- Color.

Different rocks are characteristic of their texture and visual identification of rocks is largely dependent on identification of texture based on the grain size. Typically, igneous rocks exhibit granular, medium, fine, glassy, and fragmented textures. Granular texture can be identified by naked eye and the grain size varies from 0.5 mm to about 5 mm. Minerals in the medium textured rocks can be seen but they can only be identified with the aid of a hand held lens. Fine textured rocks can only be identified by using a microscope. Fragmented texture can be identified by the presence of fragments of igneous material ranging from large blocks to fine dust.

Sedimentary rocks can be identified based on their clastic or non clastic texture. Clastic textured rocks consist of particles which are broken, transported, and deposited whereas non clastic rocks are predominantly single mineral and consist of a "network of interlocking grains" (39).

Metamorphic rocks can be generally identified based on the three major types of textures exhibited by them, namely, slaty, schistose, and gneissose types. Table 6.4 lists the principal minerals that comprise metamorphic rock, different textures, colors and major rocks. Rocks exhibiting these textures consist of different sub textures which vary from very fine grained to coarse grained depending on the alignment of grains. The major types of metamorphic rocks are identified based on their texture such as schist, gneiss, and slate.

The principal minerals, textures, and colors characteristic of different minerals for different rock types are listed in the appendix. These tables can be used as a helpful tools for aggregate identification both in the field and in the laboratory.

6.2 SHAPE CLASSIFICATION

Shape and texture of coarse aggregates can be evaluated by using the concept of fractals and the technique of video imaging. This technique can provide an objective measure of the shape and surface texture of the aggregates. Fractal characterization of surface texture is explained in the later part of this chapter. The three major steps involved in the shape computation are:

- Edge extraction,
- Computation of the Slope Density Function, and

- Calculation of Fractal Dimension by box counting.

Edge detection is the first step in the fractal characterization of aggregate shape. It involves video framing of aggregate particles which are placed on a contrasting background (for example, dark background is used for framing light colored aggregates). The video images of these aggregate particles are then digitized into pixels. Each pixel is assigned with a brightness value from a grey scale which varies from 0 for a pitch dark level to 255 for the brightest level. On account of the contrasting background, there will be a rapid change in the grey level at the boundary of the aggregate particle. A Sobel Gradient Operator, which consists of horizontal and vertical masks, is used to find the gradient of the pixel and to enhance the boundary of an aggregate. A mask is a 3X3 pixel operator which enhances an edge by multiplying with a corresponding weight contained in it. An extraction algorithm is used to extract the edge of an aggregate particle from its image. This algorithm, starting with an edge element, searches for boundary pixels in eight directions, namely, N, NE, E, SE, S, SW, W, and NW. The original image of an aggregate particle and its extracted edge are shown in Figures 6.1 and 6.2 (26).

The next step in shape characterization is the computation of the slope density function (SDF). The slope density function is based on a tangent-boundary curve (ψ-s) where ψ is an angle between a fixed line and a tangent to a point on the boundary and "s" is length of the arc that the boundary traversed. Li et al. (26) observed that "the SDF is the histogram or frequency of the angles collected over the boundary of a given shape". The jagged nature of the SDF curve can be used to explain the angularity of an aggregate particle. Figures 6.3 and 6.4 show the Slope Density Function of a limestone and a river gravel aggregate, respectively (26). These SDF curves show that the SDF of a limestone aggregate shows larger peaks than that of river gravel aggregate, which is representative of the long, straight edges and more angular nature of the limestone aggregate. Thus, SDF curves can effectively describe the shapes of different aggregate particles .

The fractal dimension of the shape of an aggregate particle can be determined by using box dimension. This procedure consists of overlay of the SDF curve of the aggregate with a set of boxes and determination of the number of boxes which contain the line segment. This procedure is repeated by changing the size of the box and the resulting values are plotted on a

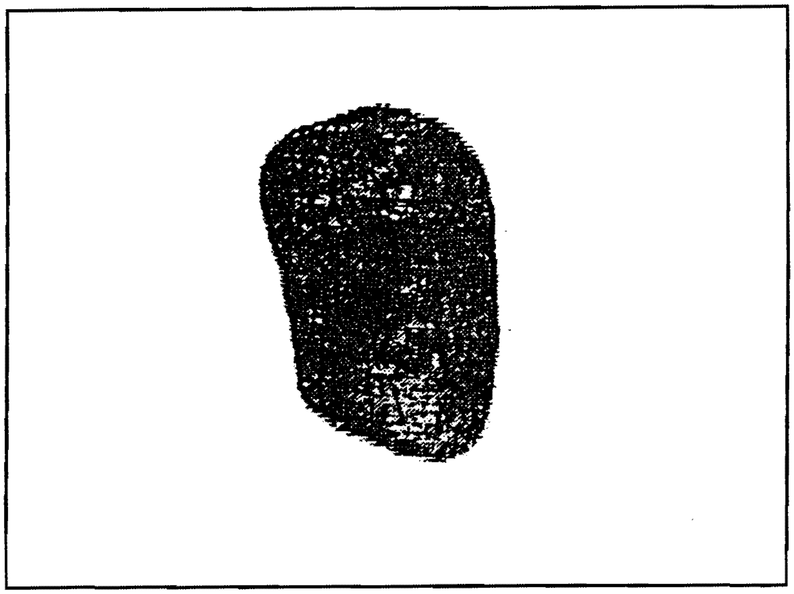


Figure 6.1. Video (Original) Image of an Aggregate Particle.

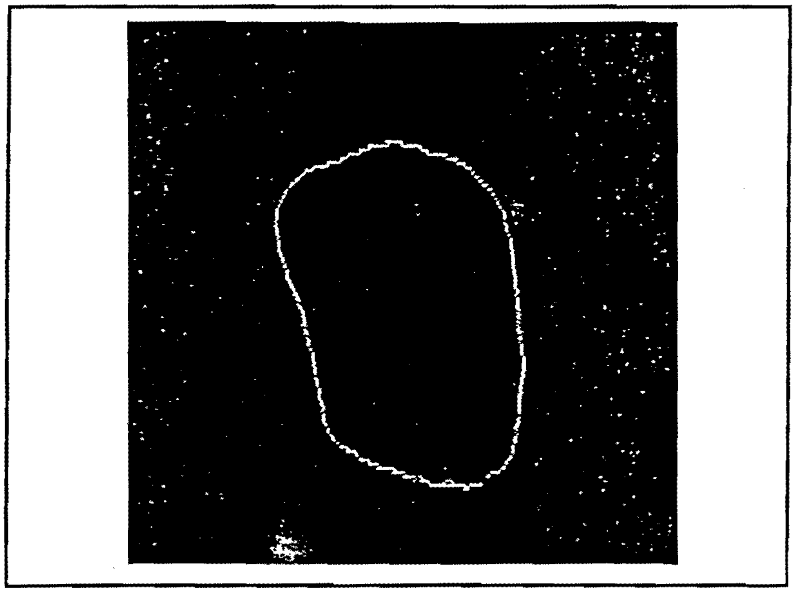


Figure 6.2. Extracted Edge of the Video Image of the Aggregate Particle.

