FINE AGGREGATE ANGULARITY IN TURKEY IN BITUMINOUS MIXTURES

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ABSTRACT

Weight and volume of mineral aggregates used in bituminous mixtures are respectively at the rate 90-95% of mixture weight, 75-85% of mixture volume. Physical and mineralogical properties of mineral aggregates on which load bearing capacity of pavement depends affect the properties of mixture, workability of fresh mixture and performance of pavement directly. The more bituminous mixtures are workable, the more they are compactable. Easily compactable bituminous mixtures (high workability) can rut easily and quickly under traffic. In contrast, mixtures with low workability (harsh mixtures) proved to be less prone to rutting under the same conditions. Because of this reason, in recent years highway engineers in the USA and some European countries prefer less workable bituminous mixtures. Angularity of aggregate particularly that of fine aggregate is a primary factor to affect the workability of a bituminous mixture.

In the eighties, SUPERPAVE in the USA and Gyratory Shear Press in France, design methods and rutting experimental studies show us that, dense graded mixtures are good for rutting and shear resistance. Also during these studies, it is determined that, angularity of aggregate and especially fine aggregate angularity (FAA) is important for rutting resistance. Because of this reason, new specifications were prepared for FAA properties. These specifications are AASHTO TP-33 and ASTM 3398 in USA, and AFNOR P18-564 in France.

The aim of this study is to investigate the angularity of fine aggregate produced in Turkey and to draw the attention of the design engineers to this subject. Because of the absence of a specification for FAA in Turkey AFNOR P18-564 was used for the tests. FAA test were performed on different samples taken from different regions and crushed by different types of crushers, including some natural sands:

In the first chapter, Fine Aggregate Angularity is defined. Definition varies depending upon country. In the following chapters, previous studies, and experimental researches are outlined. The place of this study in the literature was emphasized.

Mineral Aggregates in bituminous mixtures, and mineral aggregate properties, which are related with FAA, are explained in detail. Previous design methods, which do not take into consideration FAA and the recently developed design method (SUPERPAVE), which considers FAA directly, are summarized and compared.

Types of failures occurring in pavements and their reasons are explained and it is a relation between failures and FAA was searched. Then, crushers are classified.

Detailed experimental specifications are explained in chapter six. It was concluded that AFNOR Specification or an eventual European Specification should be adopted in Turkey since She is a candidate to European Union. In the next part, laboratory test results performed are presented and evaluated.

Finally, conclusions are drawn and suggestions are made in the last chapter. Whole study is revaluated in this section. Results obtained show that FAA depends on so many factors, which have to be considered, and it is emphasized that angularity experiments must be made in place.

ÖZET

Bitümlü karışımlarda kullanılan mineral agrega miktarı karışımın ağırlıkça % 90-95'ini, hacimce de % 75-85'ini oluşturmaktadır. Üstyapının yük taşıma kapasitesini sağlayan mineral agregaların fiziksel ve mineralojik özellikleri, karışımın özelliklerini de doğrudan etkiler, taze karışımın işlenebilirliğini ve kaplama performansını belirler. Bitümlü karışım ne kadar çok işlenebilir ise o kadar kolay sıkışmakta, kolay sıkışan karışımlar da trafik altında o kadar çabuk ve kolay oluklanmaktadır. Tersine karışım ne kadar az işlenebilir ise o kadar zor sıkışmakta ve trafik altında da o kadar az oluklanmaktadır . Bu nedenle son yıllarda üstyapı tasarımcıları zor sıkışan (işlenebilirliği düşük) bitümlü sıcak karışımları tercih etmekte ve bu özelliği yoğurmalı presle (Gyratory Shear Press veya Gyratory Compactor) belirlemektedirler. Kumun köşeliliği de işlenebilirliği etkileyen en önemli faktörlerden biridir.

1980'li yıllarda A.B.D.'nde 'SUPERPAVE' ve Fransa'da 'Gyratory Shear Press' dizayn yöntemlerinin ve tekerlek izi oluşumu (oluklanma) deneyinin (rutting test) geliştirilmesi sırasında yapılan çalışmalar yoğun gradasyonun tekerlek izi oluşumu ve kayma ile ilgili deformasyonlar açısından uygun olmadığını ortaya koymuştur. Bu çalışmalar aynı zamanda agreganın ve özellikle ince taneli agreganın köşeliliğinin önemini göstermiştir. Dolayısı ile yeni köşelilik deneyleri şartnamelere girmiştir. Bu deneyler Amerika'da AASTHO TP33 ile ASTM 3398 ve Fransa'da AFNOR P18-564 no'lu standartlarda tanımlanmışlardır.

Bu çalışmada, ülkemizde bitümlü karışımlardaki ince agrega köşeliliği standardının bulunmaması nedeni AFNOR tarafindan Aralık 1990 da yayınlanan P18-564 no'lu deneysel standart kullanılmıştır. Değişik bölge ocaklarından alınan,

farklı mineralojik özelliğe sahip ve farklı konkasör tiplerinde kırılarak elde edilmiş ince agregaların akış katsayıları (köşeliliği) tespit edilmiştir.

Birinci bölümde çeşitli ülkelerdeki ince agrega köşeliliği tarifleri verilmiştir. İzleyen bölümlerde ise daha önce yapılmış teorik ve deneysel çalışmalardan genel çerçevede bahsedilmiştir. Üzerinde durulan bir nokta da bu çalışmanın literatürdeki yeridir.

Bitümlü karışımlardaki mineral agregalar ve mineral agregaların, ince agrega köşeliliği ile doğrudan ilişkili olan fiziksel özellikleri detaylı olarak incelenmiştir. İnce agrega köşeliliğini dikkate almayan eski dizayn metodları ile, doğrudan dikkate alan, Amerika'da yeni geliştirilmiş olan (SUPERPAVE) dizayn metodları tanımlanmıştır.

Yol kaplamalarında görülen bozulmalar ve oluşum nedenleri açıklanmıştır. İnce agrega köşeliliği ile oluşan bozulmalar arasındaki ilişkiler saptanmaya çalışılmıştır. Kırıcı tipleri sınıflandırılmış ve daha iyi köşelilik değerleri sağlayan kırıcı tipleri belirtilmiştir.

Altıncı bölümde, ince taneli agrega köşeliliği ile ilgili deneysel standartlar ayrıntılı bir şekilde anlatılmıştır. Avrupa Birliğine girmeye aday bir ülke olan Türkiye için AFNOR standardının ya da çıkacak bir Avrupa standardının uygun olacağı sonucuna varılmıştır. Yedinci bölümde ise laboratuar test sonuçları, belirli bir çerçeve içinde değerlendirilmiştir.

Son olarak, sekizinci bölümde sonuçlar ve öneriler yer almaktadır. Bu bölümde tüm çalışmanın bir değerlendirilmesi yapılmıştır. Sonuçlara göre ince agrega köşeliliği bir çok faktöre bağlıdır. Bunların hepsinin laboratuar koşullarında göz önüne alınması mümkün değildir. Dolayısıyla köşelilik çalışmaları bütün faktörler dikkate alınarak ocaklarda yapılmalıdır.

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CHAPTER ONE
INTRODUCTION

1.1 Fine Aggregate Angularity

The properties of hot mix asphalt (HMA) are affected substantially by the characteristics of aggregates, including shape and surface texture. This is not surprising as approximately 75-85% of the total volume and 90-95% of the total weight of HMA consists of mineral aggregates.

“Aggregate shape is one of the important properties that should be considered in the mix design of asphalt pavements to avoid premature pavement failure and decrease in pavement performance”(Oduroh et al.,2000,p.124).

“Generally, angular and rough textured aggregates produce higher quality HMA than smooth, rounded aggregates” (Freeman et al.,1999,p.539).

Physical and mineralogical properties of mineral aggregates, which supply load-bearing capacity of pavement, affect directly properties of mixture, workability of fresh mixture and performance of pavement. The more workable bituminous mixtures, the more compactable they are. Easily compactable bituminous mixtures can rut easily and quickly under traffic. In contrast, mixtures with lower workability (harsh mixtures), are less prone to rutting under the wheel path occurs under same traffic conditions. Because of this reason, in recent years highway engineers in the USA and some European countries prefer less workable bituminous mixtures, which are difficult to compact. Angularity of aggregate is the primary factor to affect workability.

Proper selection of aggregates in HMA can minimize the potential for premature pavement failures such as rutting, stripping, and fatigue cracking. NCHRP Report 4-19 (1997) stated that a cubical and angular aggregate particle shape for both coarse and fine aggregate is desirable for increased aggregate internal friction and improved rutting resistance (Oduroh, et al.,2000,p.124) and also SHRP (1993) at the same manner states, "By specifying coarse and fine aggregate angularity SUPERPAVE seeks to achieve HMA with a high degree of internal friction and thus, high shear strength for rutting resistance".

Many researchers (Hicks,1970; Hicks and Monismith,1971; Allen,1973; Allen and Thompson,1974; Thom,1988; Barksdale and Itani 1989; Thom and Brown,1989) have reported that crushed aggregate, having angular to subangular shaped particles, provides better load spreading properties and a higher resilient modulus than uncrushed gravel with subrounded or rounded particles. A rough particle surface is also said to result in a higher resilient modulus. Barksdale and Itani (1989) investigated several types of aggregate and observed that the resilient modulus of the rough, angular crushed materials was higher than that of the rounded gravel by a factor of about 50% at low mean normal stress and about 25% at high mean normal stress. 'Although increasing particle angularity and surface roughness could result in higher resilient modulus,...(Hicks,1970; Hicks and Monismith,1971; Allen,1973)'. Lateral resilient movements being controlled by interparticle contact condition. (Freeman,1999,p.1).

'Field investigation have concluded that natural sand is a primary cause of premature rutting (Brown,1983; Anderson,1990; Ahlrich et al.,1992)' (Freeman,1999,p.1)

1.1.1 Fine Aggregate Angularity in USA (SUPERPAVE)

The selection of aggregates is based on two groups of physical property requirements, which are specified in the SUPERPAVE mixture design method in USA and also Gyratory Shear Press design method in France. The first group, which includes coarse and fine aggregate angularity, amount of flat and elongated particles and clay content; is named as *consensus properties* by Strategic Highway Research Program (SHRP) researchers. The second group of physical requirements includes toughness, soundness, and deleterious materials.

SHRP researchers believed that, the first group was critical in achieving high performance hot mix asphalt. The values of the physical requirements vary depending on the expected traffic and the location of the mixture in the pavement. High traffic levels and surface mixtures require more strict values for physical (*consensus*) properties. Many agencies in the USA and some European Countries have already used these quality requirements for aggregates used in bituminous mixtures.

The SUPERPAVE mixture design method depends on aggregate properties and volumetric properties. One of the aggregate properties of the SUPERPAVE mix design process is the fine aggregate angularity (FAA). The goal of this requirement is to insure that fine aggregates have significant effect on asphalt mixture rutting potential, because of high internal friction will minimize rutting.

If all the requirements are met, the resulting mix design should have:

- *A strong aggregate skeleton for permanent deformation resistance.*
- *Sufficient asphalt binder* (asphalt cement) *for fatigue and asphalt binder aging resistance.*
- *Sufficient air void space to hold plastic properties at bay and prevent permanent deformation* (Huber&McGennis,1996,p.4).

An issue is the difficulty of obtaining adequate voids in the mineral aggregate. The packing characteristics of aggregate particles and hence void in the mineral aggregate depends on three factors:

- Gradation
- Surface Texture
- Shape

The SUPERPAVE mix designers say that additional fine aggregate will increase voids in the mineral aggregate but the specifications prevent adding sand because of the weakening effect which will occur in the aggregate skeleton. Two competing demands are occurring during the SUPERPAVE mix design. Sufficient interparticle space must be available for a minimum amount of asphalt binder and the aggregate must have a sufficiently strong skeleton to carry traffic loads.

The shape of the particles influences the density for any gradation. Angular particles are not packed as tightly as flat particles. Under traffic conditions, the flat particles lay down, one on the top of the other. Therefore, there is not much space between them. The void in mixtures is low.

Under traffic pressure, particles are flattened out. The same effect occurs in gyratory compacted test specimen. Under Marshall compaction the particles are not so free to rotate. In fact, flat particles tend to bridge in a Marshall mold and give high voids in mixture. Therefore designer should be aware of the influence of particle shape when comparing Marshall specimens to SUPERPAVE specimens.

The following two tests are available for determination of fine aggregate shape, angularity and surface texture:

a- Index of Aggregate Particle Shape and Texture (ASTM D3398),
b- Uncompacted Void Content of Fine Aggregate (as influences by particle shape, surface texture and grading), (AASHTO TP33 or ASTM C1252).

> *Although both tests are ASTM standards, several issues need to be addressed. For example, there is an inconsistency between the usual definition of fine aggregate and the sizes of the particles tested. Other factors that need examination are the effects of gradation on the measured values and a convenient procedure for determining values for blends of several aggregates.* (Hossain et al.,1999,p.64)

Both tests have predominantly been used for research purposes. (See Chapter 6 for detail.)

In AASHTO TP33 fine aggregates defined as material passing the 2,36 mm sieve must possess sufficient internal friction to resist permanent deformation of the mix. Rounded natural aggregates are considered undesirable. Recommended values are dependent upon the amount of traffic and the depth at which the pavement layer is located (Table 1.1).

Table 1.1 Fine Aggregate Angularity Requirements in USA (Uncompacted Void Content)

Traffic Level (ESALs)*	Surface Mixes (<100 mm from surface) %	Lower Mixes (>100 mm from surface) %
$<3x10^5$	-	-
$<3x10^6$	40	-
$<3x10^7$	45	40
$\geq 3x10^7$	45	45

(AASHTO,1993). *Equivalent Single Axle Loads

1.1.1 Fine Aggregate Angularity in France

Fine aggregate defined as material passing the 4 mm (No: 5) (coarser fine aggregate) and material passing 2 mm (No: 10) sieve. Fine aggregate angularity is measured by using AFNOR P18-564 standard method of test, "Flow Rate of Fine Aggregate" (see chapter 6., for detail).

Recommended values are given in the documents of "Union Nationale des Producteurs de Granulats." which are dependent upon the amount of traffic. (Table 1.2).

Table 1.2 Fine Aggregate Angularity in France

	IC30	IC60	IC100	RC2	RC4
EC_g 6,3/10 mm	Vsi 85	Vsi 95	Vsi 105	Vsi 110	Vsi 110
FC_s 0/2 mm	Vsi 30	Vsi 35		Vsi38	

(UNPG,1990-La Norme XP P18 540)

Here,

IC = Crushing Index
RC = Crushing Ratio
Vsi = Average Flow Rate

The design aggregate structure approach ensures that the aggregate will develop a strong, stone skeleton to enhance resistance to permanent deformation while allowing for sufficient void space to enhance mixture durability.

1.1.2 Coarse Aggregate Angularity in USA

Coarse aggregate defined as particles larger than 4,75 mm in ASTM E-11

"The values of coarse aggregate angularity, which is defined by the percent of particles with one and two fractured surfaces, is required to be 95/90 for mixtures to be placed near the pavement surface and for an expected traffic level between 10^7 *ESALs and* $3x10^7$ *ESALs [where 95/90 denotes the percent of particles with*

one fractured face (95 %) and with two fractured faces (90 %)]; angularity is required to be 100/100 for a mixture to be used near the pavement surface and with an expected traffic greater than $3x10^7$ ESALs." (Chen, 1995, p.1369)

The crushing operation can make a difference on aggregate particle shape. Aggregate crushed faces ensure an adequate aggregate skeleton to resist shear forces that cause rutting. The requirement for crushed faces is dependent on traffic volume and on the pavement layer. High traffic volumes typically call for more crushed faces. Upper pavement layers particularly surface courses; require more crushed face than the lower layers.

Table 1.3 Coarse Aggregate Angularity Requirements in USA

Traffic Level (ESALs)	Surface Mixes (<100 mm from surface) %	Lower Mixes (>100 mm from surface) %
$<3x10^5$	55/-	-/-
$<10^6$	65/-	-/-
$<3x10^6$	75/-	-/-
$<10^7$	85/80	65/-
$<3x10^7$	95/90	80/75
$<10^8$	100/100	95/90
$0>10^8$	100/100[1]	100/100

(Kennedy,1994 – SHRP A-410)

CHAPTER TWO
BITUMINOUS MATERIALS AND MIXTURES

2.1 Bituminous Materials

Bitumen is defined as an amorphous, black or dark colored (solid, semisolid, or viscous) cementitious substance, composed principally of high molecular weight hydrocarbons, soluble in carbon disulfide (ASTM, 1994). For civil engineering applications, bituminous materials include primarily asphalts and tars. Asphalts may occur in nature (natural asphalts) or may be obtained as condensates in the processing of coal, petroleum, oil shale, wood or other organic materials (ASTM, 1994). For civil engineering applications, bituminous materials include primarily asphalts and tars. Asphalts may occur in nature (natural asphalts) or may be obtained from petroleum processing (petroleum asphalts). Tars don't occur in nature and are obtained as condensates in the processing of coal, petroleum, oil shale, wood or other organic materials (ASTM, 1994). Pitch is farmed when a tar is partially distilled so that the volatile constituents have evaporated off from it. The terms bituminous mixtures is generally used to denote the combinations of bituminous materials (as asphalt cement), aggregates, and additives. Tars are not used in road construction any more.

2.1.1 Types of Bituminous Materials

Asphalt Cement:

It is an asphalt that has been specially refined as to quality and consistency for direct use in the construction of asphalt pavements, and has penetration at 25^{0}C of between 5 and 300 (ASTM,1994). Asphalt cement has to be heated to an appropriate high temperature in order to be fluid enough to be mixed and placed.

Liquid Petroleum Asphalts (Cutback Asphalts):

It is a liquid asphalt, which is a blend of asphalt and petroleum solvents (such as gasoline and kerosene). Cutback asphalt can be mixed and placed with little or no application of heat. After cutback asphalt is applied and exposed to the atmosphere, the solvent will gradually evaporated leaving the asphalt cement to perform its function as a binder. Cutback asphalts are classified into three main types on the basic of the relative speed of evaporation of the solvents in them. Rapid curing (RC) cutback asphalts are composed of asphalts cement and a solvent (naphtha or gasoline), which evaporates at a fast speed. Medium curing (MC) cutback asphalts contains a solvent of volatility similar to that of kerosene, which evaporates at the medium speed. Slow curing (SC) cutback asphalt containing an oil of relatively low volatility.

Asphalt Emulsions:

It is an emulsion of asphalt cement and water, which contains a small amount of emulsifying agent. In normal emulsified asphalt, the asphalt cement is in the form of minute globules in suspension in water. Emulsified asphalt can be mixed and applied without any application of heat. After asphalt emulsion is applied, sufficient time is required for the emulsion break and the water evaporate to leave the asphalt cement, to perform its function as a binder. In inverted emulsified asphalt, minute globules of water are in suspension in liquid asphalt, which is cutback asphalt. Inverted asphalt emulsions are seldom used in pavement applications.

Asphalt emulsions are divided into three major kinds, namely anionic, cationic, and non-ionic on the basis of the electrical charges of the asphalt particles in the emulsion. Anionic asphalt emulsions have negatively charged asphalt particles and usually more suitable for use with limestone aggregates, which tend to have positive surface charges. Cationic asphalt emulsion have positively charged asphalt particles and usually more suitable for use with siliceous aggregates, which tend to have negative surface charges. However cationic emulsion, give satisfactorily results with most of the aggregate types. Non-ionic asphalt emulsions contain asphalt particles that are electrically neutral. Non-ionic asphalt emulsions are not used in pavement applications.

Asphalt emulsions are further classified into three main types on the basis of how quickly the suspended asphalt particles revert to asphalt cement that means rate of setting. The three types are rapid setting (RS), medium setting (MS) and slow setting (SS).

RS emulsions are designed to demulsify (to break) upon contact with an aggregate, very quickly. MS emulsions are designed to have good mixing characteristics with coarse aggregate and demulsify after proper mixing. It is suitable for applications where mixing with coarse aggregate is required. SS emulsions are designed to be very stable in the emulsion form and are suitable for use where good flowing characteristics are desired or where mixing with fine aggregates is required.

2.2.Bituminous Mixtures

The term *bituminous mixture* can be generically applied to the combination of bituminous materials, properly graded aggregates and other material additives. Bituminous mixture are utilized in a wide range of applications including roofing, dam facing, reservoir lining etc, although, their main use is as paving material (Asphalt Institute,1977). Thus, the emphasis of this section is on the utilization of bituminous mixture in pavement construction.