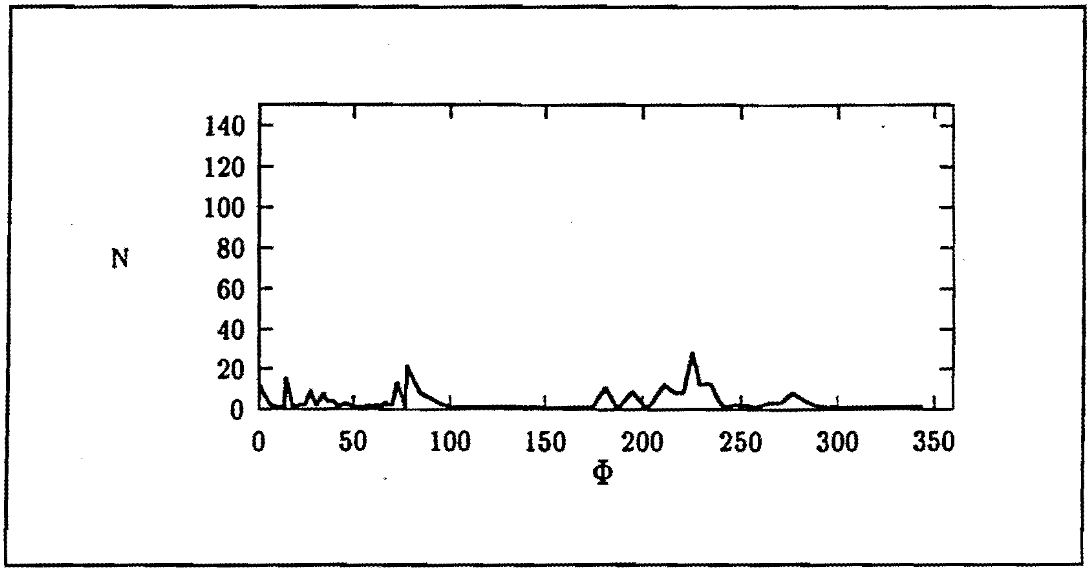


Figure 6.3. SDF Plot of a Limestone Aggregate Particle.

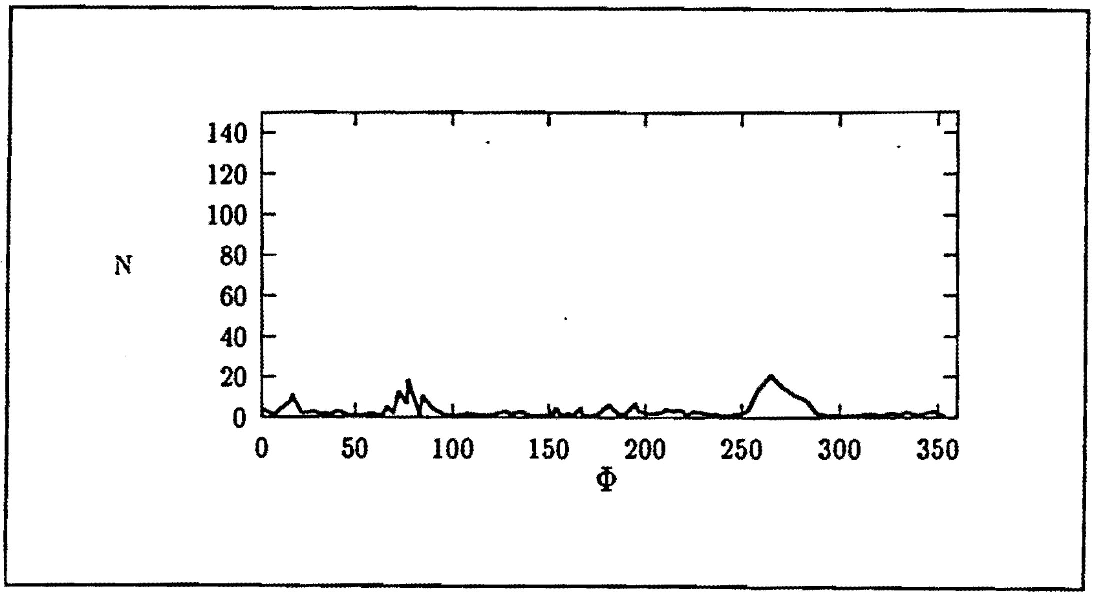


Figure 6.4. SDF Plot of a River Gravel Aggregate Particle.

log-log scale which gives the box counting plot. The absolute value of the box count plot slope gives the fractal dimension number of the shape of the aggregate particle. The fractal dimension for a near smooth surface would be one, whereas for rough surfaces, it varies from one to two (26).

6.3 TEXTURAL CHARACTERISTIC

The technique of fractal characterization can be extended to determine the surface texture of an aggregate particle. This essentially consists of determination of the rate of variation of grey levels of the adjacent pixels on the image of the aggregate particle. The variation in grey levels of the image is proportional to the roughness of the aggregate particle. In other words, the rougher the surface of the particle, the higher the variation in grey levels of the image. The fractal dimension number of texture increases with increase in the variation of grey levels or roughness. A cardboard surface, a cork particle, and a carpet material can be used for the purposes of calibration of smooth, intermediate and rough textures respectively. These calibrated values are used as standards in characterizing aggregates into different textures.

The equipment required for fractal characterization of aggregate shape and surface texture are:

- A personal computer with printer,
- A color image processing board,
- A image processing software, and
- A high resolution color video camera.

The workstation and image processor which are used in the video imaging laboratory at the Texas Transportation Institute, Texas A&M University, are shown in Figures 6.5 and 6.6.

6.4 OXIDE CONTENT

Chemical analysis can be performed on aggregates to determine their oxide content and the results obtained can be used to predict the aggregate performance. This test can be carried out using the technique of Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). It is an analysis technique used for determining the elements in solution samples using

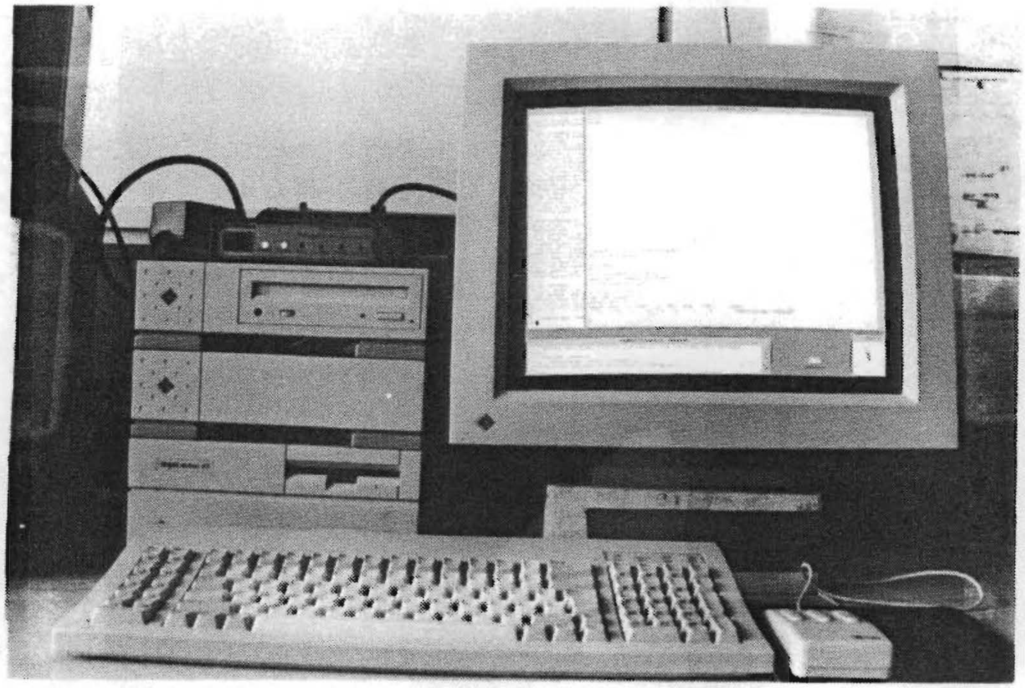


Figure 6.5. Work Station Used for Fractal Dimension Analysis.