Bituminous mixture for diverse applications is obtained by mixing different types of asphalt binders with aggregates of various gradations;

Hot Mix Asphalt (HMA) is also known as asphalt concrete, bituminous concrete, asphalt paving mix, bituminous mixture, bituminous paving mix, etc. It is typically produced in a stationary mixing plant transported to the site, placed and compacted to a specified density. In the production of HMA mixtures, asphalt cement liquefies by heating to a temperature high enough, to allow proper mixing with the aggregates but low enough to prevent premature aging of the asphalt cement. The aggregates for HMA mixtures should be selected with care and controlled to comply with stringent specifications for particle size distribution and other properties. HMA mixtures are used in construction of full depth asphalt pavements wearing and surface courses, asphalt concrete overlays for flexible and rigid pavements.

Cold laid mixes are obtained by mixing (generally at ambient temperature) mineral aggregates and asphalt emulsion or asphalt cutback. These types of bituminous mixtures are generally used in construction of pavement bases or for pavement patching and repair.

Road mixes are obtained by mixing mineral aggregates and asphalt emulsion or asphalt cutback. Road mixes are produced near the construction site in transportable plants or by mixing the asphalt and aggregate materials on the road surface by means of graders or special road mixing equipment. These type of mixtures are used in pavements for low traffic volume.

Stone Matrix Asphalt (SMA) mixes are obtained by combining gap-graded aggregates with asphalt-rich binder mastic. These types of mixtures have successfully been used in pavement construction in Europe to prevent excessive rutting.

Slurry seal mixes are utilized in crack filling and sealing of medium and highly textured pavement surfaces. Slurry seals are mixtures of emulsified asphalt, water, well-graded fine aggregate, and mineral filler. Different slurry seal mixes can be obtained by combining asphalt emulsions of varying setting times with aggregate of 3 mm (1/8 in.) to 9.5 mm (3/8 in.) maximum particle size.

2.3. Aggregates for Bituminous Mixtures

Mineral aggregates used in bituminous mixtures are respectively 90-95% by weight, 75-85% by volume of the total mix. Moreover, the aggregate is primarily responsible for the load supporting capacity of bituminous mixtures. Not only may the aggregate limit the performance of bituminous mix, as aggregate with undesirable properties cannot produce strong mix, but the physical properties, mineralogical properties and sometimes also chemical properties of aggregate affect the performance of bituminous mixture. Therefore, a detailed discussion of the physical properties of aggregates is important for the understanding of the design and performance of bituminous mixtures.

2.4 Sources of Aggregates

Aggregates may be of natural, processed or synthetic origin. The majority of aggregates used in road construction are obtained from naturally occurring deposits, natural aggregates such as sand and gravel obtained from transported deposits, river deposits, alluvial fans and glacial outwash.

Processed aggregates are obtained by crushing and screening of quarried rock, oversize gravel and boulders. Crushing reduces the size of the rock particles to make them suitable for use in bituminous mixtures. Crushing also changes the texture and shape of the particles. Screening follows crushing that is used to adjust the particle size and especially to eliminate the very fine or the very large particles.

Synthetic aggregates may be obtained as a by-product of some industrial processes or from the processing of raw materials for ultimate use as aggregates. “In Turkey and in the United States, the primary source of industrially prepared aggregates for road building is blast furnace slag which is a by product of the smelting” (Uluçaylı,2001)

Other synthetic aggregates are manufactured by high temperature processing of clay, shale, slate and other natural materials. Synthetic aggregates are typically light and may have high resistance to abrasion. "Materials obtained from the recycling of waste products such as glass and tires have also been studied as potential sources of aggregates for bituminous mixtures, especially because of the increasing awareness of the need for protection of the environment"(CHEN,1995, p.1248).

2.5 Classification of Aggregate

Mineral aggregates may be classified in a number of different ways;

2.5.1 Petrological Classification

Rocks are classified into three major groups based on their origin of formation: Igneous, sedimentary, and metamorphic rocks.

Igneous Rocks:

Rocks that have solidified from a fluid silicate melt or magma taking place either beneath or at the earth's surface. Their fabrics depend on their crystallization environment. If cooling progresses very slowly beneath the surface, crystallization occurs slowly and the resulting crystals are coarse grained. These rock formations are termed intrusive and plutonic. Rocks formed in this environment are ***granite, syenite, diorite and gabbro****. If cooling takes place rapidly at or near the earth's surface the resulting crystals are small, the rock is microcrystalline. If the cooling is very rapid, the rock is cryptocrystalline or even glassy. These fine-grained rocks are* ***basalt, andesite and rhyolite****. Between the intrusive and extrusive ignenous rocks, the minor intrustive (hypabyssal) rocks are found. These are* ***dolerite, porphyrite and quartz porphyry****. The hypabyssal rocks are found generally in dykes and sills* (Wills,1984).

The classification of igneous rocks is based on their mineral content. The main mineral component of magma is silica. Total silica quantity of the magma varies between 35-75 % by weight. Silicates are the largest group of rock-forming minerals. The silicates comprise in increasing order of the complexity of atomic structure and in decreasing order of mineral specific gravity olivine, pyroxene, amphiboles (hornblende), biotite and muscovite micas, feldspars and quartz. Rocks having high silica content are termed acid, and having low silica content that is a large group of basic oxides, are termed basic. Acid rocks contain 66% total silica basic rocks have 45-52 %. Between these rocks, intermediate rocks have 52-66 % total silica and ultra basic rocks contain less than 45%.

Acid rocks contain free quartz 10 % or more generally, while basic ultra basic rocks do not have any. Intermediate rocks have a low free quartz percentage. (Collis&Fox,1985)

Sedimentary Rocks

Rocks that have been formed by consolidation at atmospheric conditions, or cementing of deposited fragmentary materials that have been eroded from pre-existing rocks, or by the concentration of inorganic materials by chemical and/or mechanical progress.

Sedimentary rocks are divided in to two main groups according to their formation modes: clastic rocks and sedimentary rocks formed in-situ.

Clastic rocks *include the consolidated fragmentary materials that have been eroded from pre-existing rocks. These rocks are classified in decreasing order of grain size as* ***conglomerate, breccia, sandstone*** *(gritstone), and* ***shale*** *(mudstone). Sandstones and gritstones are used as aggregates in road construction*

Limestone and flint *are* ***sedimentary rocks*** *formed in-situ and they are used for road construction. The origins of limestones are chemical organic or the* *combination of them. They are composed of calcium carbonate in the form of calcite, organic remains, fossils, and may also contain magnesium carbonate as magnesian limestone. Dolomitic limestone contains both the dolomite and calcite. Limestones may contain impurities such as clay, mud, and quartz grains. Flints are irregularly shaped nodules, which occur in horizontal layers and vertical joints in the chalk. Flint particles are hard and brittle. Their shape textures are influenced by their mode of occurrence. The properties of flint are not ideal for the coarse aggregate of, durable, bituminous mixtures for roads and airfields, although their abrasion resistance is high.*

The most important characteristic of sedimentary or layered rocks is their flat and layered structure, bedding and stratification properties. The physical properties of sedimentary rocks depend upon the mineral composition, texture, fabric, structure, cementation, and porosity.

Most minerals in clastic sediments are the same as primary igneous rocks, sedimentary rocks and metamorphic rocks. Clastic sedimentary textures consist of the following components: sorting, roundness, packing, and fabric.

Sorting indicates the degree of similarity of grain sizes that reflect the transporting agent. Roundness of grains exhibits the degree of abrasion by the sharpness of the edges and corners. Packing of grains shows the relationship of the grains or to inter granular spacing. Fabric of sediments expresses the grain orientation. (Collis&Fox,1985)

Metamorphic Rocks

Rocks formed by the mineralogical, chemical and structural alteration of pre-existing igneous and sedimentary rocks caused by the effect of temperature and pressure. Main rocks of this group are ***slate, crystalline marble, quartzite, greenstone*** *and* ***serpentine.***

These rocks are classified into two main groups. Contact metamorphic rocks, which alteration has been caused by the action intense heat at cooling process and regional metamorphic rocks, which alteration has been caused by the combined action of pressure and heat in the deeps of earth's crust. Minerals of metamorphic rocks are more stable than the parent rock material.

The contact metamorphic rocks are generally termed "hornfels" expects quartzite and marble. 'The action of heat' transforms the softer minerals of the country rocks in to harder (hornblende and feldspar). Hornfels are usually tough and hard, but they are rarely used for road stone. The principal regionally metamorphic rocks are schist and gneiss. Both rocks types have a banded texture. Gneiss is much coarser than schist and it has lower platy minerals.

Not all of the metamorphic rocks have good engineering properties. Schist are rich in mica, therefore it is not suitable. Only certain gneisses, greenstone, quartzites and slates are used. (Collis&Fox,1985)

2.5.2.Group Classification

"A practical classification system of aggregates was needed to provide the systematic selection of aggregates, and deciding on the suitability of a particular aggregate source for a specific engineering purpose. (Pike,1990,p.280)

For this reason, various revisions on standards were made and BS 812:Part1: 1975 edition was adopted. This classification is given in Table 2.1

In this table, the name of each natural rock group represents the main rock within this group.

Table 2.1.Group Classification of Aggregates (BS 812:Part 1:1975)

1	Article Group	Crushed brick, slags, calcined bauxide, synthetic aggregate.
2	Basalt Group	Andesite, basalt, basic porphyrite, diabase, dolerites of all kinds, including theralite and teschenite, epidiorite, lamprophyre, quartz-dolerite, spilite.
3	Flint Group	Chert, flint.
4	Gabbro Group	Basic diorite, basic gneiss, gabbro, hornblende-rock, norite, peridotite, picrite, serpentinite.
5	Granite Group	Gneiss, granite, granodiorite, granulite, pegmatite, quarz-diorite, syenite.
6	Gristone Group	(Including fragmental volcanic rocks) Arkose, greywacke, grit, sandstone, tuff.
7	Hornfels Group	Contact-altered rocks of all kinds except marble.
8	Limestone Group	Dolomite, limestone, marble.
9	Porrphyry Group	Aplite dacite, felsite, granophyre, keratophyre, microgranite, porphyry, quartz-porpyric, rhyolite, trachyte
10	Quartzite Group	Ganister, quartzitic sandsones, recrystallized quartzite
11	Schist Group	Phyllite, schist, slate

There are four igneous rock groups in this table:

- **Granite** : Acid, coarse
- **Porphyry** : Acid, fine
- **Gabbro** : Basic, coarse
- **Basalt** : Basic fine

Four sedimentary rock groups are defined as the following rock types:

- **Flint** : Nodules of cryptocrystalline silica
- **Gritstone** : Arenaceous rocks
- **Limestone** : Carbonate rocks including marble
- **Quartzite** : Rocks including recrystallized quartzite

Two metamorphic rock groups are also given in this table:

- **Hornfels** :Contact metamorphic rocks
- **Schist** :Regional metamorphic rocks

The group classification doesn't imply suitability of any aggregate for bituminous mix making, unsuitable material can be found in any group.

2.5.3 Mineralogical Classification

Aggregate mineralogy influences of the performance of bituminous mixtures. For example, the adhesion of asphalt cement to the aggregate surface is higher in carbonate aggregates than in siliceous aggregates. The presence of certain minerals as coating on the surface of the aggregate particles affects the band with the asphalt cement and the propensity to absorb moisture.

> *Clay, gypsum, iron oxides, silt and minerals may have either poor adhesion with the asphalt binder or a propensity to absorb moisture and break the band between the aggregate and the asphalt. Certain minerals such as quartz and feldspars are hard and resistant to polish, enabling the asphalt mixture to maintain its skid resistance under the abrasive effect of traffic. Aggregates from sedimentary rocks such as limestone and dolomite, in contrast, can have a tendency to be polished under the action of traffic.* (Chen,1995)

ASTM standard C 294-86 gives a description of some of the more common or important minerals found in aggregates mineralogical classification helps in recognizing the properties of aggregate but cannot provide a basis for predicting its performance in mixtures. The ASTM classification of minerals is summarized below:

Silica minerals (quartz, opal, chalcedony, tridymite, cristobalite)
Ferromagnesian minerals
Micaceous minerals
Clay minerals
Zeolites
Carbonate minerals
Sulfate minerals
Iron sulfide minerals
Iron oxides
(Neville,1997).

2.5.4 Chemical Classification

The chemical composition of aggregates is generally given in terms of an oxide that is not informative of their potential performance in bituminous mixture. Nonetheless, the presence of certain substances can lead the performance problems. For instance, the presence of water-soluble moisture absorbing substances can produce mixtures that are susceptible to moisture damage in the form of aggregate stripping, ravelling, or loss of stability. Other substances may be susceptible to oxidation, hydration or carbonation.

2.6 Physical Properties of Aggregates

The suitability of aggregates to be used in bituminous mixtures depends on their physical and mineralogical properties and also relatively at lower level on their chemical composition. The physical properties of aggregates are, gradation, particle shape, surface texture, durability, cleanliness, toughness, and absorption. These properties are primarily control the performance of mixtures.

In this study, it is decided to investigate first three physical properties, specific gravity and absorption of fine aggregate and FAA properties in relations with these properties.

2.6.1 Gradation (Size Distribution)

One of the important classifications of aggregates for use in bituminous mixtures is based on size distribution, which affects the stability and working properties of mixture. The size of aggregate used in bituminous mixtures ranges from mineral filler (at least 65% by weight passing No. 200 sieve) to 25.4 mm (1 in.).

Aggregate particle size are typically divided into coarse [In ASTM designation, the particle size greater than No.4 (4.75mm) sieve, although some agencies use the No.8 (2.36 mm) or the No.10 (2.00 mm)], fine [Particle size between No.4 (4.75 mm) and No.200 (0.075 mm) sieve], and mineral filler [at least %70 by weight passing No.200 (0.075 mm) sieve].

In this study, sieve size of fine aggregate is taken in Pr EN 993-2 specification of aggregate size distribution, because in experimental studies, AFNOR P18-564 experimental specification was used.

Aggregate particle size is defined in terms of the maximum particle size and the particle size distribution.

> *The maximum particle size affects the workability and density of the mix, and also economy. Large particle sizes reduce the consumption of pavement per unit volume of mix. However, using larger particle size makes it more difficult to obtain proper compaction in the mix, "Especially, if the maximum particle size exceeds one-half the thickness of the compacted pavement layer."* (U.S. Army Corps of Engineers, 1991)

> *The particle size distribution is most commonly expressed as the weight percents of particle sizes mechanically screened with sieves of square openings. Other techniques are also used to separate the particles. The most common way to define the particle size distribution though is in term of the aggregate gradation,*

which is expressed in terms of weight percentages of particles retained (or passing) through a set of sieves with successively decreasing opening. (ASTM C136)

The gradation curve is the graphical representation of the particle size distribution with the ordinate defining the percent by weight passing a given size on an arithmetic scale, while the abscissa is the sieve size plotted to a logarithmic scale (Figure 2.1).

Aggregates may be divided on the basic of gradation as follows:

a) Dense-graded (Well graded)
b) Open-graded
c) One-sized
d) Gap-graded

Dense-graded Materials: "The dense-graded materials include appropriate amounts of all sizes from coarse to fine, including dust or material passing No.200. They are used in hot mix asphalts and other dense-graded types if mixtures." (Uluçaylı,2001)

Dense-graded mixture consists of well graded aggregates and asphalt cement as binder. A dense-graded mixture with nominal size of aggregate greater than 25.4mm (1 in.) is called a large-stone mix. By contrast, a sand mix is a dense-graded mix without course aggregates with %100 of the aggregate particles passing the 9.5 mm (3/8 in) sieve.

Open-graded Materials: "They may have an incomplete grading or they may differ from dense-graded materials in that they contain much less material passing the No.200 sieve. These materials are generally used for road or plant mixes." (Uluçaylı,2001)

Open-graded mixtures exhibit a very open structure with high permeability that allows water to drain through. Also open-graded mixtures exhibit a rough surface texture that enhances contact with vehicle tires, increasing the skid resistance.

One-sized Materials: "These materials contain, as the name implies, essentially one-size. These materials are generally used in penetration macadam, surface treatments and seal coats." (Uluçaylı,2001)

Gap graded Materials: Gap-graded mixtures consist of asphalt binder and a gap-graded aggregate that is an aggregate in which 2/4 or 4/6 mm fractions are missing or are present a very small amount.

"In recent years; laboratory research and field experience have shown that gab-graded aggregates when the mixture is designed lay Gyratory Shear-Press have better resistance to rutting. In addition they give "rough" surfaces with a high coefficient of friction. They are widely used in Europe and USA". (Uluçaylı,2001)

> *Stability of a bituminous mixture depends upon the number of points of contact between individual aggregate pieces resulting in high functional resistance. The number of points of contact is higher in dense graded mixes than open-graded or one-sized mixes. The increased number of contact is points result in a greater area for load transfer from one aggregate to another. This decreases the possibility of crushing of the individual aggregate piece by points loading.*
>
> *Logically, it might seem that the best method of obtaining high stability in a bituminous mixture could be to use the densest gradation possible with just enough bituminous material present to bind the aggregate together. The disadvantage of this concept is that such a mix will not contain enough space for bitumen, which is necessary to assure the durability of the mixture. Durability requires a certain amount of bitumen. (Uluçaylı, 2001)*

Table 2.2 Standard Sieve Sizes for Aggregate Given by Various Standards (mm or µm)

BS 410 :1986	BS 812: Section 13.1:1985	pr EN 993-2	ASTM E 11-87*
125.0			125
			100
90.0			
	75.0		75.0
63.0	63.0	63.0	
	50.0		50.0
45.0			
	37.5		
			37.5
31.5		31.5	
	28.0		25.0
22.4			
	20.0		
			19.0
16.0		16.0	
	14.0		
11.2			
	10.0		
			9.5
		8.00	
	6.30		6.30
5.60			
	5.00		
4.00		4.00	
	3.35		
2.80			
	2.36		2.36
		2.00	
2.00			
	1.70		
1.40			
	1.18		1.18
1.00		1.00	
	850		
710			
	600		600
500		500	
	425		
355			
	300		300
250		250	
	212		
180			
	150		150
125		125	
90			
	75		75
63		63	
45			
32			

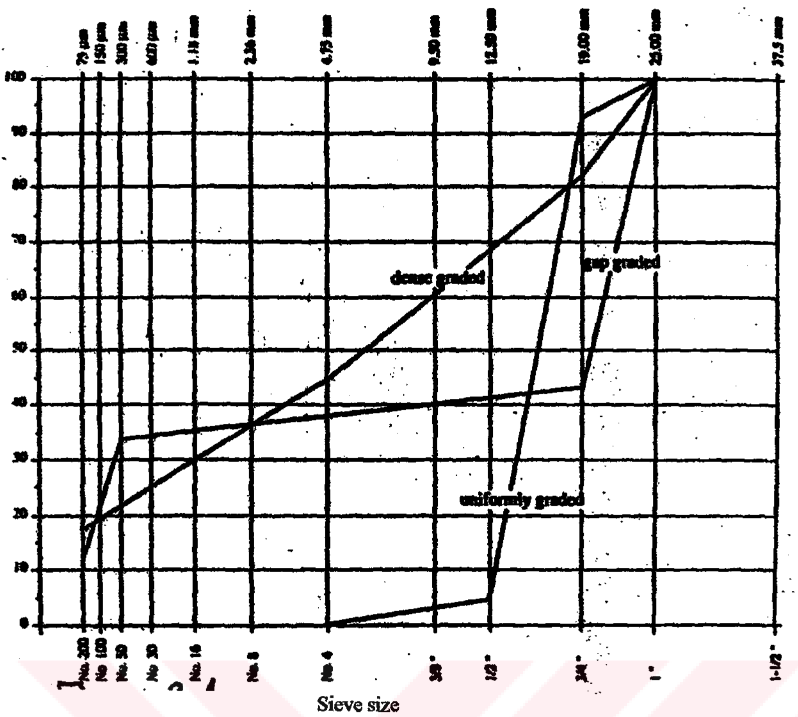


Figure 2.1 Various Gradations of Aggregates Plotted on a 0.45 Power Chart (Chen,1995)

A similar approach is given in the Civil Engineering Handbook as;

Several aggregate gradations have been proposed as optimum for the performance of bituminous mixes. The gradation that results in the best packing of particles, with minimum voids between them, produces maximum resistance to loads because of the large number of points with particle-to-particle contact. However, such an agglomerate of particles in an HMA mixture has a minimum volume of voids to be filled with the asphalt binder, which is required to ensure impermeability and cohesion in the mixture. The mixture with low voids in the mineral aggregate will tend to bleed, exuding the asphalt binder to the surface under the action of traffic. Also, a tightly packed aggregate results in a mixture that is very sensitive to small variations in asphalt content (CHEN,1995 pp.1350)

2.6.2 Particle Shape

The shape of three-dimensional particles is rather difficult to describe, therefore it is convenient to define certain geometrical characteristic of such bodies.

The shape characteristics of aggregate particles are classified in qualitative terms in BS.812 (Table 2.3)

Roundness measures the relative sharpness or angularity of the edges and corners of a particle. The strength and abrasion resistance of the main rock controls roundness. In the case of crushed aggregate, the particle shape depends on the nature of the main material, also on the type of crusher and its reduction ratio (The ratio of the size of material fed into the crusher to the size of the finished product).