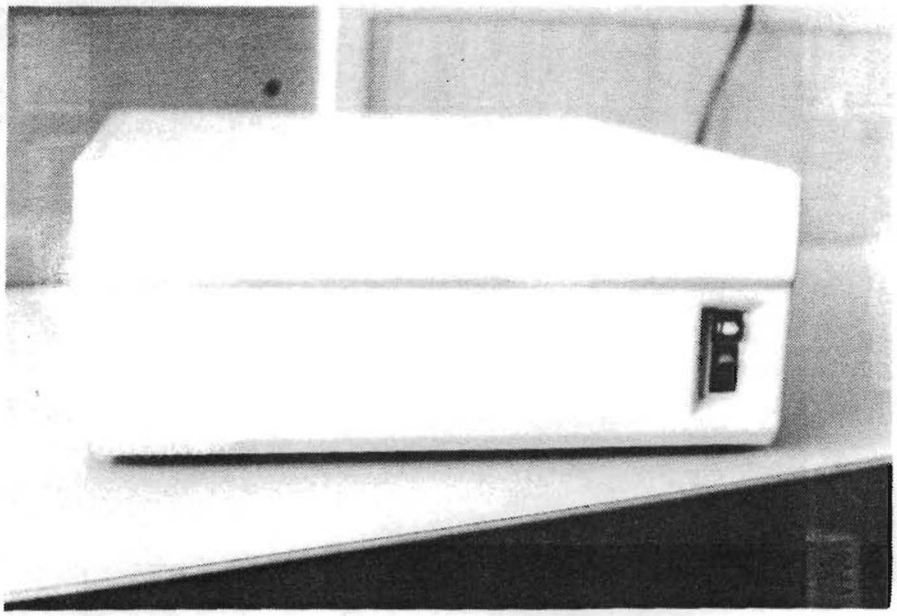


Figure 6.6. A Typical Image Processor Used in Fractal Dimension Analysis.

the spectra emitted by free atoms or ions. The atoms or ions are generated within a source such as an "Inductively Coupled Plasma". Typically, "plasma" can be defined as a "hot gas" where atoms or molecules are ionized. An inert gas such as Argon, when surrounded by a "time-varying" magnetic field, is inductively coupled. The resulting plasma will have a temperature of about 10,000 K, with the help of which it dissociates, and atomizes the elements present in the injected sample. Depending on the concentration of different elements in the sample, a light of corresponding frequency is emitted. Since the concentration of the element is proportional to the emitted light intensity, the measuring electronics in the spectrometer compute the correlation between them and quantifies the results (40).

A schematic of the ICP spectrometer is shown in Figure 6.7. It shows the required equipment and various system electronics required for carrying out this test (41). Basic components of the Inductively Coupled Plasma Optical Emission Spectroscopy instrument are:

- Spectrometer containing a grating, fine slit, an imaging system,
- Detector,
- ICP source,
- Nebulizer, Spray chamber, design torch for sample introduction,
- Mini Computer for data storage and analysis, and
- Argon gas, sulfuric acid, nitric acid, hydrochloric acid, and deionized water constitute the required reagents and glassware such as pipets, volumetric flasks are required for sample dilution.

6.5 ABRASION RESISTANCE

Abrasion resistance of aggregates can be measured according to ASTM standard test procedure ASTM C 135 or ASTM C-535, depending on the size of coarse aggregates. The Los Angeles abrasion machine is used to "measure the degradation of mineral aggregates of standard gradings". The aggregates are placed along with a specified number of steel spheres in a rotating steel drum where they are subjected to abrasion, attrition, and impact. The rotating action of the steel drum carries the aggregates and steel spheres around and causes an abrading action. The drum is rotated at a speed of 30-33 revolutions per minute for 500 revolutions and the aggregate portion is removed from the rotating drum and sieved to

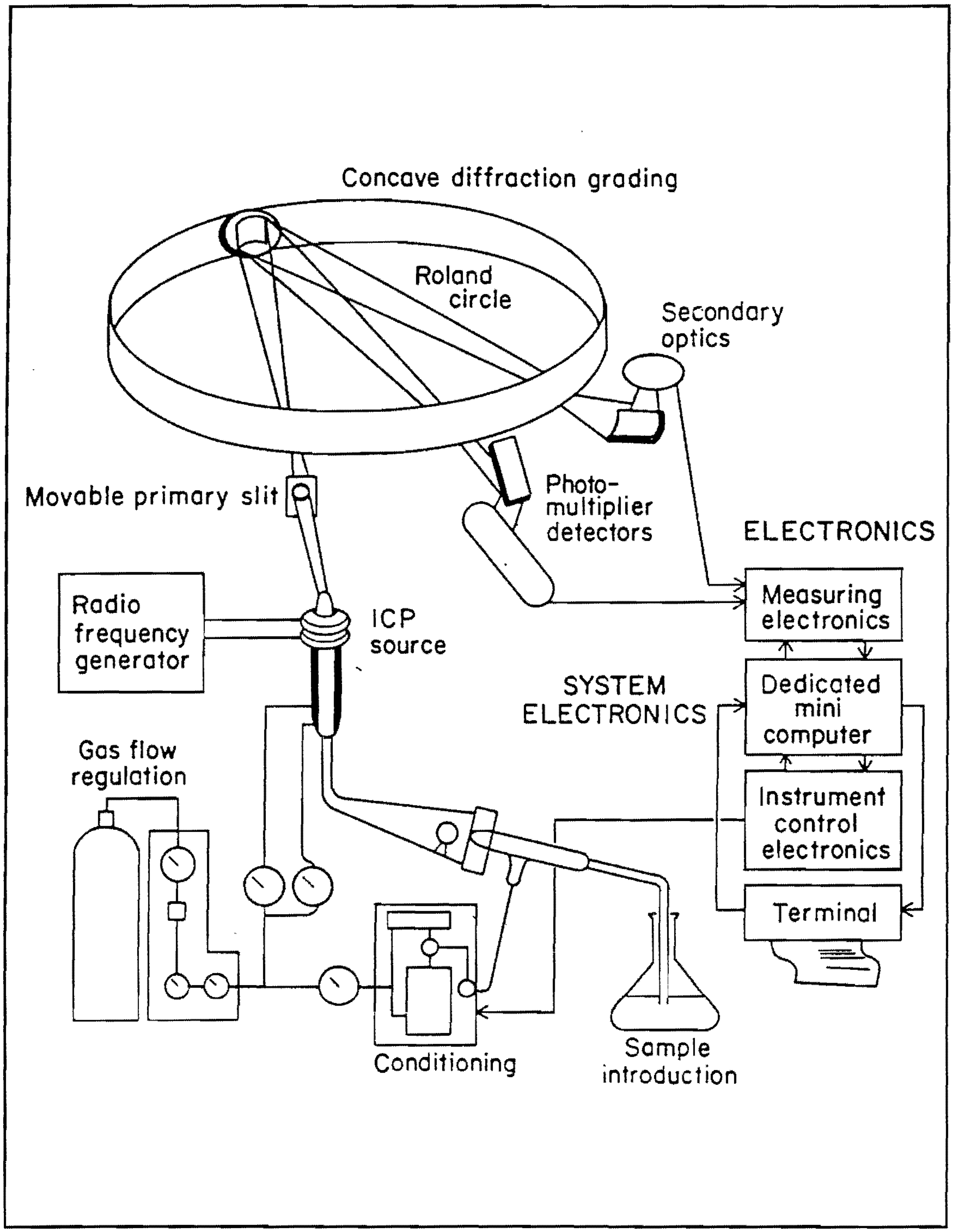


Figure 6.7. Schematic Diagram of the Inductively Coupled Plasma Optical Emission Spectrometer (41).

measure the percent abrasion loss of the aggregates. This is the difference between the original sample weight and the final sample weight expressed as a percentage of the original sample weight. This test can be used to estimate the mechanical strength and toughness of the aggregates and serves a good indicator of the relative quality of the aggregates with same mineral composition (42). The L.A. abrasion testing machine is shown in Figure 6.8 (43). The equipment required for the abrasion test are: (a) L.A. abrasion testing machine, (b) sieves, (c) balance, and (d) steel charges approximately 46.8 mm (1 27/32) in diameter and each weighing 390-445 grams.

6.6 OTHER TESTS ON AGGREGATES

All the properties of aggregates, other than the basic test parameters which are included in the aggregate classification system and their respective recommended test procedures, are listed in Table 6.2. These tests, if needed, can be performed as per the recommended test procedures. The standards listed should be referred to obtain the detailed procedures of these tests on aggregates.