A classification used in the USA is as follows;

- ***Well-rounded*** *: No original faces left*
- ***Rounded*** *: Faces almost gone*
- ***Subrounde*** *: Considerable wear, faces reduced in area*
- ***Subangular*** *: Some wear but faces untouched*
- ***Angular*** *: Little evidence of wear*

(Neville,1997)(Uluçaylı,2001)

British Standard BS 812; Part: 1975 defines the concept of angularity number; this can be taken as 67 minus the percentage of solid volume in a vessel filled with aggregate in a standard manner. The size of particles used in the test must be controlled within narrow limits.

Table 2.3 Particle Shape Classification

Classification	Description	Examples
Rounded	Fully water-wont Completely shaped by attrition	River or seashore gravel ; desert, seashore and wind-blown sand
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges	Other gravels: land or dug flint
Flaky	Material of which the thickness is small relative to the other two dimensions	Laminated rock
Angular	Posessing well-defined edges formed at the intersection of roughly planar faces	Crushed rocks of all types;talus crushed slag
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions	
Elaky and elongated	Material having the length considerably larger than the width, and the width considerably larger than the thickness	

(BS 812, 1975, Part 1)

The number 67 in the expression for the angularity number represents the percentage solid volume of the most rounded gravel, so that the angularity number measures the percentage of voids in excess of that in the rounded gravel. The higher number is the more angular the aggregate, the range for practical aggregate being between 0 and 11. A development in measurement of angularity of aggregate, both coarse and fine but of single size is an angularity factor defined is the ratio of the solid volume of loose aggregate to the solid volume of glass spheres of specified grading.

The void content of aggregate can be calculated from the change in the volume of air when a known decrease in pressure applied; hence, the volume of air, i.e. the volume of interstitial space, can be calculated.

A simple proof of dependence of the percentage of voids on the shape of particles is obtained from Figure 2.2 (Neville, 1997;Shergold's data)

The sample consisted of a mixture of two aggregates, one angular, the other rounded, in varying proportions, and it can be seen how increasing the proportion of rounded particles decreases the percentage of voids.

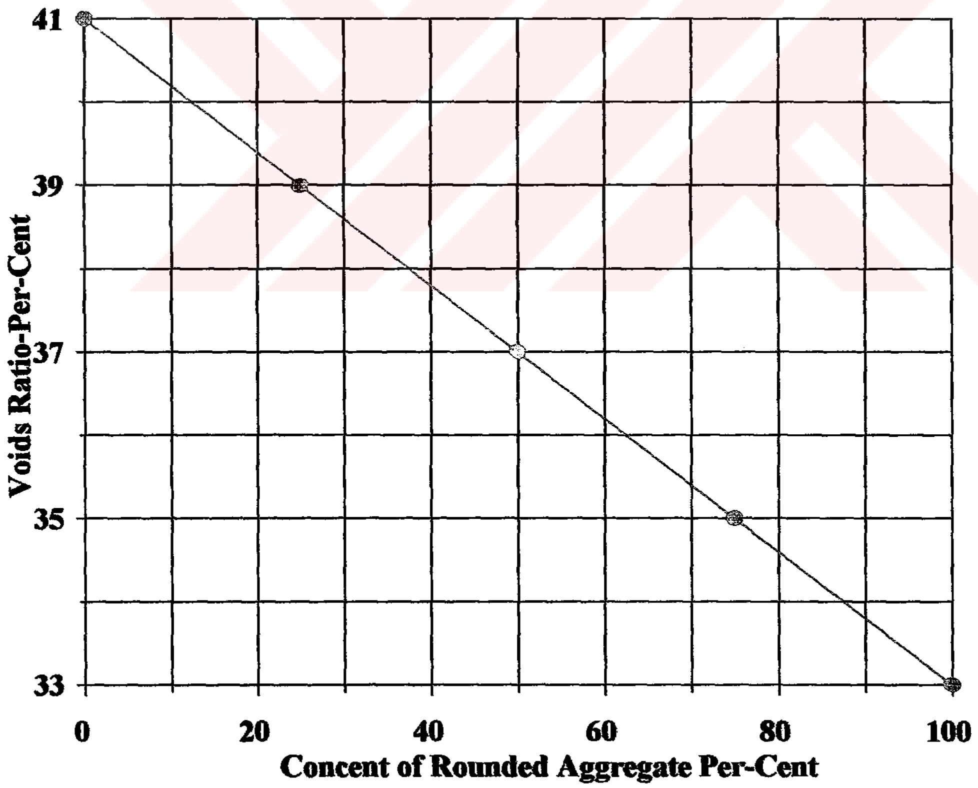


Figure 2.2 Influence of Shape of Aggregate on Voids Ratio

The shape of fine aggregate particles influences the mix properties (stability, workability, bitumen content, etc.), angular particles requiring more bitumen. Angular aggregate shape is desirable in bituminous mixtures. Neville mentioned about fine aggregate angularity as;

> "*Mixtures because better interlocking of aggregates is obtained but an objective method of measuring and expressing shape is not yet available despite attempts using measurement of the projected surface area and other geometrical approximations.* (Neville,1997)

The shape of coarse aggregate particle is concerned, equidimensional shape of particles is preferred because particles, which significantly depart from such a shape, have a larger surface area and pack in an anisotropic manner. Two types of particles, which depart from equidimensional shape, are of interest, elongated and flaky. The elongated flaky particle tend to be oriented in one plane, which affect adversely the durability of HMA.

The mass of flaky and elongated particle expressed as a percentage of the mass of the sample is called the flakiness and elongation index. The classification is described in BS 812; Section 105.1:1989:

- A particle is flaky if its thickness (least dimension) is less than 0.6 times the mean sieve size of the size fraction;

- Similarly, a particle whose length (largest dimension) is more than 1.8 times the mean sieve size of the size fraction is said to be elongated.

The mean size is defined as the arithmetic mean of the sieve size on which the particle is just retained and the sieve size through which the particle just passes. The flakiness and elongation tests are useful for general assessment of aggregates but they don't adequately describe the particle shape.

2.6.3 Particle Surface Texture

The classification of the surface texture is based on the degree to which the particle surfaces are polished or dull, smooth or rough. The type of roughness has also to be described. Surface texture depends on the hardness, grain size and pore characteristic of the parent material "hard, dense and fine-grained rocks generally having smooth surfaces"(Neville,1997) as well as on the degree to which forces acting on the particle surface have smoothed or roughened it. Visual estimate of roughness is quite reliable but, in order to reduce misunderstanding, the classification of BS 812; Part 1; 1975 given in Table 2.4, should be followed.

Table 2.4. Surface Texture of Aggregates (BS 812 Part 1:1975)

Group	Surface texture	Characteristic	Examples
1	Glassy	Conchoidal fracture	Black flint, vitreous slag
2	Smooth	Water-worn, or smooth due to fracture of laminted or fine-grained rock	Gravels, chert, Slate, marble some rhyolites
3	Granular	Fracture showing more or lesss uniform rounded grains	Sandstone, oolite
4	Rough	Rough fracture of fine-or medium-grained rock containing no easily visible crystalline constituents	Basalt, felsite, porphyry,limestone
5	Crystalline	Containing easily visible crystalline constituents	Granite, gabbro gneiss
6	Honeycombed	With visible pores and cavities	Brick, pumice, foamed slag, clinker, expanded clay

There is no recognized method of measuring the surface roughness. The shape and surface texture of aggregates influence considerably the strength of HMA the full role of shape and surface texture of aggregates in the development of HMA strength is not known, but possibly a rougher particle texture results in a larger adhesive force between the particles and the asphalt cement mix. Likewise, the larger surface area of angular aggregate means that a larger adhesive force can be developed.

2.6.4 Influence of Shape and Surface Texture on Stability

Angular and rough textured aggregates have much greater particle-to-particle contact than rounded and smooth texture aggregate. Thus, when high resistance to shearing forces is required, rough, angular-shaped aggregates are used. This influence of the particle contacts is present not only in the coarse aggregates, but also in rough, angular fine aggregates. As an example, when highly stable bituminous aggregate mixtures are needed, it is specified that both the coarse aggregates and the fine aggregates must be angular and rough surface texture crushed stone. Flaky and elongated aggregates are not used in road structures, as they tend to break easily under stress (University of Illinois Department of Civil and Environmental Engineering,1998).

2.6.5 Influence of Shape and Surface Texture on Workability

The ease of movement of one aggregate particle relative to another one is related to the number of contacts between the aggregate particles. Thus rounded, smooth textured aggregates have much better workability than rough angular aggregates. There is a noticeable increase in the ease of mixing a binder with gravel over mixing with crushed stone. It is also easier to compact gravel mixtures (University of Illinois Department of Civil and Environmental Engineering,1998).

2.6.6 Influence of Shape and Surface Texture on Amount of Asphalt Cement Required

"For the same weight of aggregate, an angular rough surface textured particle has a greater surface area than a rounded smooth surface textured particle. Larger amounts of bitumen are needed to adequately coat the larger surface areas of rough angular aggregate particles than to coat smooth rounded gravels" (University of Illinois Department of Civil and Environmental Engineering,1998)

2.6.7 Porosity

An important part of the classification scheme for aggregates is related to porosity. For an aggregate used in bituminous mixtures, the porosity affects the amount of asphalt required. Sufficient asphalt must be incorporated in the mixture to satisfy the absorption by the aggregate after mixing of me ingredients has been accomplished.

The porosity of an aggregate is generally reflected by its % absorption when immersed in water. A certain degree of porosity is desirable in an aggregate since it permits the bituminous material to penetrate in to the aggregate. This penetration aids in adhesion by forming a mechanical linkage between the aggregate and bituminous film. Thus, displacement of the bituminous film due to the action of water becomes more difficult. However, an aggregate that is highly porous has the disadvantage that the cost will be higher because of the cost of the extra bituminous material to fill the voids. (Uluçaylı, 2001)

Porosity is expressed as follows:

$$\% \text{ Absorbtion} = \frac{W_2 - W_1}{W_1} X100 \qquad (2.1)$$

W_1= Oven dry weight of aggregate

W_2= Saturated surface dry weight of aggregate after 24 hours soaking in water.

Various degrees of porosity indicated by highly porous, low porous, non-porous.

2.6.8 Specific Gravity

In general, specific gravity is defined as the ratio of a the weight of material to the weight of an equal volume of gas-free, distilled water at a specified temperature (20-25^{0}C).

Aggregates are porous materials; therefore, a distinction has to be made between the apparent volume of the aggregate particles and the volume of the solid portion of the aggregate particles, excluding the volume of the porous that can be saturated with water or with asphalt cement. Furthermore, the weight of the aggregate particles varies with the degree of saturation or presence of moisture inside the particles

The specific gravity of coarse aggregate (particles larger than the No: 4 (4.75mm) sieve) is determined by weighing the aggregate particles in air and calculating their volume from the weight of water displaced when they are immersed in it (It is described in ASTM C127). The specific gravity of fine aggregate [particles lower than No: 4 sieve (in this study No: 5(4.00 mm) sieve] is determined by some formulas (see chapter seven, Specific Gravity Test tables) used in calculations.

Several definitions of specific gravity are commonly distinguished depending on saturation conditions of the aggregate particles and on how their volume is measured as illustrated in Figure 2.3.

2.7 Voids in Bituminous Mixtures:

The compacted bituminous mixtures consist of fine and coarse aggregates, asphalt cement, mineral filler, and voids. After mixing, placing, and compaction, the mixture exhibits a relatively continuous matrix of asphalt cement and trapped air voids and the discontinuous phase of fine and coarse aggregates. Asphalt cement is used in the mixture that a part of it is absorbed in the surface porosity of the aggregates, and the remaining asphalt cement fills the space between the aggregate particles (Figure 2.4). The bulk specific gravity of the compacted bituminous mixture is the ratio between the weight in air of the compacted mix and the weight of an equal volume of water at a stated temperature.

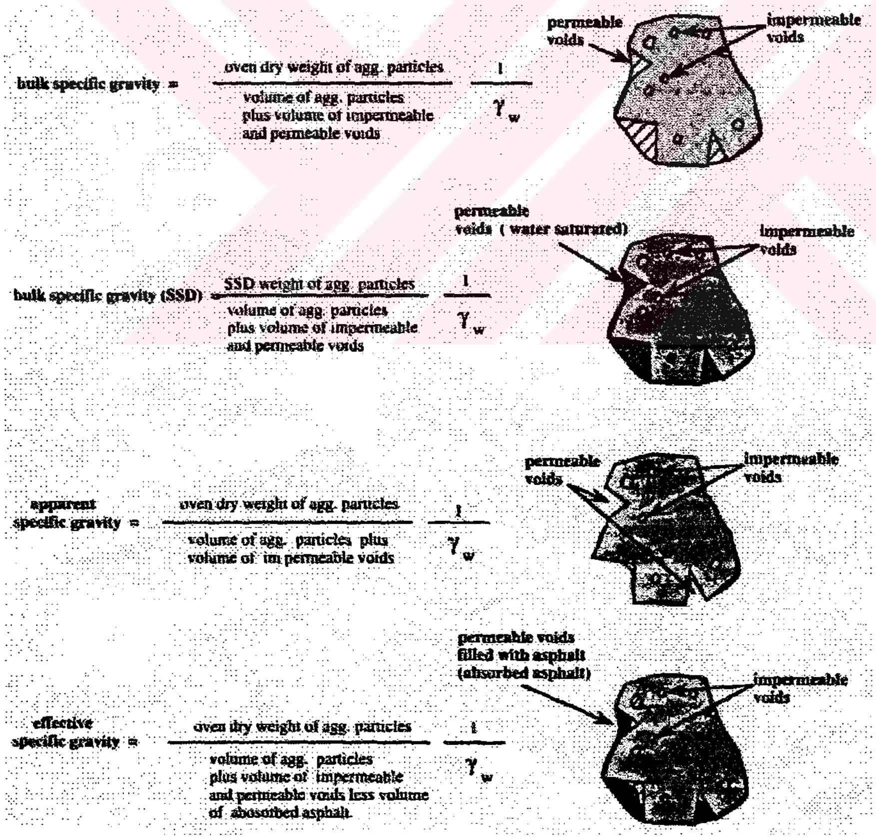


Figure 2.3 Illustration of Various Definition of Aggregate Specific Gravity (Chen,1995,p.1252)

The more aggregate surface roughness, the more asphalt cement rate absorbed in surface gaps. Also, the more aggregate angularity, the more asphalt cement rate because of increasing aggregate surface area.

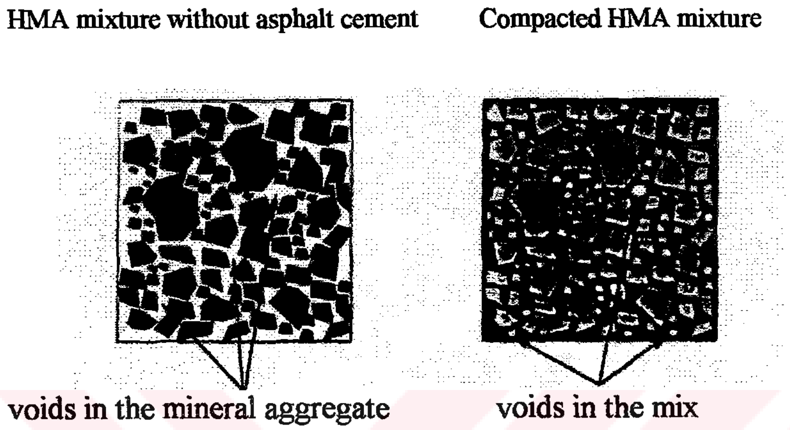


Figure 2.4 Voids in the Mineral Aggregates and in the Mixtures (Chen,1995,p.1252)

CHAPTER THREE

HOT MIX ASPHALT (HMA) DESIGN METHODS

Several procedures have been developed over the years to determine the mixture proportions. For example; Hubbard-Field method, Marshall method, Hweem method and others. Recently years, Strategic Highway Research Program (SHRP) in USA has developed a new methodology for bituminous mixture design. Although at this time the method is still in development and implementation stage.

3.1 Marshall Method

This method is the most commonly used method to design bituminous mixtures throughout the world. This method is primarily used for mixtures with a maximum size of aggregate of up to 25,4 mm (1 in). This is the method used also in Turkey. The method includes acceptance tests for aggregates and asphalt cement to comply with applicable specifications and traffic and climatic conditions. The mixture proportions are then selected by analyzing the stability, flow, voids, and density characteristics of specimens prepared with various trial proportions. The Marshall mix design method is illustrated in Figure 3.1.

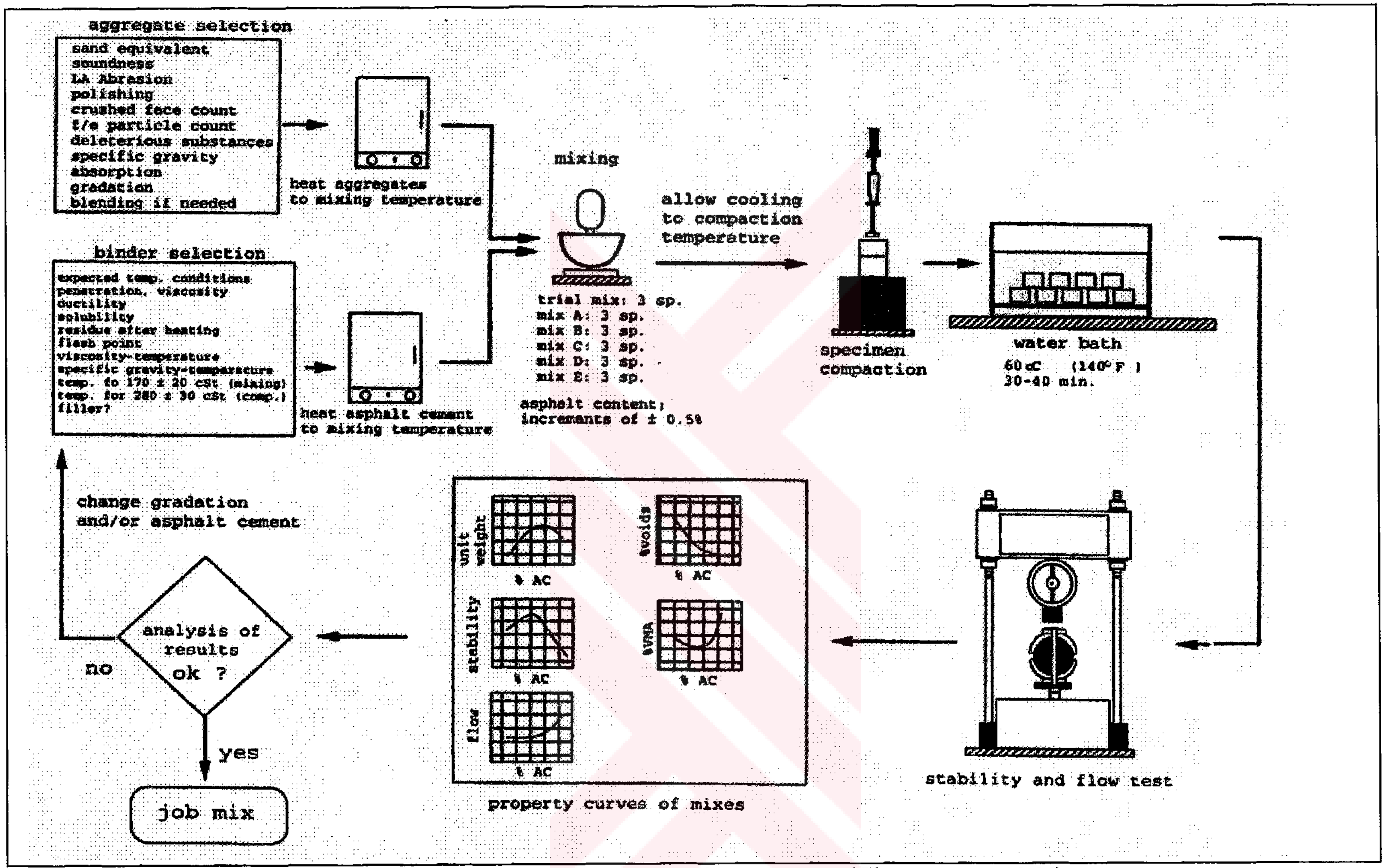


Figure 3.1. Schematic Diagram of Marshall Mix Design Method (Chen,1995,p.1364)

"One advantage of the Marshall method is its attention to density and void properties of asphalt mixtures. This analysis ensures the proper volumetric proportions of mixture materials for achieving a durable HMA..." (SHRP,1993,p.13)

"The impact compaction used with the Marshall method doesn't simulate mixture densification as it occurs in a real pavement. Furthermore, Marshall stability doesn't adequately estimate the shear strength of HMA. These two situations make it difficult to assure the rutting resistance of the designed mixture..." (SHRP,1993,p. 14).

3.2. Hveem Method

Hveem mixture design method has been used in Western United States. Hveem method is similar to the Marshall Method design procedure in selecting the optimum bitumen content from the test of trial mixtures prepared with various amounts of asphalt cement. However, the specimens prepared with various contents of asphalt cement are tested in testing device that registers the later pressure produced by the specimen when they are subject to axial load.

"The aim of the Hveem method is to select a mixture with well-graded aggregates and with as much asphalt binder as the mixture tolerates without losing stability. Also, a minimum of 3 % of VTM (percent of void) is required in the mixture." The Hveem design method is illustrated in Figure 3.2. (Chen,1995)

Hveem stability is a direct measurement of the internal friction component of shear strength. This is the primary advantage of the Hveem method. It measures the ability of a test specimen to resist lateral displacement from application of a vertical load.

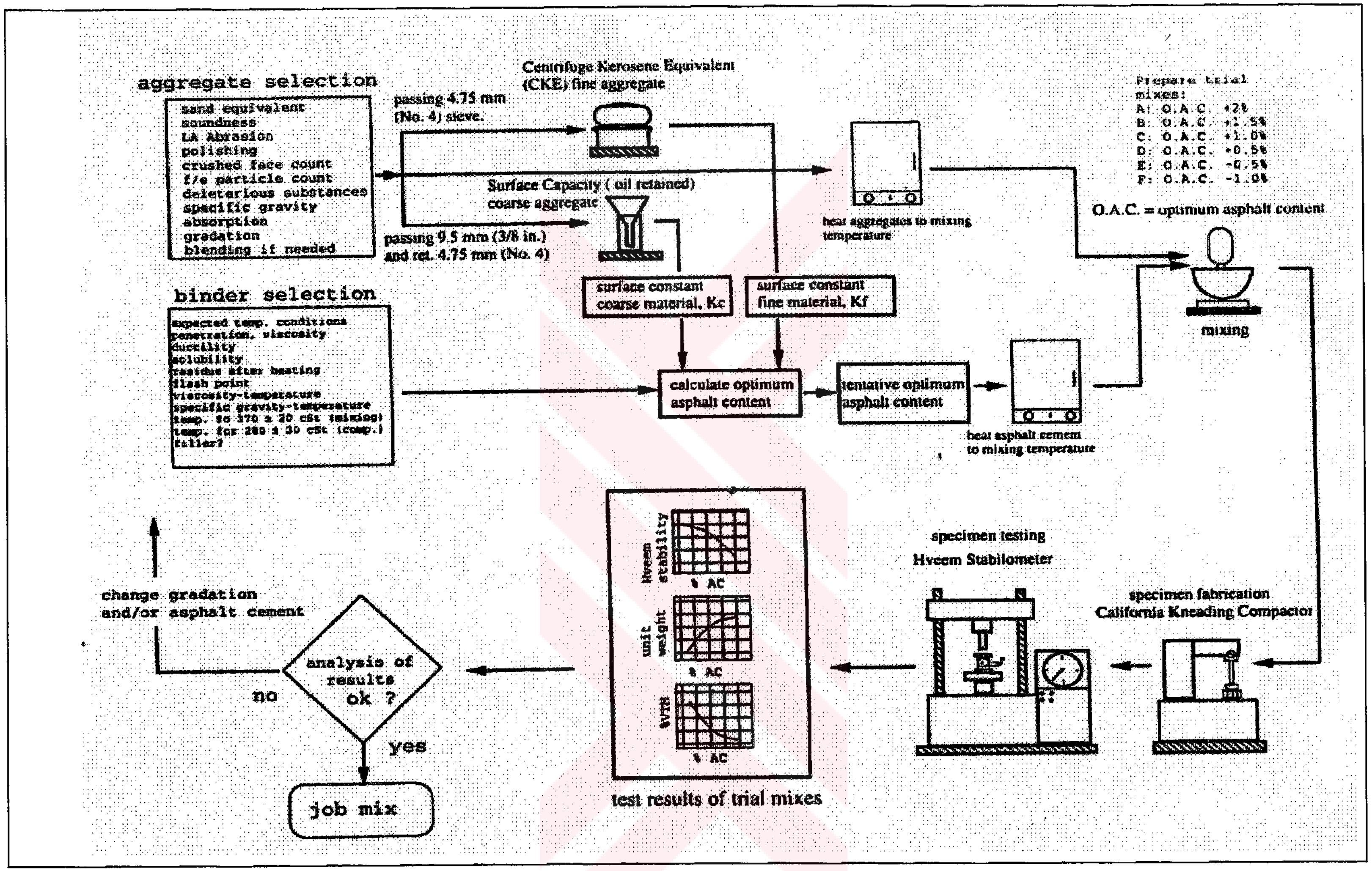


Figure 3.2. Schematic Diagram of Hveem Mix Design Method (Chen,1995,p.1367)

3.3 SHRP Method (SUPERPAVE)

The Marshall and Hveem design methods do not provide procedures to measure fundamental mechanical properties of HMA mixtures. The results are test-specific, and their validity resides primarily on the past experience accumulated over many years of use and empirical correlations between mix design results and performance results. For these reasons, a new system for material selection and design of bituminous mixtures has been developed by SHRP of the Federal Highway Administration (FHWA). The new system known as ***Superior Asphalt Pavements*** *(SUPERPAVE)* (SHRP,1993,p.15)

"SUPERPAVE consists of two major parts, the Superpave asphalt binder analysis and the Superpave asphalt mixture design and analysis. It is considered to be a superior system for grading asphalt binders, selecting aggregate materials, conducting asphalt mix design, and predicting pavement performance." (Wang, et al.,2000)

It includes selection of the asphalt cement, the aggregates, and the amount of mixed components. Unlike previous mixture design procedures, the new design system combines the material properties with pavement structural properties to predict actual pavement performance in terms of rutting and cracking. The mixture design is carried out in accordance with three different levels of expected traffic expressed in terms of equivalent single axle load (ESAL) repetitions. The degree of refinement and complexity of the design procedure depends on the expected traffic.

Table 3.1 Recommended Design Traffic Level 1, 2, and 3 Mix Designs

Design Level	Design Traffic (80 kN ESALs)
1 (low)	$\leq 10^6$
2 (intermediate)	$\leq 10^7$
3 (high)	$>10^7$

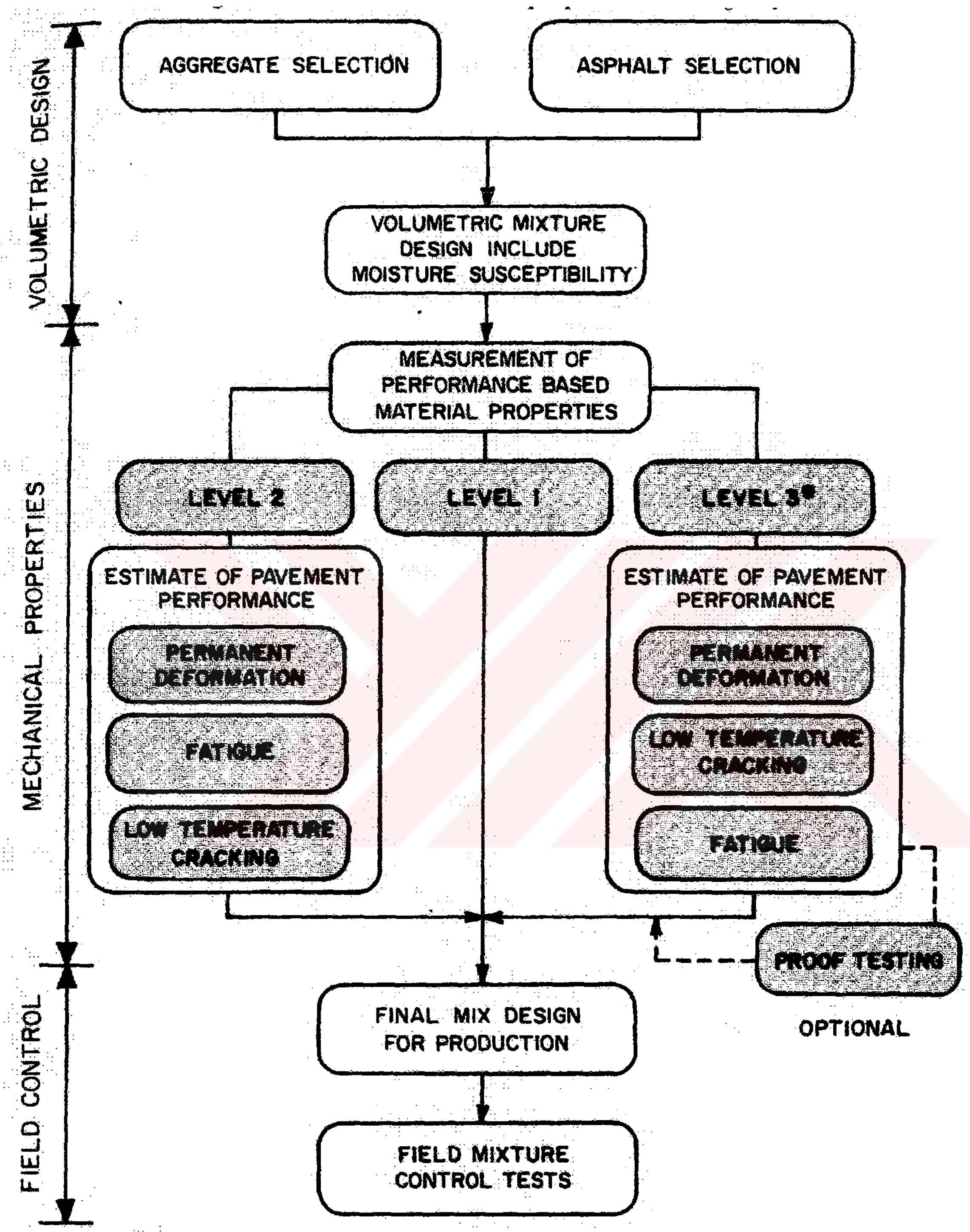


Figure 3.3 Structure of the SUPERPAVE Mix Design System (Cominsky et al.,1994,p.3)

> *The complexity of the design process increases significantly from Level 1 to Level 3. Level 3 requires a greater number of tests, more test specimens, and more time to complete a design. In return, the reliability of the design – that is, probability that the paving mix will provide satisfactory pavement service under the anticipated conditions of traffic and climate-increases proportionality.* (Cominsky et al., 1994, p.5)

> *The widely used Marshall and Hveem methods of mix design are neither performance-based nor performance-related. They are concerned primarily with achieving a mix design with a stable, economical balance of aggregate and asphalt binder that features sufficient workability to permit efficient placement of the mix. Both methods attempt to gauge anticipated performance with empirical properties, such as Marshall stability and flow, but neither method can ensure that a trial mix design will meet specific pavement performance criteria.* (Cominskyet al.,1994, p.4)

"SUPERPAVE volumetric mixture design recognizes the weak link between Marshall stability and rutting performance" (Huber,et al.1998,p.28)

Mineral aggregate properties are obviously important to bituminous mixture performance. However, the Marshall and Hweem methods do not incorporate aggregate criteria into their procedures. Conversely, aggregate criteria are directly incorporated into SUPERPAVE mixture design procedures. Two types of aggregate properties are specified in the SUPERPAVE:

- **Concencus Properties :** Fine aggregate angularity, coarse aggregate angularity, flat and elongated particles and clay content.
- **Source properties** : Toughness, soundness and deleterious materials. (SHRP,1994,p.16)

CHAPTER FOUR

TYPES OF PAVEMENT FAILURES AND THEIR CAUSES

Many types of failures frequently occur in bituminous pavements. Some of these failures are a result of the inherent properties of bituminous mixtures. Others are due to improper choice of design method and materials, to local factors such as traffic and climatic conditions, inadequate quality control or lack of proper control during construction.

4.1 Pavement Performance

Current concepts of pavement performance in USA and other industrial countries include considerations of functional performance, structural performance, and safety.

"The structural performance of a pavement relates to its physical condition; for example; occurrence of cracking, faulting, raveling or other conditions, which would adversely affect the load-carrying capability of the pavement structure and would require maintenance" (AASHTO,1993).

The functional performance of a pavement concerns how well the pavement serves the user. In this situation, riding comfort is the dominant characteristic. In order to quantify riding comfort, the serviceability-performance concept was developed by the AASHTO Road Test.

The serviceability of a pavement is expressed in term of the present serviceability index (PSI). The PSI is based upon a rating scale that ranges from through 5 designates the condition of the pavement at any instant of time. *A rating of 5 indicates a "perfect" pavement, whereas a rating* (Hunter, 1995).

The PSI is obtained from measurements of roughness and distress; for example, cracking, patching and rut depth (flexible), at a particular time during the service life of the pavement. Roughness is the dominant factor in estimating the PSI of a pavement. Thus, a reliable method for measuring roughness is important in monitoring the performance history of pavements (AASHTO,1993).

4.2. Types of Failures

There are two different types of failures that have been occurring in the pavement;

- Structural Failures
- Functional Failures

'Structural failures include a collapse of the pavement structure or a break down of one or more pavement components of such magnitude to make the pavement incapable of sustaining the loads imposed upon its surface.

Functional failure, may or may not be accompanied by structural failure but is such that the pavement will not carry out its intended function without causing discomfort to passengers or without causing high stresses in the plane or vehicle that passes over it, due to its roughness (Yoder&Witczak; 1985)' (Uluçaylı,2001)

Functional failure may be repaired by resurfacing upper layer of the pavement. However, the structural failure may require complete rebuilding of the pavement structure.

The distresses occurring in the flexible pavements can be grouped as;

Deformations;

-Rutting

-Upheaval

-Depression

-Distortion

-Swelling

-Settlement

-Tire imprint

Crackings;

-Alligator Cracking

-Edge Cracking

-Joint Cracking

-Fatigue cracking,

-Low temperature cracking

-Reflection cracking

-Shrinkage cracking

-Lane joint Cracking

Disintegrations;

-Stripping

-Bleeding or Flushing

-Polishing

-Raveling and Weathering

-Pot-holes

-Lack of Bond (Peeling)

4.3 Causes of Failures

The factors having adverse effects on pavement life may be categorized as,

- Destructive effects of traffic;

  Overload including excessive gross loads, high repetitions of loads, and high tire pressures.

- Destructive effects of weathering;

  Climatic conditions as well as environmental conditions which cause surface irregularities and structural weakness to develop,

  Disintegration of the paving materials, due to the freezing and thawing and/or wetting and drying.

- Lack of adequate supporting capacity of base and/or subbase course

There are two main reasons of deformations in a flexible pavement. The first is, deformations due to inadequate asphalt mixture. The second is deformations due to low carrying capacity of the subgrade.

There are three main reasons for cracking; these are stood in line; fatigue cracking; and low temperature cracking in the bituminous layers, and cracking because of sufficient tensile strength of the asphalt mixture.

4.4. Bituminous Mixture Behavior

When a wheel load is applied on a pavement, two primary stresses are transmitted to the bituminous mixture;

-Vertical compressive stress within the bituminous layer
-Horizontal tensile stress at the bottom of the bituminous layer.

The bituminous mixtures must be internally strong and resilient to resist to compressive stresses and prevent permanent deformation within the mixture. In the same manner, the materials must also have tensile strength at the base of the bituminous layer, and also be resilient to withstand many load applications without fatigue cracking. Bituminous mixtures must also resist the stresses imparted by rapidly decreasing temperatures and extremely cold temperatures while the individual properties of bituminous mixture behavior is explained by considering mineral aggregate and asphalt cement acting together.

4.4.1 Permanent Deformations

Permanent deformation represents an accumulation of small amounts of unrecoverable deformations that occur each time a load is applied. Rutting (Wheel Track Rutting) is the most common form of permanent deformation. While rutting can have many sources (e.g., underlying HMA weakened by moisture damage, abrasion, traffic densification), it has two principal causes:

In one case, the rutting is caused by too much repeated stress being applied to the subgrade (or subbase or base) below the asphalt layer (figure 4 1). *Although stiffer paving materials will partially reduce this type of rutting, it is normally considered a structural problem rather than a materials problem. Essentially, there is not enough pavement strength or thickness to reduce the applied stresses to a tolerable level. A pavement layer that has been unexpectedly weakened by the intrusion of moisture may also cause it. The deformation occurs in the underlying layers rather than in the asphalt layers.* (Asphalt Institute, 1996)

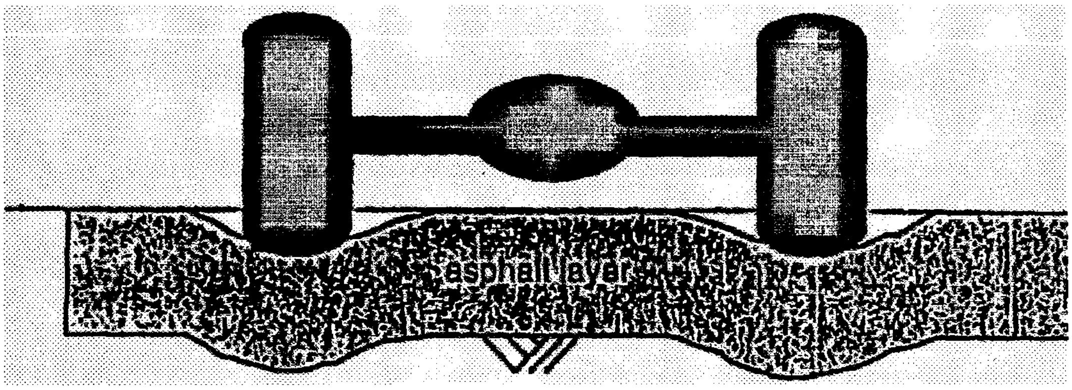


Figure 4.1 Rutting from Weak Subgrade (V Profile) (Asphalt Institute, 1996)

This is referred to a structural rutting, and the resulting ruts are wide and not have humps to their sides (V profile).

> *The second mechanism is the result of individual deformation of the bituminous courses due to load-induced stresses exceeding the stability threshold of the material. This is called flow (or instability) rutting, and the resulting ruts have humps to their sides (W profile under the action of dual tires, and asymmetric under the action of wide-based single tires). Flow ruts are most often formed on ascending gradients, on junction approaches and in bends, i.e. where heavy lorries have to reduce speed and tangential stresses in the tire-pavement contact area are higher* (Verstraeten,1994, p.14).

This type of rutting has to do with mix design rather than structural design. The relevant factors are the characteristic of the various constituents; their proportions in the mix, and laying.

> *The type of rutting of most concern to asphalt mix designers is deformation in the asphalt layers. This rutting results from an asphalt mixture without enough shear strength to resist repeated heavy loads* (Figure 4.2). *A weak mixture will accumulate small, but permanent, deformations with each truck pass, eventually forming a rut characteristic by a downward and lateral movement of the mixture. The rutting may occur in the asphalt surface course, or the rutting that shows on*

the surface may be caused by a weak underlying asphalt course (Asphalt Institute,1996)

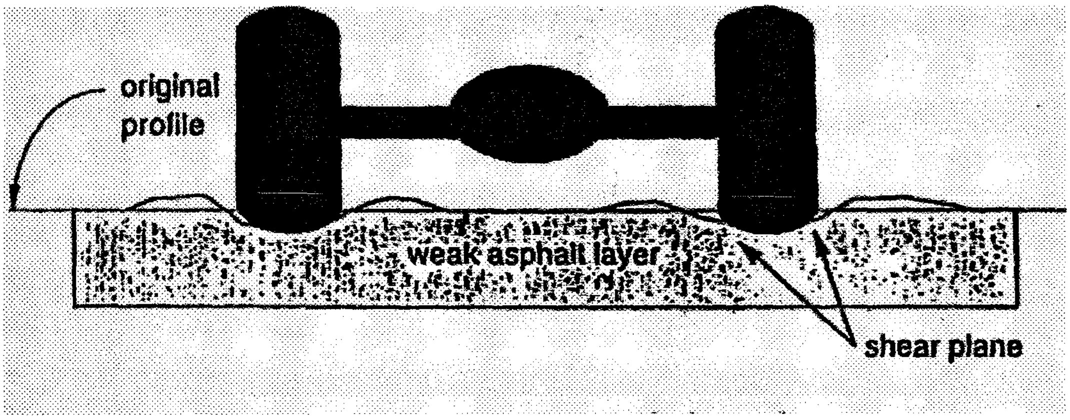


Figure 4.2 Rutting from Weak Mixture (W Profile) (Asphalt Institute, 1996)

Rutting of a weak mixture typically occurs during the summer under higher pavement temperatures. While this might suggest that rutting is solely an asphalt cement problem, it is more correct to address rutting by considering the combined resistance of the mineral aggregate and asphalt cement.