As shown in the above table, most of the aggregate properties can be evaluated as per the available ASTM standard test procedures. However, some of properties cannot be quantified using ASTM procedures because of non-availability of relevant test procedures or because of some shortcomings of the existing test procedures. There are no ASTM standard procedures available for quantifying the fracture toughness, mineralogy, and oxide content of the aggregates. The recommended test procedure for fracture toughness could not only be used for evaluating the bond strength of the aggregates but also for carrying out stress analysis on the pavement structure subsequently, if needed, to evaluate the performance of the pavement. The oxide content test determines the percent of oxides present in aggregates which can be used not only to back calculate the mineral composition of the aggregate material but also assists in inferring the thermal characteristics of the material.

The shape and texture of aggregates can be determined according to ASTM D 3398 test procedure. However, this test procedure is based on the percent void content in the aggregate sample at two compactive efforts, which is used to arrive at a particle index. The calculated particle index is used to arrive at an overall measure of shape and texture of aggregate

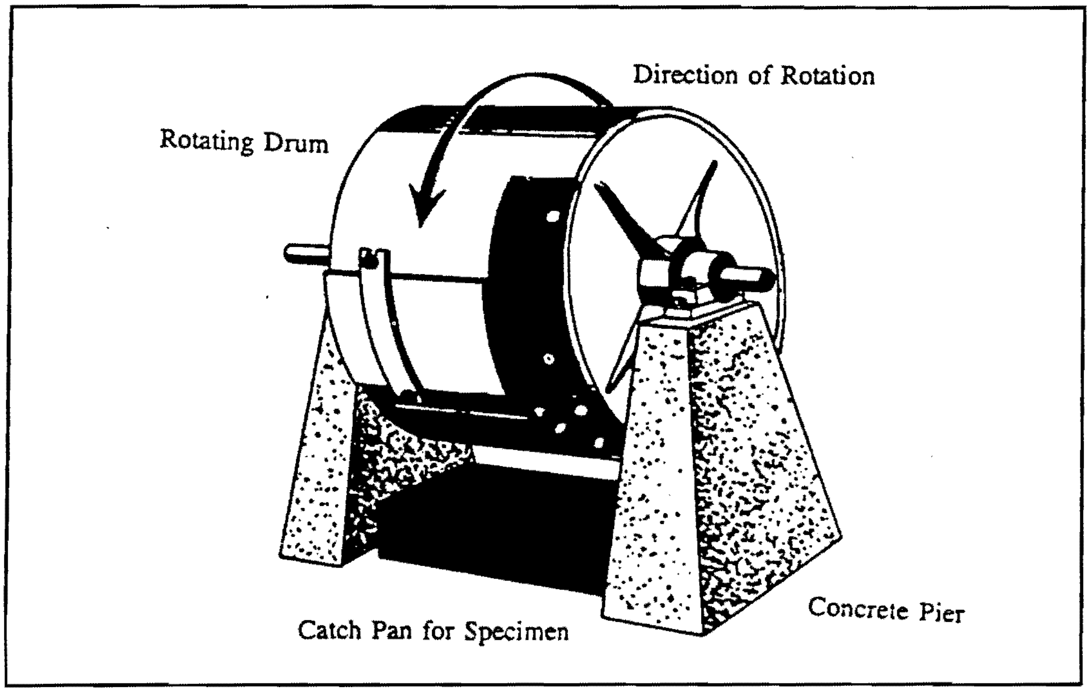


Figure 6.8. L.A. Abrasion Testing Machine (After 43).

Table 6.2. Other Aggregate Properties and Their Respective Test Procedures.

Aggregate Property	Test Procedure
Particle Size	ASTM C 136
Specific Gravity	ASTM C 127
Mineralogy	X-Ray Diffraction
Alkali-Silica Reactivity	ASTM C 289 ASTM C 227
Alkali-Carbonate Reactivity	ASTM C 586
Accelerated Polish Value	TeX-438-A
Soundness	ASTM C 88
K_{IF}	RILEM TC-89
Thermal Coefficient of Expansion	CRD-C-125
Specific Heat	CRD-C-124

particles. One of the shortcomings of this procedure is that it requires repetition of the test for each size fraction whose overall percentage in the gradation exceeds 10 percent. This test method provides an approximate measure of particle shape and texture and does not effectively characterize the aggregate geometry. Hence, fractal dimension analysis, which has been proved as a good characterization technique, has been recommended as the test procedure for evaluation of shape and texture.

Polish value test can be performed as per ASTM test standards D 3319 and E-303. However, these ASTM test procedures do not outline the method for determination of polish value of blended aggregates. The test procedure which is adopted by the Texas Department of Transportation is recommended to be carried out for determination of polish value of aggregates. This test procedure, unlike the ASTM test procedures, provides detailed guidelines for assessment of polish value of blended aggregates.

The standard test procedures are recommended for evaluation of all aggregate properties listed in this classification system. Apart from the basic tests, which are explained earlier in this chapter, all other tests are advised to be carried out as per the recommended test procedures, depending on the level of information and accuracy required.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Based on the framework developed for the coarse aggregate classification system, the following conclusions are made:

1. The proposed aggregate classification system is expected to serve as an effective tool in aggregate identification and subsequent prediction of the behavior of different aggregate types.
2. Suitable coarse aggregate type can be selected based on the evaluation of aggregates, which actually minimizes the chances of aggregate related failures of pavements and other structures.
3. The suggested basic tests are expected to provide adequate information for appropriate material selection. This will reduce maintenance and rehabilitation costs for the implementing agency of this classification system.
4. The recommended tests for aggregate identification and performance evaluation are simple, quick, and informative.
5. Performance evaluation of aggregates based on this classification system can be utilized to develop better pavement design models where aggregate type can be incorporated as a design parameter.
6. Based on the preliminary assessment of aggregates, suitable blending of aggregates can be used as an alternative to enhance the performance of structures.
7. The aggregate classification system should be implemented at three levels. The first two levels of implementation are expected to provide comprehensive identification and performance evaluation of aggregates and require some knowledge of physical geology. The third level consists of complex tests, but it can be used as a tool to confirm the results obtained from the first two levels.
8. Successful implementation of the proposed classification system is expected to provide a cost effective alternative to the petrographic examination of aggregates which is tedious, time consuming and requires the special skills of a petrographer.
9. TxDOT should consider further investigation of second and third level implementation.

7.2 RECOMMENDATIONS FOR IMPLEMENTATION AND FURTHER RESEARCH

1. The proposed aggregate classification system should be implemented at three levels.
2. The first level of implementation, which largely consists of visual examination of aggregates, should be used for aggregate identification and their preliminary assessment based on the identification of aggregates.
3. The second level of implementation should consist of quantitative determination of aggregate quality by laboratory investigation of suggested basic test parameters. The results obtained should be used in performance assessment of aggregates and subsequent material selection processes.
4. The third level of implementation essentially consists of special tests on aggregates and in view of the complexity of the tests, it is recommended that this level should only be implemented when it is deemed absolutely necessary.
5. The first two levels of suggested implementation should be carried out in a phased manner and the results obtained should be carefully evaluated and methods for improvements suggested.
6. More research needs to be carried out to validate the proposed classification system. Trial field implementation should be carried out to check the accuracy of the results.
7. Another area which most definitely needs more research is the evaluation of test methods for better aggregate characterization, which will provide patterns by which complex properties can be inferred by more simpler tests on aggregates.
8. More extensive research should be performed to investigate the feasibility of inferring the Alkali-Silica reactivity and the Alkali-Carbonate reactivity from the oxide content tests.
9. The feasibility of characterizing of surface characteristics of aggregates by gas chromatography should be explored. The mechanical aspect of bond strength of aggregates could be studied if this technique proves successful.
10. Successful implementation of the aggregate classification system could be used for developing a functional classification system for coarse aggregates.

REFERENCES

1. *Concrete and Aggregates*, ASTM D 8-91, Standard Terminology Relating to Materials for Roads and Pavements, Section 4, Vol. 04.02, ASTM, Philadelphia, PA, 1991.
2. *Concrete and Aggregates*, ASTM C 125-88, Standard Terminology Relating to Concrete and Concrete Aggregates, Section 4, Vol. 04.02, ASTM, Philadelphia, PA, 1991.
3. M. W. Witczak, C. W. Lovell, Jr., and E. J. Yoder. A Generalized Investigation of The Potential Availability of Aggregate by Regional Geomorphic Units Within the Conterminous 48 States. Presented at the 50th Annual Meeting of the Highway Research Board, Washington, DC, 1971.
4. T. Dossey, H. Castedo, and B. F. McCullough. Prediction of Concrete Properties Using Coarse Aggregate Chemical Composition Data. In *Transportation Research Record 1284*, TRB, National Research Council, Washington, DC, 1990, pp. 1-7.
5. J. W. Button, D. Perdomo, and R. L. Lytton. Influence of Aggregate on Rutting in Asphalt Concrete Pavements. In *Transportation Research Record 1259*, TRB, National Research Council, Washington, DC, 1989, pp. 141-152.
6. *Significance of Tests and Properties of Concrete and Concrete Making Materials*, ASTM STP 169B, ASTM, Philadelphia, PA, 1978.
7. T. K. Liu. A Review of Engineering Soil Classification Systems. Presented at the 45th Annual Meeting of the Transportation Research Board, Washington, DC, 1965.
8. D. A. Williamson, and C. R. Kuhn. The Unified Rock Classification System. *Rock Classification Systems for Engineering Purposes*, ASTM STP 984, ASTM, Philadelphia, PA, 1988.
9. *PCA Soil Primer*, Portland Cement Association, Skokie, IL.
10. *Airport Pavement Design and Evaluation*, Advisory Circular, AC 150/5320-6C, Department of Transportation, Federal Aviation Administration, Washington, DC.
11. H. J. Pincus, Opening Remarks. *Rock Classification System for Engineering Purposes*, ASTM STP 984, ASTM, Philadelphia, PA, 1988.

12. Edited by C. W. Finkl, Jr. *Soil Classification,* Benchmark Papers in Soil Science V.1, Hutchinson Ross Publishing Company, Stroudsburg, PA.
13. B. E. Butler. *Soil Classification for Soil Survey,* Clarendon Press, Oxford, 1980.
14. K. H. Northcote. The Factual Classification of Soils and Its Use in Soil Research, *Soil Classification*, Benchmark Papers in Soil Science V.1, Hutchinson Ross Publishing Company, Stroudsburg, PA, 1982.
15. L. D. Mantuani. *Handbook of Concrete Aggregates*, National Research Council of Canada, Published by Noyes Publications, NJ, 1983.
16. Z. T. Bieniawski. *Engineering Rock Mass Classifications*, A complete manual for Engineers and Geologists in Mining, Civil and Petroleum Engineering, John-Wiley & Sons, NY, 1989.
17. Edited by L. Collis and R. A. Fox. *Aggregates: Sand, Gravel, & Crushed Rock Aggregates for Construction Purposes*, Engineering Geology Special Publication No. 1, Published by The Geological Society, Piccadilly, London, W1V 0JU, 1985.
18. H. H. Weinert. *The Natural Road Construction Materials of Southern Africa*, Cape Town, S. Africa, 1980.
19. *The Asphalt Handbook*, Manual Series No. 4 (MS-4), Asphalt Institute Building, College Park, MD, 1989.
20. A. M. Neville, and J. J. Brooks. *Concrete Technology*, Longman Group UK Limited, Essex, CM20 2JE, England, 1987.
21. Fédération Internationale de la Précontrainte (FIP). *FIP Manual of Lightweight Aggregate Concrete*, Halsted Press, a division of John Wiley and Sons Inc., NY, 1983.
22. W. B. Ledbetter et al. *A Recommended Synthetic Coarse Aggregate Classification System*, Final Report, Synthetic Aggregate Research, Research Report 81-15, Texas Transportation Institute, Texas A&M University, College Station, TX, 1971.
23. Edited by D. C. Pike. *Standards for Aggregates*, Ellis Horwood Series in Applied Geology, West Sussex, England, 1990.

24. *Road and Paving Materials: Pavement Management Technologies.* ASTM D-3398-91, Index of Aggregate Particle Shape and Texture, Annual Book of ASTM Standards, Section 4, Vol. 04.03, ASTM, Philadelphia, PA, 1990.
25. W. C. Krumbein. Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles. *Journal of Sedimentary Petrology*, Vol. 13, No. 2, 1941, pp. 79-81.
26. L. Li, P. Chan, D. G. Zollinger, and R. L. Lytton. Quantitative Analysis of Aggregate Shape Based on Fractals. *Journal of the American Concrete Institute*, Vol. 90, No. 4, 1993, pp. 357-365.
27. H. W. Kummer, and W. E. Meyer. NCHRP *Report 37: Tentative Skid Resistance Requirements For Main Rural Highways.* HRB, National Research Council, Washington, DC, 1967.
28. R. E. Graves. *Physical, Mineralogical and Interfacial Bonding Properties of Carbonate and Silicate Mineral Aggregates Used in Portland Cement Concrete in Florida*, Ph.D. Dissertation, University of Florida, Gainesville, FL, 1991, pp. 22-41.
29. D. G. Zollinger, T. Tang, and R. H. Yoo. Fracture Toughness of Concrete at Early Ages. *Journal of American Concrete Institute*, Vol. 90, No. 5, 1993, pp. 463-471.
30. E. J. Callan. *The Relation of Thermal Expansion of Aggregates to the Durability of Concrete*, Bulletin No. 34, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, MS, February 1950.
31. *Living With Marginal Aggregates*, ASTM STP 597, ASTM, Philadelphia, PA, 1975.
32. A. Dumas. *Effects of Aggregate Blends on the Properties of Portland Cement Concrete Pavements*, Master's Thesis, The University of Texas at Austin, TX, May 1994, pp. 10-25.
33. S. Mindess. Interfaces in Concrete. *Materials Science of Concrete*, The American Ceramic Society, Vol. 1, 1989, pp. 163-180.
34. A. E. Kehew. *General Geology for Engineers*, Published by Prentice Hall, Inc., A Division of Simon & Schuster, NJ, 1988.

35. T. Dossey, J. V. Salinas, and B. F. McCullough. A Methodology for The Improvement of Oxide Residue Models for Estimation of Aggregate Performance Using Stoichiometric Analysis, Presented at the 73rd Annual Meeting of the Transportation Research Board, Washington, DC, January 1994.

36. T. Tang, D. G. Zollinger, and B. F. McCullough. *Concrete Pavement Field Tests in Texarkana and La Porte, Texas, and Analysis.* Research Report 1244-7, Texas Department of Transportation, Austin, May 1994.

37. D. Stark, B. Morgan, P. Okamoto, and S. Diamond. *Eliminating or Minimizing Alkali-Silica Reactivity.* SHRP-87-202, Final Report, Construction Technology Laboratories, Skokie, IL, February 1993.

38. P. E. G. Bellew. *Alkali-Aggregate Reactions*, Proceedings of the 7th International Conference, 1986, Ottawa, Canada, Published by Noyes Publications, NJ, 1987.

39. J. Pitts. *A Manual of Geology for Civil Engineers*, Published by Halsted Press, A Division of John Wiley & Sons, NY, 1984.

40. A. Varma. *Handbook of Inductively Coupled Plasma Atomic Emission Spectroscopy*, Published by CRC Press, Inc., N.W. Boca Raton, FL, 1991.

41. V. A. Fassel, and R. N. Kniseley. Inductively Coupled Plasma Optical Emission Spectroscopy. *Journal of Analytical Chemistry*, Vol. 46, 1974, p. 1110A.