Since rutting is an accumulation of very small permanent deformations, one way to increase mixture shear strength is to use not only stiffer asphalt cement but also one that also behaves more like an elastic solid at high pavement temperatures. Then, when a load is applied, the asphalt cement will act like a rubber band and spring back to its original position rather than deforming.

Another way to increase the HMA shear strength is by selecting an aggregate that has a high degree of internal friction-one that is cubical, has a rough surface texture, and is graded to develop particle-to-particle contact. When a load is applied to the mixture, the aggregate particles lock tightly together and function more as a large, single, elastic stone. As with the asphalt cement, the aggregate will act like a rubber band and spring back to its original shape when unloaded. In that way, no permanent deformation accumulates (Asphalt Institute,1996).

4.4.2. Fatigue Cracking

Fatigue cracking occurs in asphalt pavements when the applied loads overstress the asphalt materials, causing cracks to form. An early sign of fatigue cracking is intermittent longitudinal cracks in the traffic wheel path. Fatigue cracking is progressive because at some point the initial cracks will join, causing even more cracks to form. An advanced stage of fatigue cracking is called alligator cracking, characterized by transverse cracks connecting the longitudinal cracks.

For fatigue cracking, the aggregate properties, the mix properties, and the pavement structure are more important: For permanent deformation, the properties of aggregate and the asphalt (bituminous) *mix are dominant* (SHRP-A-410).

It must be recognized that the asphalt binder (asphalt cement), *while important, cannot make up for poor aggregates, poor mix characteristic, poor construction or inadequate structural design* (Asphalt Institute,1995).

Table 4.1 Analysis of Types and Causes of Failures in Asphalt Paving Mixtures (Monisminth, 1961,p148)

OBJECTIVE	TYPES OF PROBLEMS ENCOUNTERED	CAUSES	FUNCTION OF
Improving Performance of Asphalt Paving Mixtures	Instability	Low interparticle friction	Particle surface texture Quantity of asphalt (excess) Particle contact pressure (compaction)
		Low liquid friction (or "mass viscosity")	Gradation or surface area (i.e. points of contact) Type and amount of asphalt Density
		Lack of inertia resistance	Speed of vehicle Weight of vehicle Mass of pavement affected
	Disintegration	Low tensile strength (or "cohesion")	Surface area (i.e. points of contact) Type and amount of asphalt Density
		Stripping (water action)	Adhesiveness, viscosity and amount (film thickness) of asphalt Wettability characteristics of aggregate Density
		Abrading (traffic action)	Amount of asphalt (insufficient) Relative hardness of aggregate Brittleness of binder
	Fracture (or cracking)	Shrinkage (volume change)	Loss of volatiles and temperature changes Absorption of asphalt by aggregate Internal structural adjustments in asphalt
		Brittleness (inflexibility)	Amount, viscosity and brittleness of binder Grading of aggregate and thickness of asphalt paving Resiliency ("rebounding") characteristics of base or sub-grade
		Slippage	Bond between courses (insufficient) Tensile strength of pavement Thickness of slipping layer

CHAPTER FIVE

CRUSHERS

5.1 What is Crushing?

Crushing is a process of reducing the dimension of big rocks to desired values. It is generally a dry operation and it is usually performed in two or three stages. Lumps of rock can be as large as 1.5m across and these are reduced in the primary crushing stage to 10-20 cm in heavy-duty machines. Secondary crushing includes all operations for reclaiming the primary crusher product, which is usually between 4 mm and 19 mm in diameter. Secondary crushing plants generally consist of two or three size-reduction stages with appropriate crushers and screens. More than two size- reduction stages with appropriate crushers and screens. More than two size-reduction stages used in secondary crushing if rock is extra-hard or where it is important to minimize the production of fines.

There are four basic ways to obtain processed aggregate: by impact, attrition, shear or compression. All crushers employ one, or a combination of these four methods:

5.1.1 Impact

In crushing terminology, impact refers to the sharp, instantaneous impingement of one moving object against another. Both objects may be moving, together, one object may be motionless, such as a rock being struck by hammer blows. There are two variations of impact;

- Gravity impact
- Dynamic impact

An example of gravity impact is rock being dropped onto a hard surface such as a steel plate. This method is most often used to separate two materials, which have different friability. The more friable material is broken, while the less friable material remains unbroken. Screening then does separation. When crushed by gravity impact, the stationary object momentarily stops a free falling material.

Material dropping in front of a moving hammer (both objects in motion) illustrates dynamic impact. When crushed by dynamic impact, the material is unsupported and the force of impact accelerates movement of the reduced particles toward breaker blocks and/or other hammers. Dynamic impact has definite advantages for the reduction of many materials and is specified under the following conditions:

- When a cubical particle is needed.
- When finished product must be well graded, and meet intermediate sizing as well as top and bottom specifications.
- When ores must be broken along natural cleavage lines in order to free and separate undesirable inclusions (such as mica in feldspars).
- When materials are too hard and abrasive for hammer mills, but where jaw crushers cannot be used because of particle shape requirements, high moisture content or capacity.

The bottom of the crusher is open, allowing sized materials to pass through almost instantaneously. Liberal clearance between hammers and the breaker blocks eliminates attrition. Crushing is done by impact only.

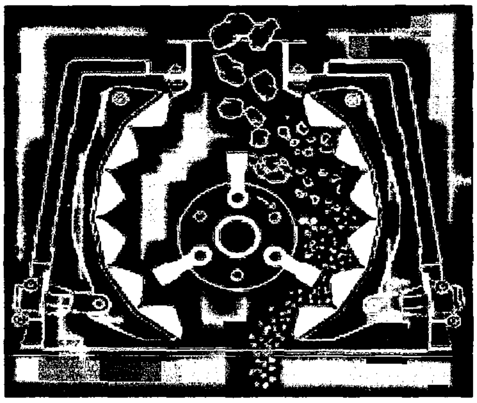


Figure 5.1 Impactor (Pennsylvania Crusher Corporation)

5.1.2 Attrition

Attrition is a term applied to the reduction of materials by scrubbing it between two hard surfaces. Though attrition consumes power and exacts heavier wear on hammers and screen bars, it is practical for crushing less abrasive materials such as pure limestone and coal. Attrition crushing is most useful in the following circumstances:

- When material is friable or not too abrasive
- When a closed-circuit system is not desirable to control top size.

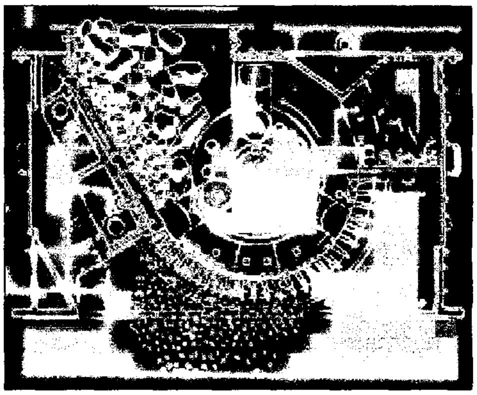


Figure 5.2 Hammer Mill (Pennsylvania Crusher Corporation)

Material is broken first by impact between hammers and material and then by a scrubbing action (attrition) of material against screen bars.

5.1.3 Shear

Shear consists of a trimming or cleaving action rather than the rubbing action associated with attrition. Shear is usually combined with other methods. For example, single-roll crushers use a combination of shear, impact and compression methods. Shear crushing is usually called for under these circumstances:

- When material is somewhat friable and has relatively low silica content.
- For primary crushing with a reduction ratio of 6 to 1.

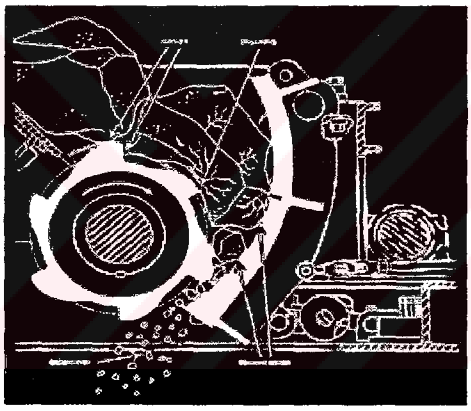


Figure 5.3 Single-Roll Crusher (Pennsylvania Crusher Corporation)

5.1.4 Compression

As the name implies, crushing by compression is done between two surfaces, with the work being done by one or both surfaces. Jaw crushers using the compression method are suitable for reducing extremely hard and abrasive rock. However, some jaw crushers employ attrition as well as compression and are not as suitable for abrasive rock since the rubbing action accentuates wear on crushing surfaces. As a mechanical reduction method, compression should be preferred under these circumstances:

- If the material is hard and tough
- If the material is abrasive
- If the material is not sticky
- When the material will break cubically

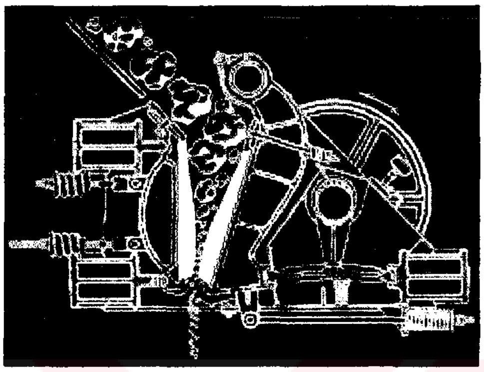


Figure 5.4 Jaw Crusher (Pennsylvania Crusher Corporation)

Selecting the proper crusher requires the development of out aggregate size and shape including the physical (aggregate size, shape etc.) characteristics of the feed material. Often the same materials can vary widely used for bituminous mixtures such as limestone and basalt. Material variances will definitely influence the type of crushers.

5.2 General Classification of Crushers

Crushers are classified into two as:

Primary Crushers:

- Jaw Crushers
- Gyratory Crushers

Secondary Crushers:

- Jaw Crushers
- Gyratory Crushers
- Cone Crushers
- Impact Crushers
- Roll Crushers

Some crushers are used for primary and also secondary crushing applications. But in primary crushing largeness and capacity of crushers are higher than secondary crushing application

5.2.1 Primary Crushers

Primary crushers are heavy-duty machines, used to reduce the run-of- mine ore down to a size suitable for transport and for feeding the secondary crushers.

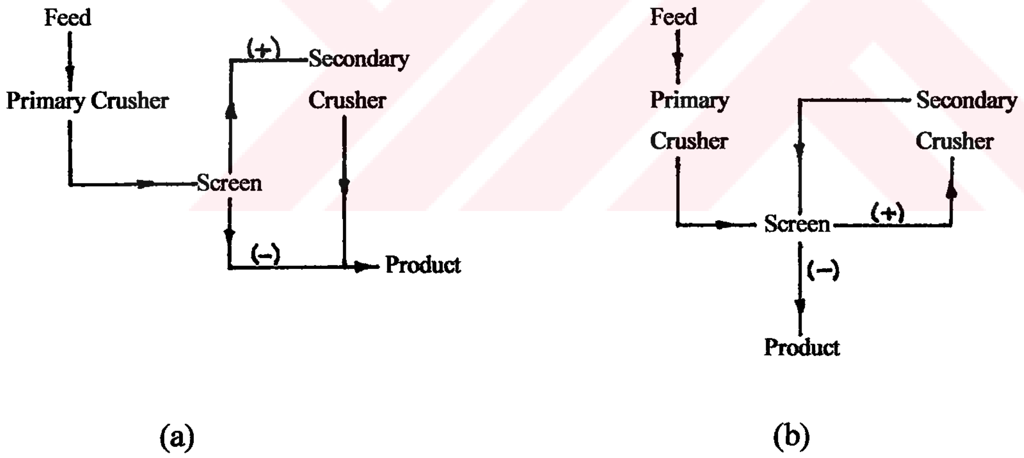


Figure 5.5 (a) Open-Circuit Crushing, (b) Closed Circuit Crushing.

They are always operated in open circuit, with or without heavy-duty scalping screens (grizzlies). There are two main types of primary crusher in metalliferous operations-jaw and gyratory crushers-although the impact crusher has limited use as a primary crusher and will be considered separately.

5.2.1.1 Jaw. Crushers

Jaw crushers are referred to as "jaw crusher used for obtaining coarse aggregate" by Technical Dictionary of General Directorate of the State Highway in USA.

The distinctive feature of this class of crusher is the two plates which open and shut like animal jaws. The jaws are set at an acute angle to each other, and one jaw is pivoted so that it swing relative to the other fixed jaw. Rock particles fed into the jaws is alternately nipped and released to fall further into the crushing chamber. Eventually it falls from the discharge aperture.

Jaw crushers are classified by the method of pivoting the swing jaw (Figure 5.6). In the *Blake crusher* the jaw is pivoted at the top and thus has a fixed receiving area and a variable discharge opening. In the *Dodge crusher* the jaw area and a variable feed area but fixed delivery area. The Dodge crusher is restricted to laboratory use. Where close sizing is required and is never used for heavy-duty crushing as it chokes very easily. The *Universal crusher* is pivoted in an intermediate position and thus has a variable and receiving area.

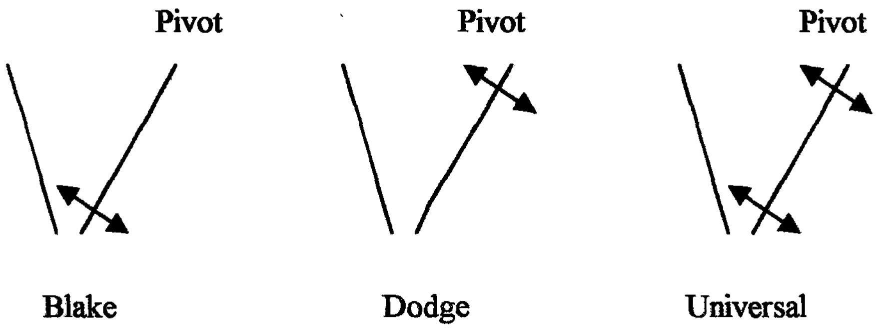


Figure 5.6 Jaw-Crusher Types

5.2.1.2 Gyratory Crushers

The gyratory crusher (Figure 5.7) *consists essentially of along spindle, carrying a hard steel conical grinding element, the head, seated in an eccentric sleeve. The spindle is suspended from a "spider" and as it rotates normally between 85 and 150 rev min*$^{-1}$ *.It sweeps out a conical path within the fixed crushing chamber or shell due to the gyratory action of the head occurs near the discharge. This tends to relieve the choking due to swelling the machine thus being a good arrested crusher. The spindle is free to turn on its axis in the eccentric sleeve so that during crushing the lumps are compressed between the rotating head and the top shell segments and abrasive action in a horizontal direction is negligible* (Ipekoğlu&Tanrıverdi,1994)

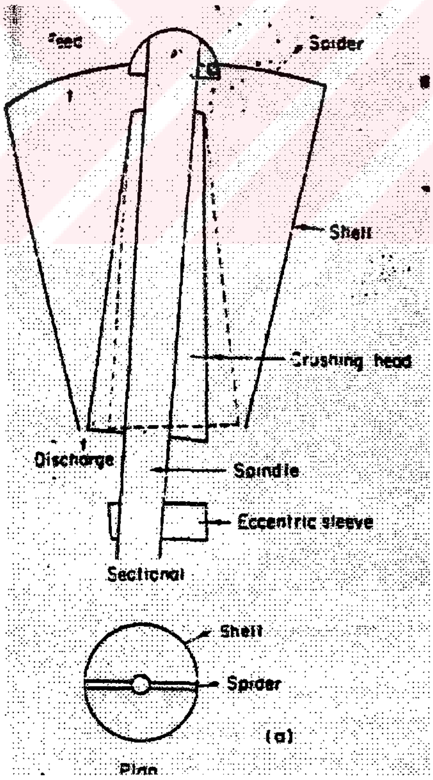


Figure 5.7 Gyratory Crusher Functional Diagram

5.2.1.3 Comparison of Primary Crushers

In deciding whether a jaw or a gyratory crusher should be used in a particular plant, the main factor is the maximum size of the aggregate, which the crusher will be required to handle, and the capacity.

Gyratory crushers are, in general, used where high capacity is required. Since they crush on full cycle, they are more efficient than jaw crushers; *Jaw crushers tend to be used where the crusher's gape is more important than the capacity. For instance, if it is required to crush material of a certain maximum diameter then a gyratory having the required gape would have a capacity about three times that of a jaw crushers of the same gape. If high capacity is required then a gyratory is the answer. If however, a large gape is needed but not capacity then the jaw crushers will probably be more economical as it is a smaller machine and the gyratory would be running idle most of the time...*

T*he capital and maintenance costs of a jaw crusher are slightly less than those of the gyratory but they may be offset by the installation costs, which are lower with the gyratory since it occupies about two-thirds the volume and has about two-thirds the weight of a jaw crusher of the same capacity* (Ipekoğlu&Tanrıverdi,1994)

The type of material being crushed may also determined the crusher used. Particularly suitable for hard rock and they tend to give more cubic product than jaw crushers.

5.2.2 Secondary Crushers

Secondary crushers are much lighter than the heavy-duty, primary machines. Since they take the primary crushed rock as feed, the maximum feed size will normally be less than 10-20 cm in diameter. There are two many types of secondary crushers. They are described in the following paragraphs.

5.2.2.1 Cone Crushers

"The cone crusher is a modified gyratory crusher. The essential difference is that the shorter spindle of the cone crusher is not suspended as in the gyratory, but is supported in a curved, universal bearing below the gyratory head or cone". (Wills,1984)

Power is transmitted from the source to the countershaft through a V-belt or direct drive. The countershaft has a bevel pinion pressed and keyed to it, and drives the gear on the eccentric assembly. The eccentric has a tapered; offset bore and provides the means whereby the head and main shaft follow an eccentric path during each cycle of rotation.

Since a large gape is not required the crushing shell or 'bowl' flares outwards which allows for the swell of broken rock providing an increasing cross-sectional area towards the discharge end. The cone crusher is therefore an excellent arrested crusher. The flare of the bowl allows a much greater head angle than in the gyratory crusher. (Wills,1984)


(a) (b)

Figure 5.8 Head and Shell Shapes of (a) Gyratory, and (b) Cone Crushers

While, retaining the same angle between the crushing members (Figure 5.8). This gives the cone crusher a high capacity, since the capacity of gyratory crushers is roughly proportional to the diameter of the head.

The throw of cone crushers can be up to five times that of primary crushers, which must withstand heavier working stresses. They are also operated at much higher speeds. The material passing through the crusher is subjected to a series of hammer-like blows rather than being gradually compressed as by the slowly moving head of the gyratory.

The high-speed action allows particles to flow freely through the crusher and the wide travel of the head creates a large opening between it and bowl when in the fully open position. This permits the crushed fines to be rapidly discharged making room for additional feed.

The parallel section between the linear at the discharge of all cone crushers and is incorporated to maintain a close control on product size. Material passing through the parallel zone receives more than one impact from the crushing from the crushing members. The set on the cone crushers is thus the minimum discharge opening

The distributing plate on the top of the cone helps to centralise the feed distributing it at a uniform rate to the entire crushing chamber.

An important feature of the crusher is that the bowl is held down either by an annular arrangement of springs or by a hydraulic mechanism. These allow the bowl to yield if 'tramp' material enters the crushing chamber so permitting the offending object to pass. If the springs are continually 'on the work' as may happen with ores containing many very tough particles oversize material will be allowed to escape from the crusher. This is one of the reasons for using closed circuit crushing in the final stages. It may be necessary to choose a screen for the circuit, which has apertures slightly larger than the set of the crusher. This is to reduce the tendency for very tough particles, which are slightly oversize to 'spring' the crusher causing an accumulation of such particles in the closed circuit and a build up of pressure in the crushing throat.

The set on the crusher can easily be changed or adjusted for liner wear by screwing the bowl up or down by means of a capstan and chain arrangement or by adjusting the hydraulic setting. The set is often checked in particle by dropping lead weights the crushing chamber and measuring their diameter on emerging. (Wills,1984)

5.2.2.2 Gyradisc Crushers

The gyradisc crusher is a specialised form of come crusher used for producing fine material.

The main modification to the conventional cone crusher is that the machine has very short liners and a very flat angle for the lower liner. Crushing is by interparticle comminution by the impact and attrition of a multi-layered of particle.

The angle of the lower liner is less than the angle of repose of the ore so that when the liner is at rest the material does not slide. Transfer through the crushing zone is by movement of the head. Each time the lower liner moves away from the upper liner material enters the attrition chamber from the surge load above.

When reduction begins material is picked up by the lower liner and is moved outward. Due to the slope of the liner it is carried to an advanced position and caught between the crushing members.

The length of stroke and the timing are such that after the initial stroke the lower liner is withdrawn farter than the previously crushed material falls by gravity. This permits the lower liner to recede and return to strike the previously crushed mass as it is falling, thus scattering it so that a new alignment of particles is obtained prior to another impact. At each withdrawal of the head the void is filled by particles from the surge chamber. (Wills,1984)

At no time does single-layer crushing occur, as with conventional crushers. Crushing is by particle on particle so that the setting of the crusher is not as directly related to the size of product, as it is cone crusher.

Their main use is in quarries for producing sand and gravel. When used in open circuit they will produce a product of chipping from about 1 cm downward of good cubic shape with a satisfactory amount oft sand, which obviates the use of blending and rehandling. In closed circuit they are used to produce large quantities of sand. They may be used in open circuit on clean metalliferous ores with no primary slimes to produce an excellent ball-mill feed. Minus-19mm material may be crushed to about 3 mm.

5.2.2.3. Roll Crushers

Roll crusher, or crushing rolls, are still used in some mills, although they have been replaced in many installations by cone crushers. They are also used in a primary crushing application. They still have a useful application in handling friable sticky, frozen and less abrasive feeds; such as limestone jaw and gyratory crushers have a tendency to choke near the discharge when crushing friable rock with a large proportion of maximum size pieces in the feed.

The mode of operation of roll crushers is extremely simple, the standard spring rolls (Figure 5.9) consisting of two horizontal cylinders, which revolve towards each other. The set is determined by shims, which cause the spring-loaded roll to be held back from the solidly mounted roll. Unlike jaw and gyratory crushers where reduction is progressive by repeated pressure as the material passed down to the discharge point, the crushing process in rolls is one of single pressure.

Roll crushers are also manufactured with only one rotating cylinder, which revolves towards a fixed plate. Other roll crushers use three, four or six cylinders.

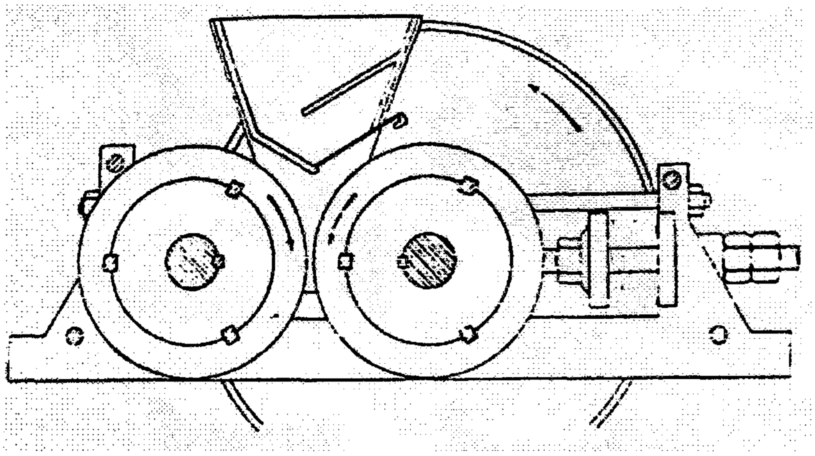


Figure 5.9 Crushing Rolls (Wills,1984,p.148)

5.2.3.4. Impact Crushers

In this class crusher comminution is by impact rather than compression by sharp blows applied at high speed to free-falling rock. The moving parts are beaters, which transfer of their kinetic energy to the ore particles on contacting them. The internal stresses created in the particles are often large enough to cause them to shatter. Causing the particles to impact upon an anvil or breaker plate increases these forces.

> *There is an important difference between the states of materials crushed by pressure and by impact. There are internal stresses materials broken by pressure, which can cause later cracking. Impact causes immediate fracture with no residual stresses. This stress-free condition is particularly valuable in stone used for brick making, building, and road-making, in which binding agents, such as bitumen are subsequently added to the surface. Impact crushers; therefore have a wider use in the quarrying industry than in the metal-mining industry. They may give trouble-free crushing on ores that tend to be plastic and pack when the crushing forces are applied slowly, as is the case in jaw and gyratory crushers. These types of ore tend to be brittle when the crushing force is applied instantaneously by impact crushers.* (Wills,1984,p.150)

CHAPTER SIX

EXPERIMENTAL STANDARDS OF FINE AGGREGATE ANGULARITY

6.1 Introduction

Actually these are three standardized test methods for fine aggregate angularity. They are French method (AFNOR P18-564), AASHTO (TP 33) and ASTM (3398) methods. The letters two are in fact the same. These methods are presented below.

6.2 AFNOR P18-564

P18-564 was published by AFNOR in 1990. It is an experimental specification of fine aggregate angularity.

6.2.1 Scope:

The aim of this specification is to define the procedure to measure flow rate of fine aggregate.

This specification has an application area on natural or processed sand used in civil engineering.

6.2.2 Definition:

Flow rate of fine aggregates of a given volume is defined as the flow time in seconds through an orifice under specified conditions.

6.2.3 Apparatus:

- 0.08 , 2, 4 mm sieves (No.200 , No.10 , No.5)
- Scale or balance, accurate to ± 0.1 g within the range of use. Capable of weighing cylindrical measuring apparatus and its contents.
- Chronometer in 1/10 seconds divisions.
- Oven- an oven of appropriate size capable of maintaining a uniform temperature of 105 ± 5 ^{0}C

Specific Apparatus:

- Flow apparatus which is a demountable assembly (Figure 6.1) including:
  - Two funnel made of plastic; (polycarbonate for example) the first is with an orifice of 12 mm in diameter, and the second is 16 mm in diameter. Height of funnels is 85 mm. The angle is 60^0 at the top.
  - A cylinder; with inside diameter of 90 mm is assembled to hold to funnel. The overall height of cylindrical part is 125 mm.
  - A support holds a mobile shutter to open or close the orifice.
  - Pan; a metal or plastic pan of sufficient size to contain the funnel content to prevent loss of material.

6.2.4 Materials Use in Experimental Studies:

Samples are prepared according to AFNOR P18-553 specification.

P18-553 specification requires that, material be dried to 105 ^{0}C till constant weight is observed. It means that, it shows differences less than %0,1 in the interval of an hour measurement.

Tests are performed using 0,08 – 2 mm (No.200-No.10) or 0,08 - 4 mm (No.200-No.5) sized sand samples.

Mass in terms of kg of the sample, is given by Pr/2.7 relation.

Pr is real volumic mass of material in terms of t/m^3

6.2.5 Summary of Test Method:

For 0,08 – 2 mm sized fine aggregate, the funnel with 12 mm orifice is used, for 0,08 – 4 mm sized coarser fine aggregate, the funnel with 16 mm orifice is employed. Openings are closed with mobile shutter. Sample is placed into the funnel. Chronometer is started by the time of the mobile shutter is opened. The materials start to flow into the pan and flow time for the total material flow is measured with 1/10-second precision. The test is repeated at least five times with the same materials.

6.2.6 Results:

Coefficient of flow E_0 (O/D) is determined by the average of 5 measurements in seconds rounded to the nearest second.

6.2.7 Precision:

Reproductibility and repeatibility were determined for each material by testing in 18 laboratories.

The interpretation of the results was made according to NF ISO 5725

For 0,08 – 2 mm sized fine aggregate (sand) and for a value over 40 ; repeatibility (r) is 1,2 and reproductibility(R) is 2,9.

For 0,08 – 4 mm sized fine aggregate (sand) and for a value over 20 ; repeatability (r) is 0,8 and reproductibility is R = 1,2.

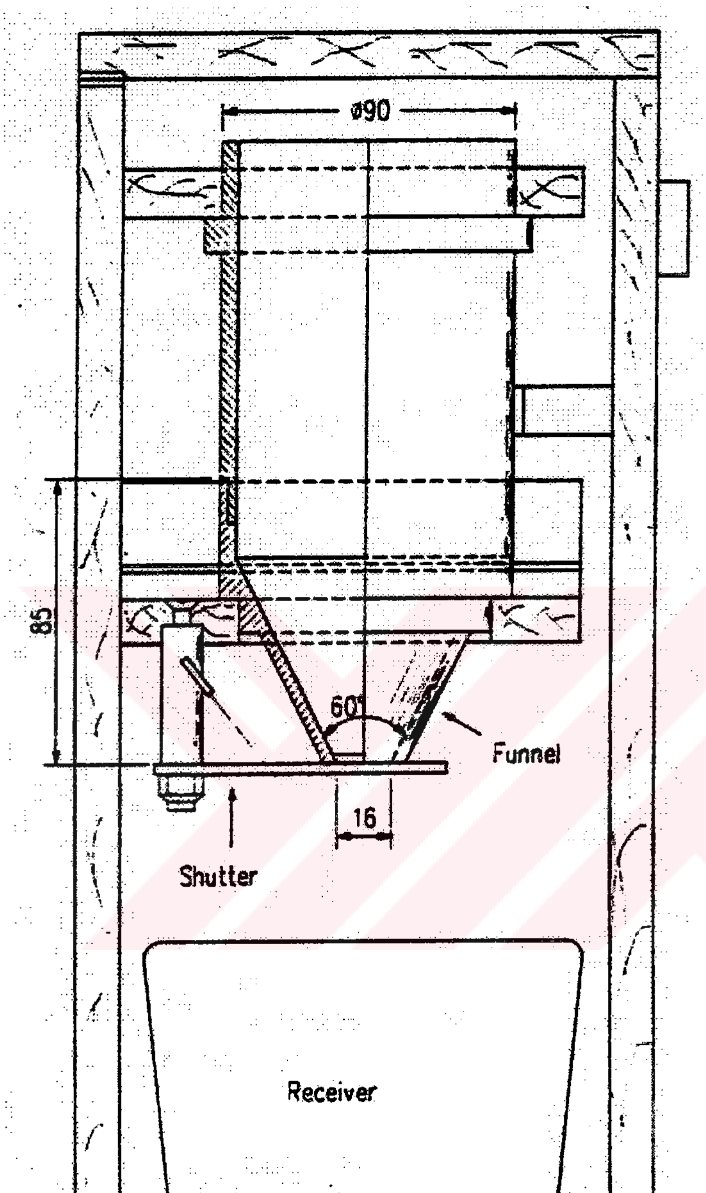


Figure 6.1 Flow Apparatus (Verstraeten,1994,p.49).

6.3. AASHTO TP33 (ASTM Designation C1252)

AASHTO TP 33 Standard test method based on the technical substance provided by the Strategic Highway Research Program (SHRP) researchers. This standard was colleted and formatted jointly by the AASHTO and SHRP staffs. (AASHTO, 1993)

Standard test method is designated for uncompacted void content of fine aggregate as influenced by particle shape, surface texture and grading. This method describes the determination of the loosely uncompacted void content of a sample fine aggregate. When measured on any aggregate of a knowing grading, void content provides an indication of aggregate's angularity, sphericity and surface texture compared with other fine aggregates tested in same grading.

"When void content is measured on as-received fine aggregate grading, it can be indicator of the effect of the fine aggregate on the workability of a mixture in which it may be used". (SHRP, 1993, p.1)

> *Three procedures include for the measurement of void content. Two use graded fine aggregate (standard grading or as-received grading), and the other uses several individual size fractions for void content determinations:*
>
> ...
>
> ***Standard Graded Sample (Method A)-*** *This method uses a standard fine aggregate grading that is obtained by combining individual sieve fractions from a typical fine aggregate sieve analysis. See the section on Preparation of Test Sample for the grading.*
>
> ***Individual Size Fractions (Method B)-*** *This method uses each of three fine aggregate size fractions: (a) 2.36 mm (No.8) to 1.18mm (No.16;(b) 1.18-mm (No.16) to 600-µm (No.30); and (c) 600-µm (No.30) to 300-µm (No.50). For this method each size is tested separately.*

As-Received Grading (Method C)- *This method uses that portion of the fine aggregate finer than a 4.75 mm (No.4) sieve.* (AASTHO,1993)

6.3.1. Summary of Test Method

This test method involves calculating the uncompacted void content of fine aggregate after 190g of the aggregate falls from a funnel into a nominal 100 mL cylindrical measure. Aggregates that are round and smooth (e.g. natural sand) tend to compact tighter after free fall than angular particles.

A nominal 100-mL calibrated cylindrical measure is filled with fine aggregate of prescribed grading by allowing the sample to flow through a funnel from a fixed height into the measure. The fine aggregate is struck off, and its mass is determined by weighing. Uncompacted void content is calculated as the difference between the volume of the cylindrical measure and the absolute volume of the fine aggregate collected in the measure. Uncompacted void content is calculated using the bulk dry specific gravity of the fine aggregate. Two runs are made on each sample and the results are averaged.

For a graded sample (Method A or Method C) the percent void content is determined directly, and the average value from two runs is reported.

For the individual size fractions (Method B), the mean percent void content is calculated using the results from tests of each of the three individual size fractions. (AASTHO,1993)

6.3.2 Significance and Use

Method A and B provide percent void content determined under standardized conditions which determined under standardized conditions which depends on the particle shape and texture of a fine aggregate. An increase in void content by these procedures indicates greater angularity, less sphericity, or rougher surface *texture, or some combination of the three factors. A decrease in void content results is associated with more rounded, spherical, smooth surfaced fine aggregate, or a combination of these factors.*

Method C measures the uncompacted void content of the minus 4.75-mm (No.4) portion of the as-received material. This void content depends on grading as well as particle shape and texture.

The void content determined on the standard graded sample (Method A) is not directly comparable with the average void content of the three individual size fractions from the same sample tested separately (Method B). A sample consisting of single size particles will have a higher void content than a graded sample. Therefore, use either one method or the other as a comparative measure of shape and texture, and identify which method has been used to obtain the reported data. Method C does not provide an indication of shape and texture directly if the grading from sample to sample changes.

The standard graded sample (Method A) is most useful as a quick test, which indicates the particle shape properties of a graded fine aggregate. Typically, the material used to make up the standard graded sample can be obtained from the remaining size fractions after performing a single sieve analysis of the fine aggregate.

Obtaining and testing individual size fractions (Method B) is more time consuming and requires a larger initial sample than using the graded sample. However, Method B provides additional information concerning the shape and texture characteristics of individual sizes.

Testing sample in the as-received grading (Method C) may be useful in selecting proportions of components used in a variety of mixture. In general, high void content suggests that the material could be improved by providing additional *fines in the fine aggregate or more cementations material may be needed to fill voids between particles.*

The bulk dry specific gravity of the fine aggregate is used in calculating the void content. The effectiveness of these methods of determining void content and its relationship to particle to shape and texture depends on the bulk specific gravity of various size fractions being equal, or nearly so. The void content is actually a function of the volume of each size fraction. If the type of rock or minerals, or its porosity, in any of size fractions varies markedly it may be necessary to determine the specific gravity of the size fractions used in the test.

Void content information from Methods A, B or C will be useful as an indicator of properties such as: the mixing water demand of hydraulic cement concrete; flowability, pumpability, or workability factors when formulating grouts or mortars; or, in bituminous concrete, the effect of the fine aggregate on stability and voids in the mineral aggregate; or the stability of the fine aggregate portion of base course aggregate. (AASTHO,1993)

6.3.3. Apparatus

- Cylindrical Measure- *A right cylinder of approximately 100-ml capacity having an inside diameter of approximately 39-mm and an inside height of approximately 86-mm made of drawn copper water tube meeting ASTM Specification B88 Type M, or B88M Type C. The bottom of the measure shall be metal at least 6-m thick, shall be firmly sealed to the tubing, and shall be provided with means for aligning the axis of the cylinder with that of the funnel.* (AASTHO,1993,TP-33)

- Funnel
- Funnel stand
- Glass plate
- Pan

- Metal spatula
- Scale or balance accurate and readable to = 0.1 g.

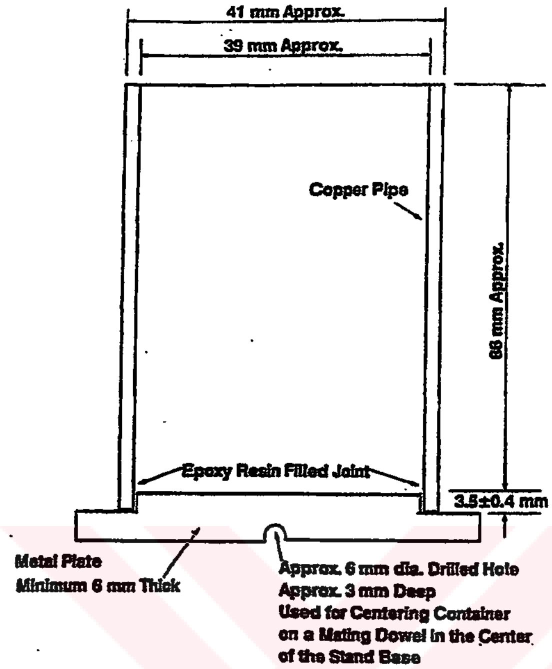
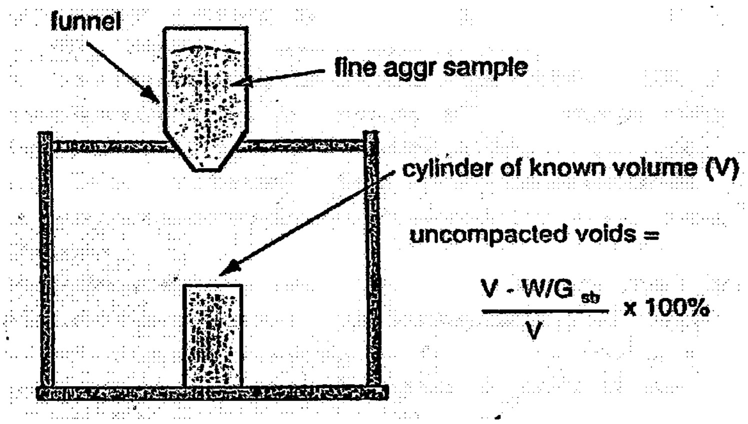


Figure 6.2 Nominal 100 ml Cylindrical Measure



$$\frac{V - W/G_{sb}}{V} \times 100\%$$

Figure 6.3 Fine Aggregate Angularity Apparatus

6.3.4. Sampling

The sample (s) used for this test shall be obtained from sieve analysis samples used for Test Method ASTM C136. For Methods A and B, the sample is washed over a 150-µm (No. 100) or 75-µm (No. 200) sieve in accordance with Test Method ASTM C177 and then dried and sieved into separate size fractions according to Test Method ASTM C136 procedures. The necessary size fractions are obtained from one (or more) sieve analysis in dry condition in separate containers for each size. For Method C, a split, in accordance with the drying procedure in Test Method ASTM C136, dries as-received sample.

6.3.5. Calibration of Cylindrical Measure

Apply a light coat of grease to the top edge of the dry, empty cylindrical measure. Weight the measure, grease, and glass plate. Fill the measure with freshly boiled, deionized water at a temperature of 18 to 24°C. Record the temperature of the water. Place the glass plate on the measure, being sure that no air bubbles remain. Dry the outer surfaces of the measure and determine the combined mass of measure, glass plate, grease, and water by weighing. Following the final weighing, remove the grease and determine the mass of the clean, dry, empty, measure for subsequent tests.

Calculate the volume of the measure as follows:

$$V = 1000\frac{M}{D} \tag{6.1}$$

where:

V= volume of cylinder, mL

M= net mass of water, g

D= density of water. Kg/m^3

Volume is determined to the nearest 0,1 mL

6.3.6. Preparation of Test Samples

Method A- Standard Graded Sample-weigh out and combine the following quantities of fine aggregate which has been dried and sieved in accordance with Test Method ASTM C136.

Individual Size Fraction	*Mass, g*
2.36-mm (No.8) to 1.18-mm (no. 16)	*44*
1.18-mm (No.16) to 600-μm (No.30)	*57*
600-μm (No.30) to 300-μm (No.50)	*72*
300-μm (No.50) to 150-μm (No.100)	*17*
	190

The tolerance on each of these amounts is ± 0.2 g.

Method B- Individual Size Fractions-Prepare a separate 190-g sample of fine aggregate, dried and sieved in accordance with Test Method C136, for each of the following size fractions:

Individual Size Fraction	*Mass, g*
2.36-mm (No.8) to 1.18-mm (No.16)	*190*
1.18-mm (No.16) to 600-μm (No.30)	*190*
600-μm (No.30) to 300-μm (No.50)	*190*

The tolerance on each of these amounts is ± 1 g. Each size is tested separately.

Method C- As Received Grading-Pass the sample (dried in accordance with Method C136) through a 4.75-mm (No.4) sieve. Obtain a 190 ± 1-g sample of the material passing the 4.75-mm (No. 4) sieve for test.

Specific Gravity of Fine Aggregate-If the bulk dry specific gravity of fine aggregate from the source is unknown; determine it on the minus 4.75-mm (No, 4) material according to Test Method C128. Use this value in subsequent calculations unless some size fractions differ by more than 0.05 from the specific gravity typical of the complete sample, in which case the specific gravity of the fraction (or fractions) being tested must be determined. An indicator of differences in specific gravity of various particle sizes is a comparison of specific gravities run on the fine aggregate in different gradings. Specific gravity can be run on gradings with and without specific size fractions of interest. If specific gravity difference exceed 0.05, determine the specific gravity of the individual 2.36-mm (No.8) to 150-µm (No. 100) sizes for use with Method A or the individual size fractions for use with Method B either by direct measurement or by calculation using the specific gravity data on gradings with and without the size fraction of interest. A difference in specific gravity of 0.05 will change the calculated void content about one percent. (AASHTO,TP33)

6.3.7. Procedure

1-Each test sample is mix with the spatula until it appears to be homogeneous. Use a finger to block the opening of the funnel. The test sample is pour into the funnel. The material is leveled in the funnel by the spatula. The finger is removed and the sample fells freely into the cylindrical measure.