42. *Concrete and Aggregates*, ASTM C 131-89, Standard Terminology Relating to Concrete and Concrete Aggregates, Vol. 04.02, Section 4, ASTM, Philadelphia, PA, 1991.

43. Asphalt Institute. *Principles of Construction of Hot-Mix Asphalt Pavements*, Manual Series No. 22, Asphalt Institute Building, College Park, MD, January 1984.

44. "Rock and Mineral Identification for Engineers", U.S. Department of Transportation, Federal Highway Administration, November 1991.

APPENDIX A

GUIDELINES FOR CLASSIFICATION

1. BASED ON THE INFORMATION AND ACCURACY REQUIRED ON AGGREGATES, IDENTIFY THE LEVEL OF IMPLEMENTATION REQUIRED.

2. FOR THE FIRST LEVEL OF CLASSIFICATION, REFER TO FIGURES A-2 THROUGH A-3 AND TABLES B-1 THROUGH B-3.

3. SECOND LEVEL CLASSIFICATION IS OUTLINED IN FIGURE A-4. THIS INVOLVES EVALUATION OF TEXTURE, OXIDE CONTENT AND ABRASION RESISTANCE. FOR A BETTER INFERENCE OF BOND STRENGTH, IT IS RECOMMENDED THAT BOND TEST ON CONCRETE SPECIMENS (UNDER 24 HOURS AGE) BE CARRIED OUT AS PER RILEM TC-89 TEST PROCEDURE.

4. THIRD LEVEL OF IMPLEMENTATION SHOULD BE CARRIED OUT AS NEEDED BASED ON THE CHARACTERISTIC OF AGGREGATES WHICH NEEDS FURTHER EVALUATION. THE BASIC PROCEDURE FOR THIS LEVEL IS SHOWN IN FIGURE A-5 AND TEST PROCEDURES ARE LISTED IN FIGURE A-6 FOR QUICK REFERENCE.

Figure A-1. Guidelines for Classification of Aggregates.

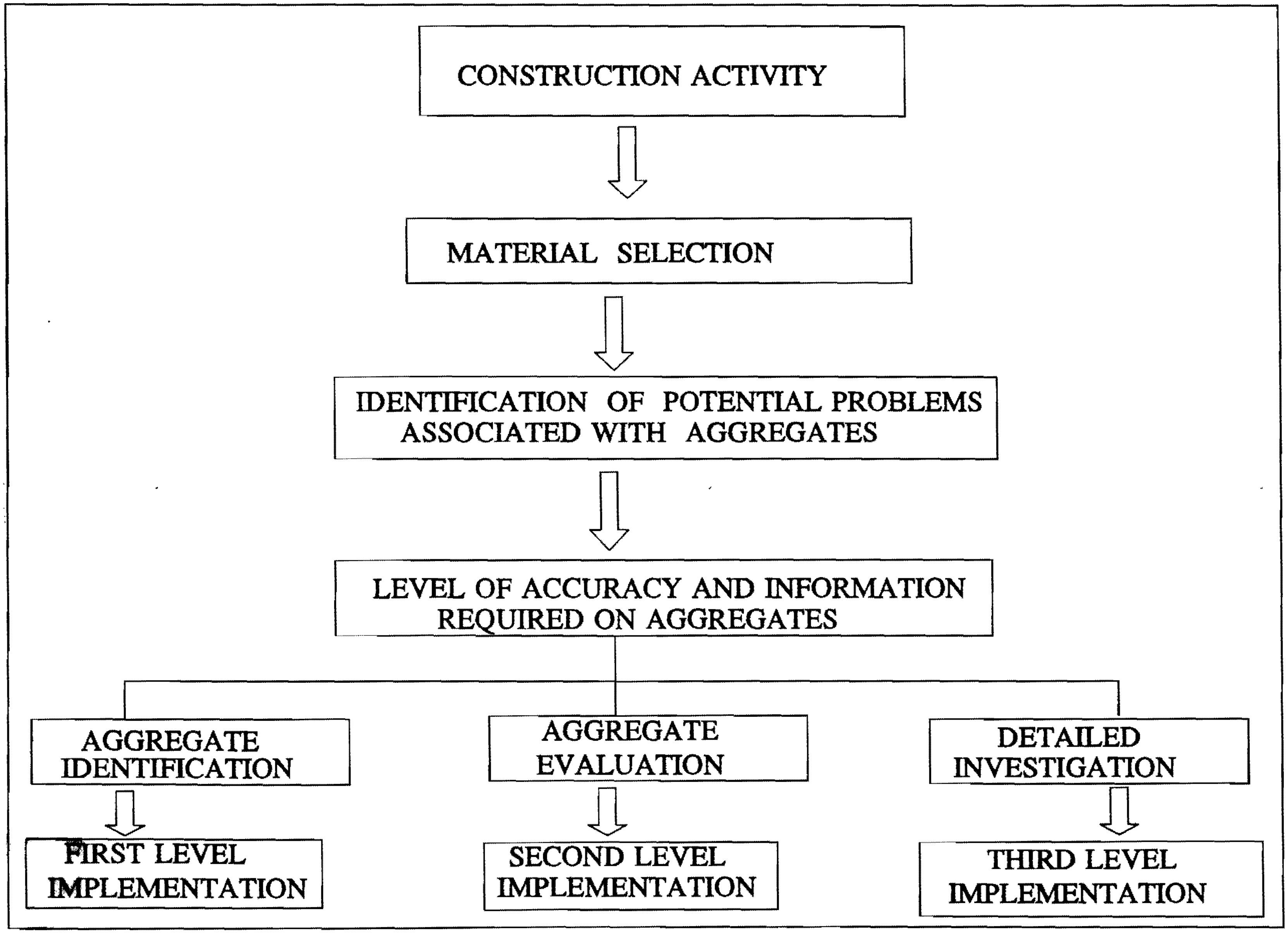
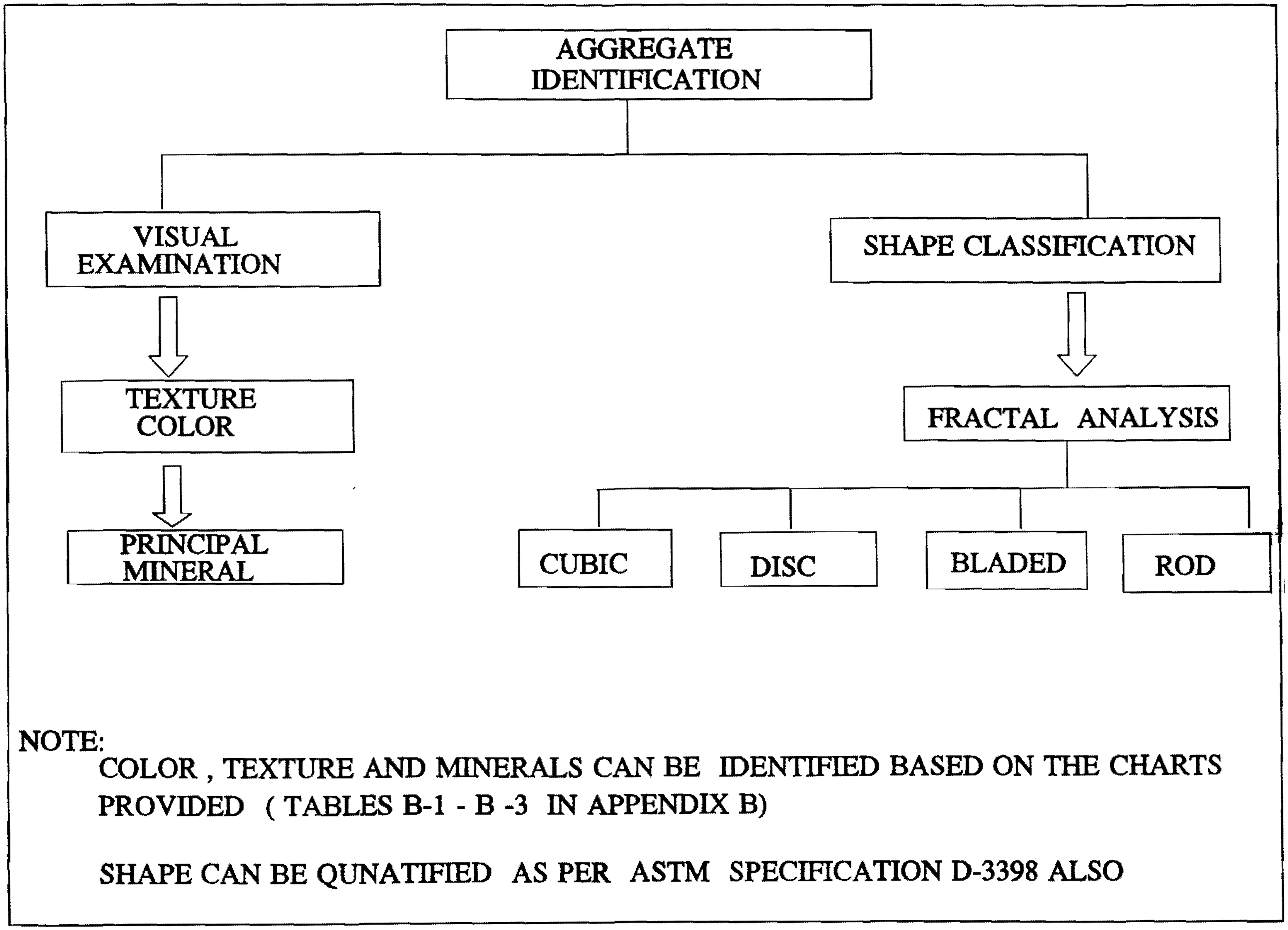