2- After the funnel empties, strike-off excess heaped fine aggregate from the cylindrical measure by a single pass of the spatula with the width of the blade vertical using the straight part of its edge in light contact with the top of the measure. Until this operation is complete, exercise care to avoid vibration or any disturbance that could cause compaction of the fine aggregate in the cylindrical measure. The mass of the cylindrical measure is determined

3- The sample from the retaining pan and cylindrical measure are recombined and the procedure is repeated. The results of two runs are averaged. See 6.2.8. Calculation section.

4- The mass of the empty measure is recorded and also, the mass of the measure and fine aggregate is recorded for each run.

6.3.8. Calculation

The uncompacted voids are calculated for each determination by the following equation (6.2):

$$U = \frac{V - \langle F/G \rangle}{V} x100 \tag{6.2}$$

Where:

V = volume of cylindrical measure, mL

F = net mass, g, of fine aggregate in measure (Gross mass minus the mass of the empty measure).

G = bulk dry specific gravity of fine aggregate.

U = uncompacted voids, percent, in the material.

The average uncompacted voids for the Standard Graded Sample (Method A) are calculated for the two determinations and the result reports as U_s.

For the Individual Size Fractions (Method B) calculate:

First, the average uncompacted voids for the determinations made on each of the three size-fraction samples:

U_1 = *Uncompacted Voids, 2.36-mm (No.8) to 1.18-mm (N0.16), percent*

U_2 = *Uncompacted Voids, 1.18-mm (No.16) to 600-μm (No.30), percent*

U_3 = *Uncompacted Voids, 600-μm (No.30) to 300μm (No.50), percent*

Second, the mean uncompacted voids (U_m) including the results for all three sizes:

$$U_m = (U_1 + U_2 + U_3) / 3 \qquad (6.3)$$

For the As-Received grading (Method C) calculate the average uncompacted voids for the two determinations and report the results as U_g.(AASHTO TP33,1993,pp.352)

6.3.9. Fine Aggregate Angularity Criteria

The results of this test are used in the laboratory during SUPERPAVE mix design process. Fine aggregate angularity criteria for increasing levels of total traffic in ESALs over the planned or estimated service life of the pavement are presented in Table 6.1.

Table 6.1. Fine Aggregate Angularity Criteria in AASHTO TP33

Traffic Level (ESALs)	Depth From Surface	
	<100 mm	>100 mm
$<3x10^5$	----	---
$<1x10^6$	40%	---
$<3x10^6$	40%	40%
$<3x10^7$	45%	40%
$<1x10^8$	45%	45%
$>1x10^8$	45%	45%
Criteria are presented as minimum air voids in % loosely compacted fine Aggregate		

(Cominsky et al, 1994,p.33)

6.4. ASTM D3398

ASTM D3398 is a standard test method for index of aggregate particle shape and texture. This method covers the determination of the particle index of aggregate as a overall measure of particle shape and texture characteristics.

6.4.1 Significance and Use

"The method provides an index valve to the relative particle shape and texture characteristics of aggregates. This valve is a quantitative measure of the aggregate shape and texture characteristics that may affect the performance of road and paving mixtures. The method has been successfully used to indicate the effect of these characteristics on the compaction and strength characteristics of sail-aggregate and asphalt concrete mixtures." (ASTM D 3398-81)

6.4.2. Apparatus

-- Cylindrical Mold;

(It may be appropriate to use a smaller cylindrical mold for the testing of fine aggregate (passing No.4) less fine material will be needed and sample size can be adjusted accordingly)

-- Tamping rod; A round straight steel rod 0,625 ± 0,010 in. (15,88 ± 0,25) in diameter and 24 in. (610 mm) diameter. The weight of the tamping rod shall be 930 ± 10g

-- Weighting device – At least 15 kg capacity, sensitive to 2 g or less.

6.4.3. Calibration of Mold

Calibration process is explained in AASHTO TP-33 (see for detail 7.2.5.)

6.4.4. Preparation of Test Sample

A sample is obtained that it will yield at least 13 lb (6 kg) of each size of the aggregate, which is available in amounts of 10 % unless it is specifically requested.

The sample of aggregate is washed by decantation of the wash water through the No. 200 (75-µm) sieve. Washing operation continues until the wash water is clear. The sample is dried to constant weight by a temperature of 230 ± 9°F (110 ± 5°C) and the sample is sieved by the following sieve fractions;

Passing	**Retained**
¾ in. (19 mm)	½ in
½ in. (12,5 mm)	3/8 in
3/8 in. (9,5 mm)	No. 4
No. 4 (4,75 mm)	No. 8
No. 8 (2,36 mm)	No.16
No.16 (1,18 mm)	No. 30
No.30 (600 µm)	No.50
No. 50 (300 µm)	No.100
No.100 (150 µm)	No. 200 (75 µm)

After the required amount of material has been sieved for each size fraction to be tested. The bulk dry specific gravity of each size group are determined by method ASTM C127 and ASTM C128

6.4.5. Percentage of Voids

1- *"Using oven-dried samples for each size fraction, run determinations of percentage of voids at each of the two levels of compaction in accordance with the procedure given in this section. First, run two test on the sample for each size at the compaction of 10 drops of the tamping rod per layer. Then using the same samples for each size, fill the mold twice using 50 drops of the rod per layer as the compactive effort."*

1.1- *Place the cylindrical mold on a uniform, solid foundation. Fill the mold in three layers. Gently place the aggregate, from the lowest height possible, into the* *mold until it is approximately one-third full. Level the surface with the fingers, and compact the layer using 10 drops of the tamping rod evenly distributed over the surface. Apply each drop by holding the rod vertically with its rounded end approximately 2 in (50 mm) above the surface of the aggregate and releasing it so that it falls freely place a second layer in the mold using the same procedure, filling the mold approximately two thirds full. As before, level the surface and apply 10 drops of the rod. Fill the remaining space in the mold with a third layer and again level the surface and apply the same compactive effort, 10 drops of the rod. After the final layer has been compacted, add individual pieces of aggregate to make the surface of the aggregate mass even with the rim of the mold, with no projections above the rim. Determine the net weight of the aggregate in the mold to an accuracy of at least 4 g.*

1.2- *Repeat the filling of the mold using the same sample and compaction. Make a second determination of the net weight of the aggregate in the mold as described in. Use the average weight of the two runs in calculating the percentage of voids at 10 drops for each size.*

1.3- *For the higher degree of compaction, follow the steps outlined in 1.1 and 1.2, except use 50 drops of the tamping rod in compacting each layer. Again average the net weights from the two runs for use in computing the percentage of voids at 50 drops for each size fraction.*

Calculate the percentage of voids in each size fraction of the aggregate at 10 drops per layer and at 50 drops per layer, respectively, by the following relationships:

$$V_{10} - [1 - (W_{10}/sv)] x\ 100 \quad (6.4)$$

$$V_{50} - [1 - (W_{50}/sv)] x\ 100 \quad (6.5)$$

Where:

V_{10} = *Voids in aggregate compacted at 10 drops per layer %,*

V_{50} = *Voids in aggregate compacted at 50 drops per layer %,*

W_{10} = *Average net weight of the aggregate in the mold compacted at 10 drops per layer, g,*

W_{50} = *Average net weight of the aggregate in the mold compacted at 50 drops per layer, g,*

s = *Bulk dry specific gravity of the aggregate size fraction, and*

v = *Volume of the cylindrical mold, mL.*

6.4.6. Particle Index

The particle index (I_a) is determined cach size fraction tested by the nomograph in Figure 6.4 or as follows:

$$I_a = 1.25\ V_{10} - 0.25\ V_{50} - 32.0 \tag{6.6}$$

"Calculate the weighted particle index of an aggregate containing several sizes by averaging the particle index data for each size group, weighted on the basis of the percentage of the groups in the original grading of the sample as received; or preferably, on the basis of the average grading of the material proposed to be used in the work" (ASTM D 3398, 1981)

Table 6.2 Specific Volume of Water at Different Temperatures

Temperature, °F (°C)	*Specific Volume, mL/g*
54 (12)	*1.0005*
57 (14)	*1.0007*
61 (16)	*1.0010*
64 (18)	*1.0014*
68 (20)	*1.0018*
72 (22)	*1.0022*
75 (24)	*1.0027*

79 (26)	*1.0032*
82 (28)	*1.0038*
86 (30)	*1.0044*
90 (32)	*1.0050*

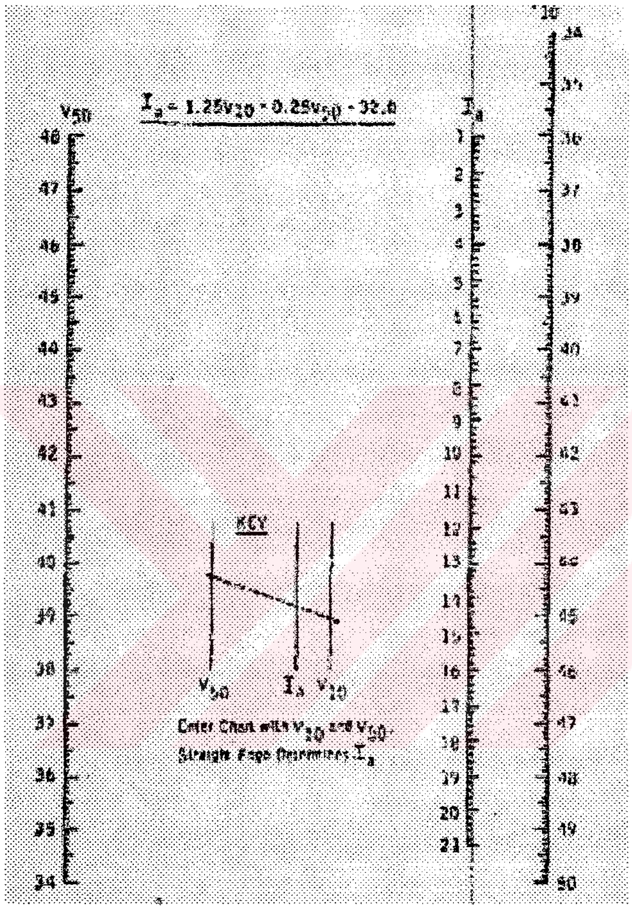


Figure 6.4 Chart for Determining Particle Index (1_a) (ASTM D3398, 1981)

6.5 Other Research Relating to Aggregate Angularity

SUPERPAVE includes two other tests for aggregate angularity, coarse aggregate angularity and fine aggregate angularity. Coarse aggregate angularity is measured using Pennsylvania Department of Transportations Test Method No. 621, *Determining the Percentage of Crushed Fragment in Gravel.* Specifications are provided for minimum percentage of the aggregate blend to have at least one, or two or more fractured faces based on traffic level (3). ASTM has just approved a new test method which more clearly defines the way fractured faces are measured. (Kandhal, 1996)

Fine aggregate angularity is measured using AASHTO TP 33, *Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)*, Method A. This test method is based on the National Aggregate Associations Flow Test. The SUPERPAVE Specifications are based on traffic level.

In 1993, Colorado implemented a minimum VMA specification. Prior to these *Aschenbrener et al.* conducted a study to determine factors, which affect VMA. Gradations, quantity of P200, size of P200 and fine aggregate angularity were examined. Gradation was fond to affect VMA the most. Whit Colorado's aggregates, gradations on the fine side of the maximum density line were found to produce the highest VMA. Gradations on the coarse side of the maximum density line were found to be significantly affected by fine aggregate angularity. VMA's on the coarse side of the maximum density line were found to be less sensitive to changes in P200 content.

> *Several studies have been completed relating aggregate angularity to rutting performance. NCAT conducted a national study on rutting which encompassed 42 pavements in 14 states. Approximately eleven 150 mm (6 in) cores were obtained at 0.3 m (1 ft) intervals across the surveyed lane. Percent of crushed faces was measured on the coarse and fine aggregate fractions and the NAA aggregate flow test* (uncompacted voids...) *were performed on the extracted aggregate. Percent of crushed faces of the coarse aggregate and the uncompacted void content were found to be highly correlated with rut depth. Based on a model to predict rutting developed from the data, the following aggregates properties were recommended to produce a rut resistant pavement.*

Coarse aggregate with 2 or more crushed faces = 100 % minimum
NAA uncompacted voids (method A) = 43.3 % minimum (AASHTO TP33,1993,p.9)

These results are supported by a study by Khandal et al. The Particle Index measured by ASTM D 3398. Standard Test Method for Index of Aggregate Particle Shape and Texture was compared to the results obtained from percent crushed faces and uncompacted voids in fine aggregate. The particle index is determined by compacting individual size fractions in a container of known volume. The particle index is determined from a nomograph using the percent of uncompacted voids for the size fraction at two compaction levels. For coarse aggregate, the particle index was shown to increase sharply as percent crushed faces increased from 80–100% the dividing line between natural and manufactured fine aggregates was found to be 44.5 % with NAA Flow Test (Method A)

CHAPTER SEVEN

SAMPLING AND TESTING OF FINE AGGREGATES

The fine-grained aggregate samples were collected from 24 different quarries and 4 river deposits in different locations of Turkey (Figure 7.1). During the collection of sampling ASTM D 75 (Standard Practice for Sampling Aggregates) procedure was followed. The procedure briefly was crushed aggregates piles of minus No.4 sieve (4.75 mm) and samples were taken from about 0.5 m, then average 10-15 kg of samples were collected from each pile.

The collected samples were dried in an oven at 105 ± 5 °C until constant weight. The dried samples were divided into two groups: The first group was sieved between No.5 (4mm) and No.200 (0.075mm) meshes. The second group was sieved between No.10 (2mm) and No.200 (0.075mm) meshes. The samples were washed through No. 200 mesh until the washing water became clear. The washed samples were placed in a pan; then water was added until it covered the surface of the aggregates completely for 24 hours. Afterwords, the samples were carefully drained in a manner to avoid loss of any fine particles. Once, the particles were saturated-surface dry (to make the samples saturated surface dry, the samples are mixed thoroughly under air flow. The drying process was verified by cone test.), about 500 gr saturated surface dry sample was placed in a picnometer. Then, the weight of the picnometer and the sample were determined. Water was added to the picnometer until the surface of the sample was fully covered. Then, picnometer was shaked until whole air bubbles were disappeared. The picnometer was placed into the water bath at temperature of 25 °C for about half an hour. The sample was weighed after the picnometer was taken off the water bath and checked for right water level.

The fine aggregates were placed in a pan and dried at 105 ± 5 °C for 24 hours. After 24 hours, the samples were left in room temperature to cool. The accuracy of weighing was 0.1 gr. Tables 7.1 to 7.55 present the specific gravity and water adsorption values.

The weight of the sample for flow rate experiment was determined with Pr/2.7 equation. The determined weights were placed in 16 mm and 12 mm cylindrical molds for the samples passing through No.5-No.200 and No.10-No.200 meshes, respectively. The samples were placed in the flow apparatus by free-fall procedure (Figure 7.2). After the shutter was opened, the flow rates were determined with an accuracy of 0.01 (Figure 7.3). The results are presented in Tables 7.2 to 7.56. When the results are presented in graphic form, significant differences are observed in the flow rates, (Figure 7.4). In Figure 7.4, the quarries were grouped according to crusher types. The flow rates of the samples passing through No.5-No.200 and No.10-200 are plotted in bar form. The mineral types are indicated in different colors in all figures.

When Figure 7.4 is studied, it is seen that the limestone sample, crushed by VSI Gyratory crusher, obtained from Betonsa/Gebze has the highest flow rate between 49-25. The other samples having high flow rates; the ***limestone*** obtained from Karatepe/Çorlu and ***basalt*** obtained from Polatlı/Ankara samples crushed with impact crusher; and the ***andesite*** obtained from Madra/Ayvalık crushed with jaw crusher.


Kesan
Istanbul
Sile
Gebze
Izmit
Bursa
Balikesir
Polatli
Ankara
Ayvalik
Salihli
Izmir
Torbali
Odemis
Kusadasi
Söke
Aydin
Antalya
Adana

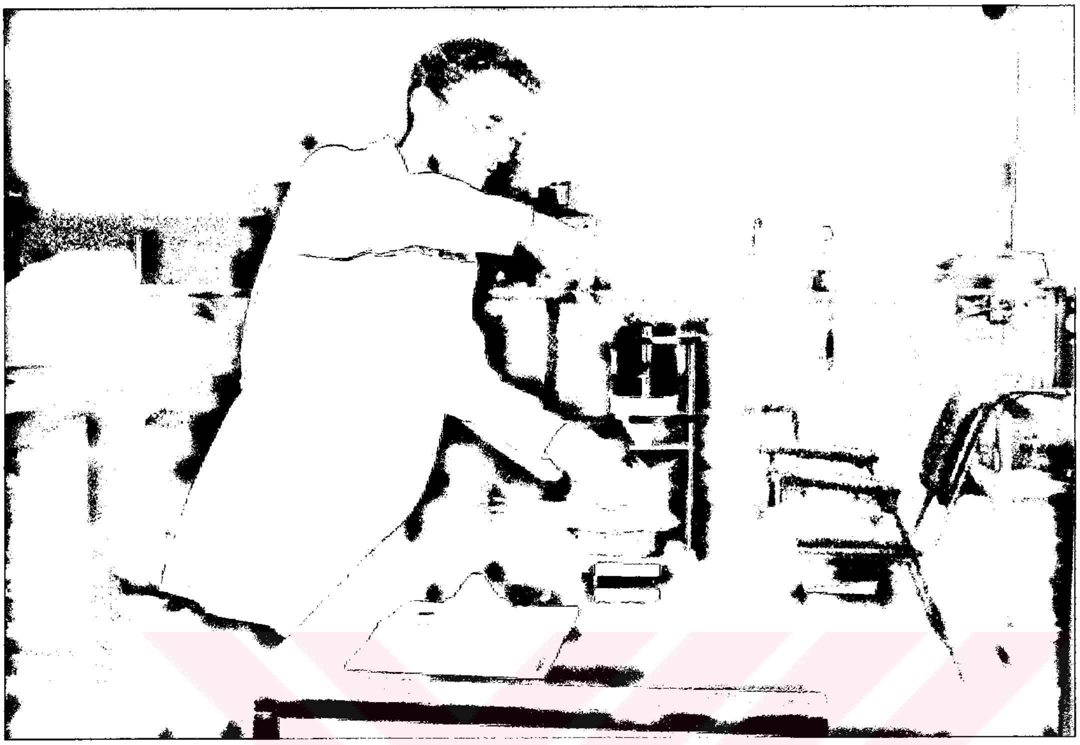


Figure 7.2 Filling Procedure of Fine Aggregate.

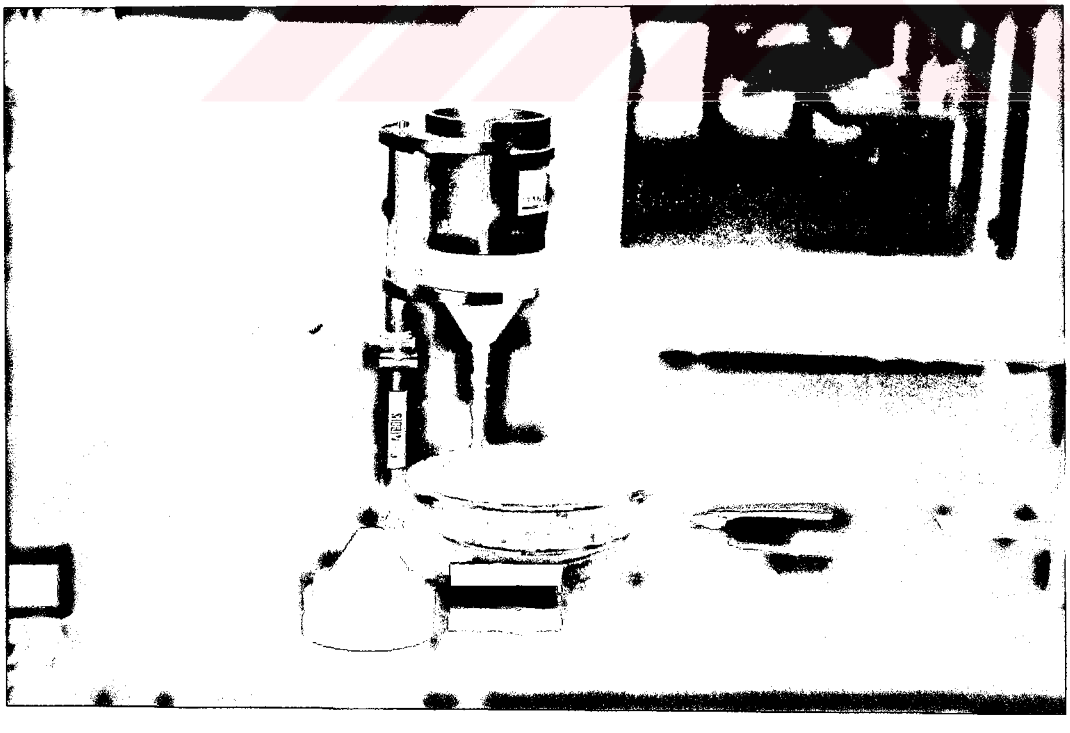


Figure 7.3 Flow Rate Process of Fine Aggregate.