Figure A-2. Criteria for Selection of Different Levels of Classification.



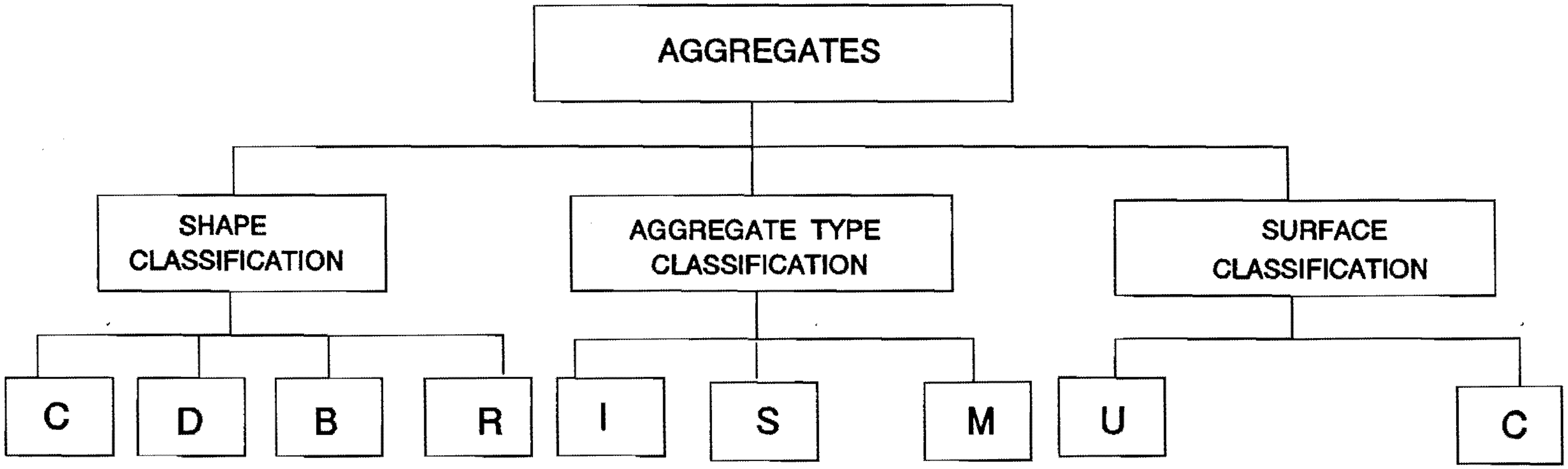
NOTE:

COLOR , TEXTURE AND MINERALS CAN BE IDENTIFIED BASED ON THE CHARTS PROVIDED (TABLES B-1 - B -3 IN APPENDIX B)

SHAPE CAN BE QUNATIFIED AS PER ASTM SPECIFICATION D-3398 ALSO

Figure A-3. First Level Classification of Aggregates.

AGGREGATE IDENTIFIERS (DESIGNATORS)



A TYPICAL CLASSIFICATION OF AN AGGREGATE BASED ON THIS CLASSIFICATION SYSTEM WOULD BE "DSC"

Figure A-4. Typical Classification of Aggregates Based on the Classification System.

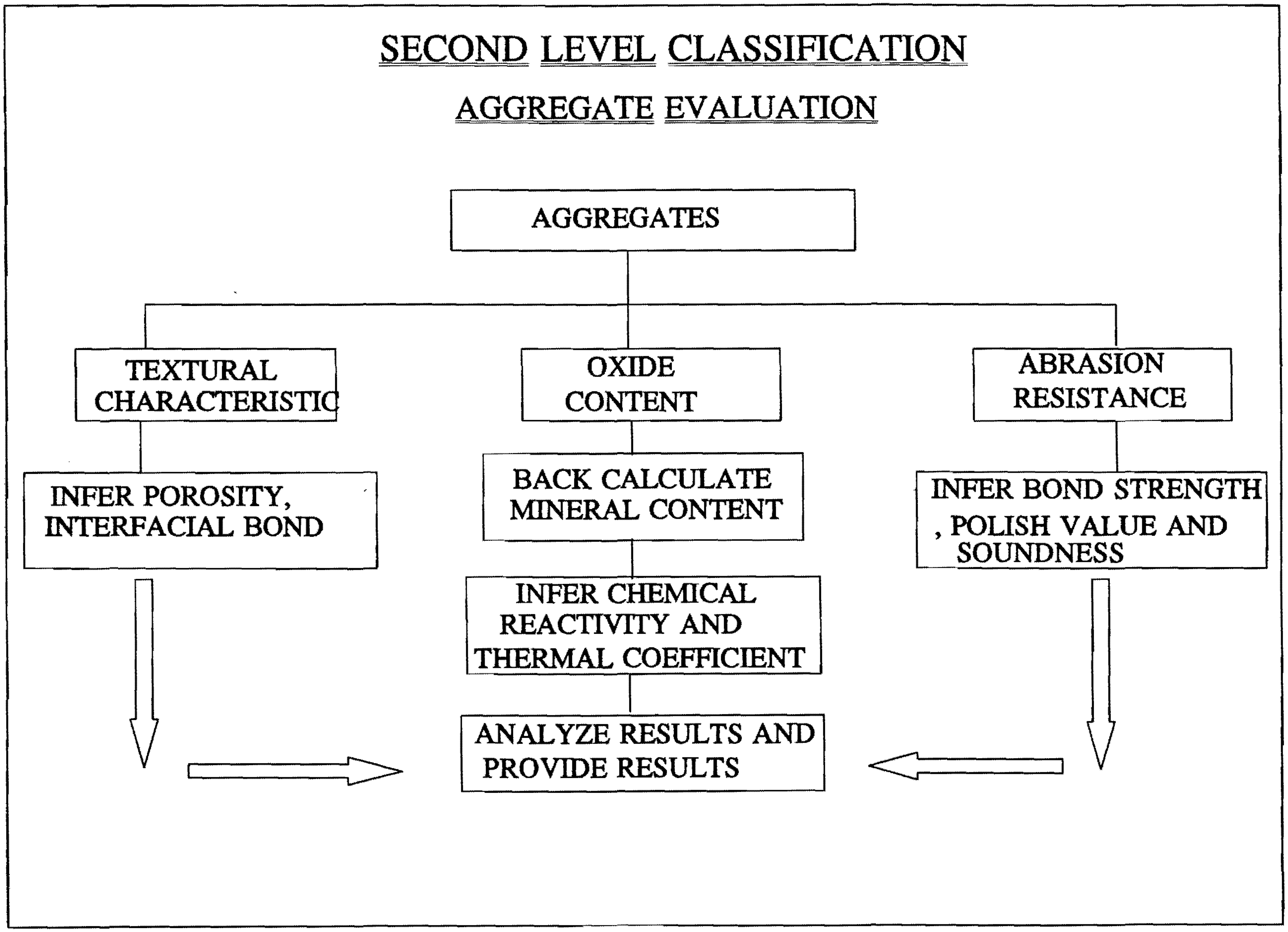
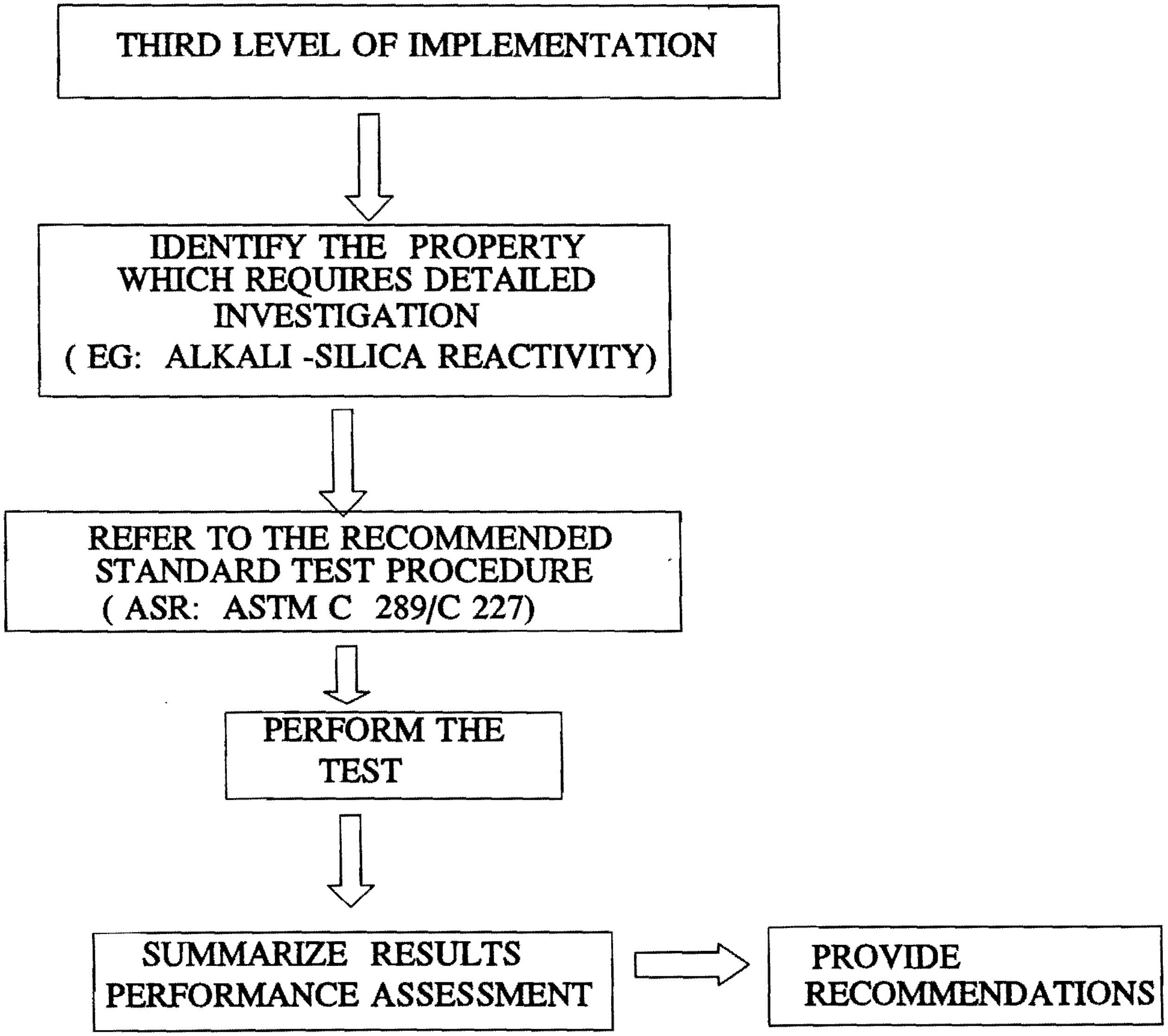


Figure A-5. Second Level Classification of Aggregates.



Figures A-6. Third Level Classification of Aggregates.

THIRD LEVEL PROPERTIES AND RESPECTIVE TEST PROCEDURES

PROPERTY	TEST PROCEDURE
MINEROLOGY	X-RAY DIFFRACTION
ACCELERATED POLISH VALUE	TEX-438-A
SOUNDNESS	ASTM C 88
ALKALI-SILICA REACTIVITY	ASTM C 289/ ASTM C 227
ALKALI-CARBONATE REACTIVITY	ASTM C 586
K_{IF}	RILEM TC 89
THERMAL COEFFICIENT OF EXPANSION	CRD C 125
SPECIFIC HEAT	CRD C 124
PARTICLE SIZE	ASTM C 136
SPECIFIC GRAVITY	ASTM C 127

Figure A-7. Properties and Respective Test Procedures Included in the Third Level Classification.

APPENDIX B

Table B-1. Identification of Aggregates of Igneous Origin (39).

Texture	Principal Minerals	Color
Granular Medium Fine Glassy Fragmented	Quartz	Colorless, White
	Feldspars	White, Greenish, Pink, Grey
	Mica	Pale Grey, White, Dark Brown, Black
	Amphiboles	Dark Green, Black
	Pyroxenes	Black
	Olivine	Colorless

Table B-2. Identification of Aggregates of Sedimentary Origin (39).

Texture	Principal Minerals	Color
Clastic Non Clastic	Calcite	White
	Dolomite	White, Yellow tinge, Red brown
	Gypsum	White, Pink tint, Yellow and Grey
	Kaolinite	White-Grayish
	Illite	White to Pale
	Pyrite	White, Yellow, or Green
	Montmorillonite	Brass-Yellow

Table B-3. Identification of Aggregates of Metamorphic Origin (39).

Texture		Color	Principal Minerals	Major Rock
Sub-Parallel Alignment or Banding of Minerals	Very Fine grained	Dark Grey, Green or Red	Mica flakes, Quartz, Feldspar	SLATE
	Fine Grained	Medium to Dark Grey		PHYLLITE
	Medium to Coarse Grained with well developed alignment	Silvery, Green or Black	Biotite, Muscovite, Chlorite Quartz, Feldspar	SCHIST
	Banded:Medium to Coarse Grained	Pale	Quartz, Feldspar, Mica, Hornblende	GNEISS
Rare Alignment of Minerals or Banding	Fine to Very Fine Grained	Dark Colored	Granular Quartz, Mica	HORNFELS
	Medium to Coarse Grained	White, Grey, Red	Quartz, Muscovite	QUARTZITE
		White,Grey	Calcite	MARBLE

Table B-4. Format for Tabulation of Classification Results.

FIRST LEVEL CLASSIFICATION	Aggregate Type	Surface Type	Shape
Comments on First Level Classification			
SECOND LEVEL CLASSIFICATION	Texture	Oxide Content	Abrasion Resistance
Comments on Second Level Classification			
THIRD LEVEL CLASSIFICATION	Property	Test Procedure	Desired Characteristic
Comments on Third Level Classification			
CONCLUSIONS AND RECOMMENDATIONS			