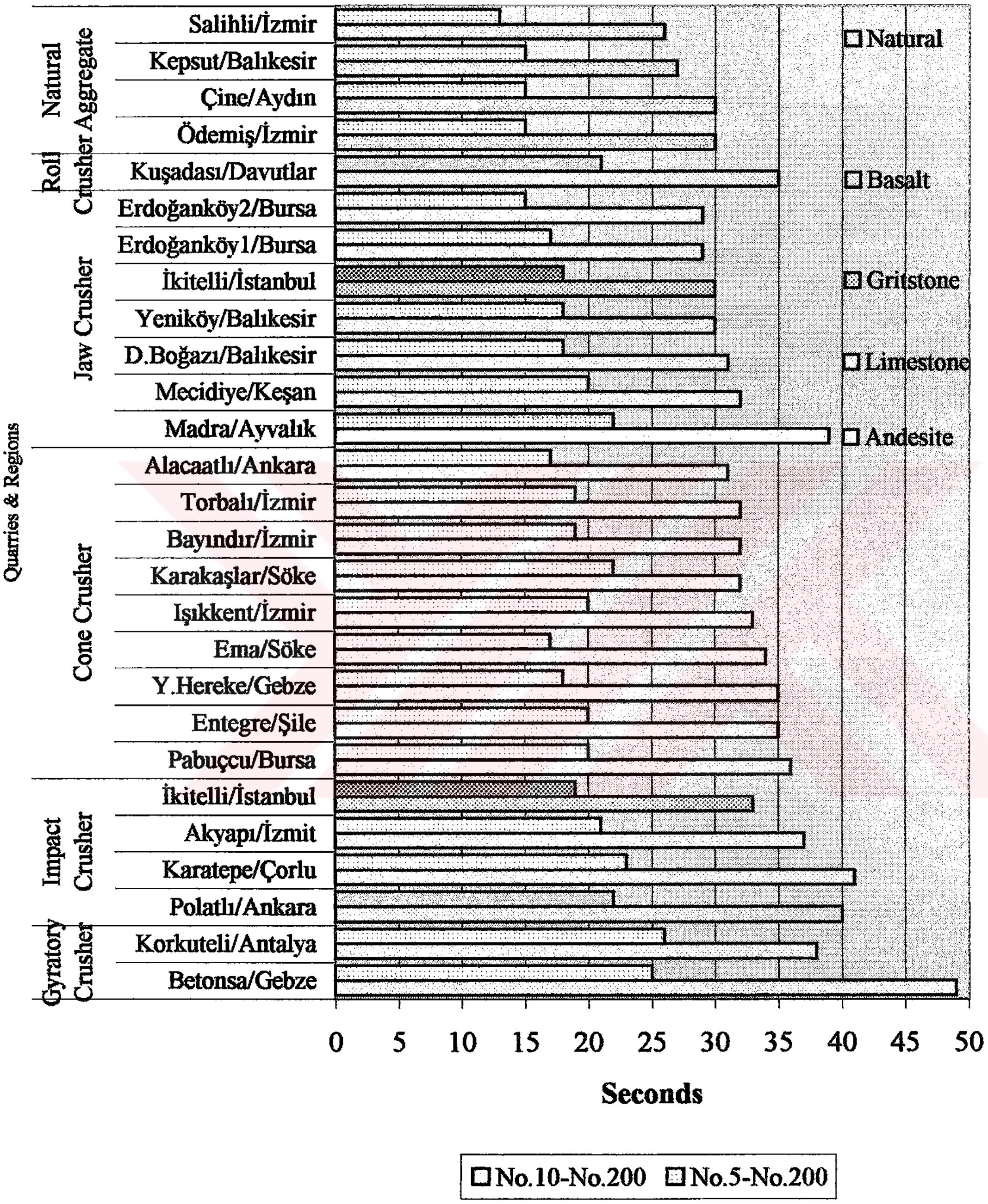


Figure 7.4 Flow Rates of Fine Aggregate Samples by AFNOR P18-564

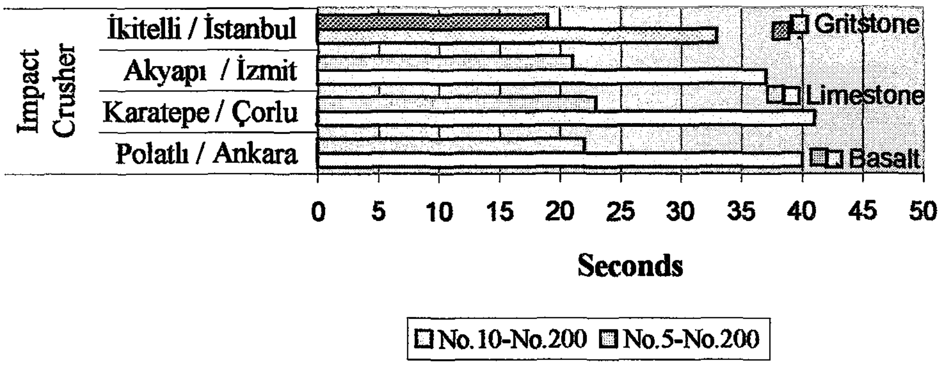


Figure 7.5 Flow Rates of Fine Aggregate Samples that are Crushed by Impact Crusher.

If the samples were grouped according to crusher type, the samples crushed by impact Crusher [Polatlı/Ankara (40/22) and Karatepe/Çorlu (41/23)] have the highest flow rates (Figure 7.5)

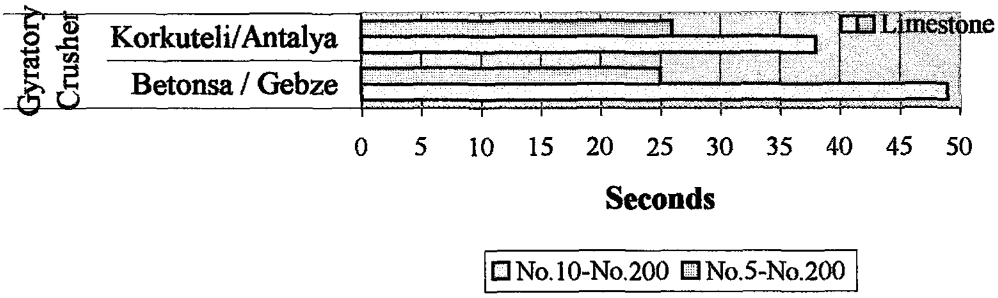


Figure 7.6 Flow Rates of Fine Aggregate Samples that are Crushed by Gyratory Crusher.

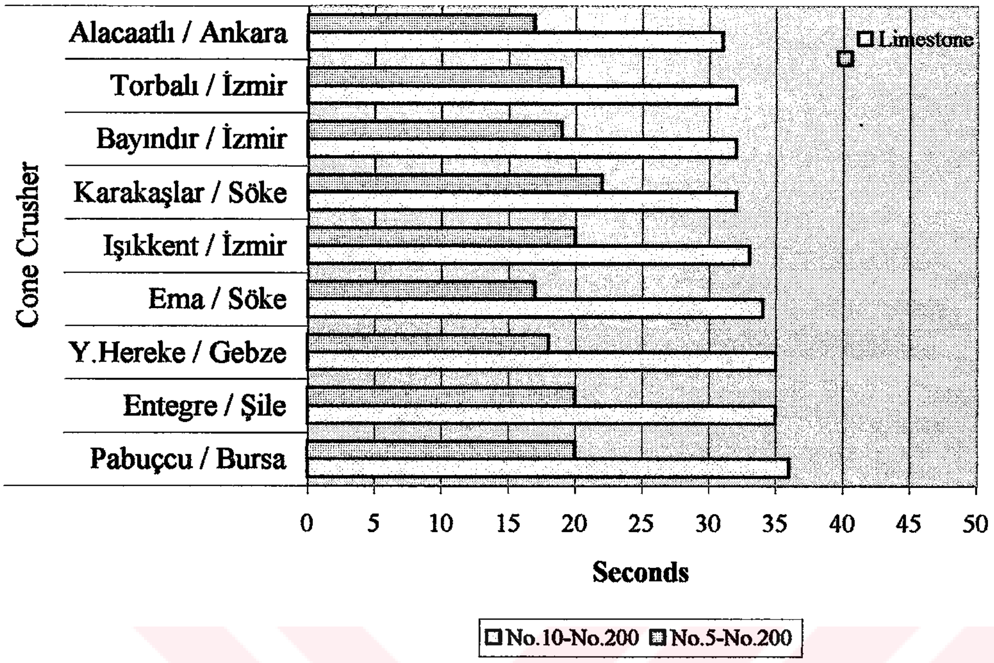


Figure 7.7 Flow Rates of Fine Aggregate Samples that are Crushed by Impact Crusher.

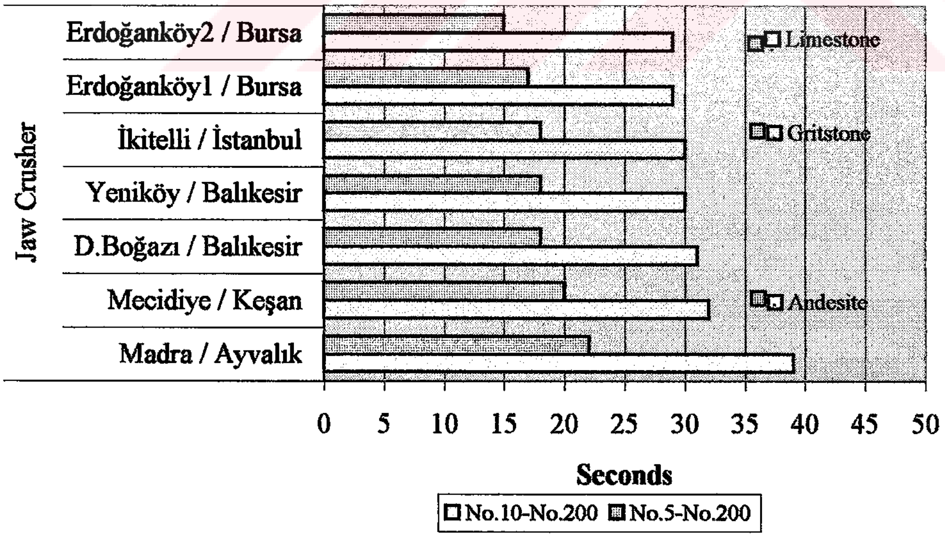


Figure 7.8 Flow Rates of Fine Aggregate Samples that are Crushed by Jaw Crusher.

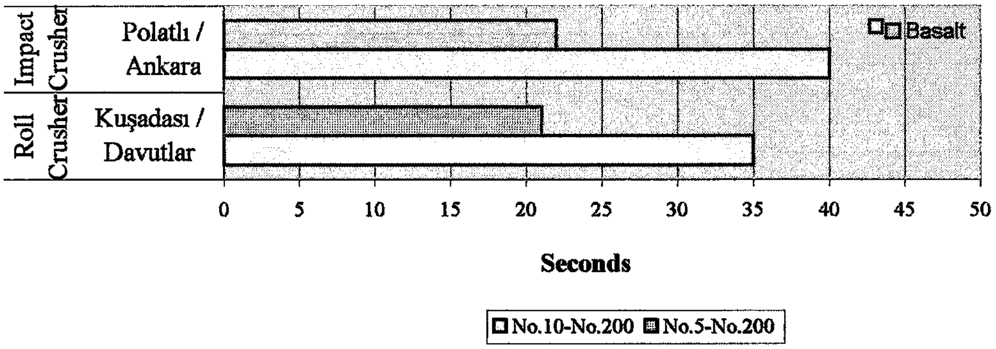


Figure 7.8 Flow Rates of Fine Basalt Samples that are Crushed by Impact and Roll Crusher.

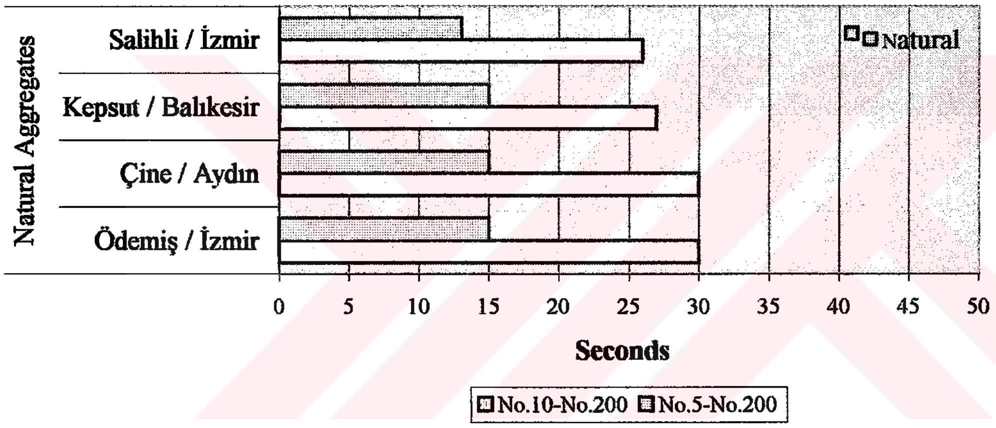


Figure 7.9 Flow Rates of Natural Fine Aggregate Samples

After an overall evaluation of the results, it can be said that gyratory crushers, especially VSI ones, and impact crushers give the highest flow rates that means highest angularity. The flow rates of the samples obtained from these crushers are in the ranges of Level 2 and Level 3 of AFNOR standards. The flow rates of the samples crushed with jaw crusher and cone crusher is may be appropriate for the Level 1 of AFNOR standards.

The flow rates of river deposits having pyrite (Çine, Aydın and Ödemiş, Izmir in Figure 7.8) may also appropriate values for the Level 1 of AFNOR standards, which shows that the existing of pyrite leads to higher angularity in natural sands.

Table 7.1 Specific Gravities of the Fine Aggregate Samples (Yılankale / Adana)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Yılankale / Adana
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	496.5	496
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	948	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	185.5	
BULK DRY W_1+B-A	V_2	182	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		971
P+W	B		655.5
BULK SSD W_2+B-A	V_1		184.5
BULK DRY W_1+B-A	V_2		180.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.677	2.688
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.695	2.710
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.728	2.748

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.705	0.807

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.2 Flow Rates of the Fine Aggregate Samples (Yılankale / Adana)

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Adana / Yılankale
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.677 / 2.7	**Pr / 2.7**	**:** 2.688 / 2.7
Weight	**:** 0.991 kg	**Weight**	**:** 0.996 kg
1.Flow Time	: 32.19	1.Flow Time	: 19.73
2.Flow Time	: 32.48	2.Flow Time	: 18.98
3.Flow Time	: 32.17	3.Flow Time	: 18.95
4.Flow Time	: 32.33	4.Flow Time	: 19.69
5.Flow Time	: 32.24	5.Flow Time	: -
		6.Flow Time	: 19.71
Average	: 32.28 ≅ 32	7.Flow Time	: -
		8.Flow Time	: -
		9.Flow Time	: 19.52
		10.Flow Time	: 19.60
		Average	: 19.52 ≅ 20

Table 7.3 Specific Gravities of the Fine Aggregate Samples (Alaçaatlı / Ankara)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
QUARRY&REGION.. : Alaçaatlı / Ankara
DATE : ../../2000
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	494.7	496.7
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	966	
P+W	B	654.5	
BULK SSD W_2+B-A	V_1	188.5	
BULK DRY W_1+B-A	V_2	183,2	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		968.3
P+W	B		655
BULK SSD W_2+B-A	V_1		186,7
BULK DRY W_1+B-A	V_2		183.4

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.624	2.660
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.652	2.678
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.692	2.708

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.071	0.664

P : Weight of Picnometer
SSD : Saturated Surface Dry
W : Weight of Water
M : Weight of Material

Table 7.4 Flow Rates of the Fine Aggregate Samples (Alaçaatlı / Ankara).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Alaçaatlı / Ankara
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.624 / 2.7	**Pr / 2.7**	2.660 / 2.7
Weight	0.972kg	**Weight**	0.985kg
1.Flow Time	31.06	1.Flow Time	16.53.
2.Flow Time	31.41	2.Flow Time	16.75.
3.Flow Time	31.04	3.Flow Time	16.66
4.Flow Time	31.18	4.Flow Time	16.47
5.Flow Time	31.16	5.Flow Time	16.72
Average	31.21 ≅ 31	Average	16.63 ≅ 17

Table 7.5 Specific Gravities of the Fine Aggregate Samples (Polatlı / Ankara).

SPECIFIC GRAVITY TEST

TESTED BY	: A.Topal	QUARRY&REGION	: Polatlı / Ankara
DATE	: ../../2000	MINERAL AGGREGATE	: Basalt

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	481.5	481.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	970.5	
P+W	B	646.5	
BULK SSD W_2+B-A	V_1	176	
BULK DRY W_1+B-A	V_2	157.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		961.6
P+W	B		646
BULK SSD W_2+B-A	V_1		173.2
BULK DRY W_1+B-A	V_2		154.7

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.735	2.780
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.842	2.887
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.900	2.920

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	3.870	3.870

P	: Weight of Picnometer	SSD	: Saturated Surface Dry
W	: Weight of Water	M	: Weight of Material

Table 7.6 Flow Rates of the Fine Aggregate Samples (Polatlı / Ankara).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Polatlı / Ankara
MINERAL AGGREGATE : Basalt
CRUSHER TYPE : Impact Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.735 / 2.7	**Pr / 2.7**	: 2.780 / 2.7
Weight	: 1.013 kg	**Weight**	: 1.030 kg
1.Flow Time	: 40.30	1.Flow Time	: 21.57
2.Flow Time	: 39.98	2.Flow Time	: 21.58
3.Flow Time	: 40.07	3.Flow Time	: 21.62
4.Flow Time	: 39.95	4.Flow Time	: 21.30
5.Flow Time	: 39.45	5.Flow Time	: 21.44
Average	: 39.93 ≅ 40	Average	: 21.50 ≅ 22

Table 7.7 Specific Gravities of the Fine Aggregate Samples (Korkuteli / Antalya).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Korkuteli / Antalya
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	492.5	488.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	956	
P+W	B	645.5	
BULK SSD W_2+B-A	V_1	189.5	
BULK DRY W_1+B-A	V_2	182	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		964
P+W	B		655
BULK SSD W_2+B-A	V_1		191
BULK DRY W_1+B-A	V_2		179.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.599	2.558
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.638	2.618
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.706	2.721

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.523	2.354

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.8 Flow Rates of the Fine Aggregate Samples (Korkuteli & Antalya).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Korkuteli & Antalya
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Gyratory Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.599 / 2.7	**Pr / 2.7**	: 2.558 / 2.7
Weight	: 0.963 kg	**Weight**	: 0.947 kg
1.Flow Time	: 38.84	1.Flow Time	: -
2.Flow Time	: 38.16	2.Flow Time	: 24.13
3.Flow Time	: 38.38	3.Flow Time	: 24.97
4.Flow Time	: 38.03	4.Flow Time	: -
5.Flow Time	: 38.20	5.Flow Time	: -
		6.Flow Time	: -
Average	: 38.32 ≅ 38	7.Flow Time	: -
		8.Flow Time	: 27.36
		9.Flow Time	: 27.62
		10.Flow Time	: 24.94
		11.Flow Time	: -
		12.Flow Time	: -
		13.Flow Time	: 27.82
		Average	: 26.14 ≅ 26

Table 7.9 Specific Gravities of the Fine Aggregate Samples (D.boğazı / Balıkesir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : D.boğazı / Balıkesir
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	482	483
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	962.5	
P+W	B	655.5	
BULK SSD W_2+B-A	V_1	193	
BULK DRY W_1+B-A	V_2	175	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		943.5
P+W	B		633.5
BULK SSD W_2+B-A	V_1		190
BULK DRY W_1+B-A	V_2		173

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.497	2.542
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.591	2.630
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.754	2.792

ABSORPTION

% ABSORPTION	$100\frac{W_2 - W_1}{W_1}$	3.734	3.520

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.10 Flow Rates of the Fine Aggregate Samples (D.boğazı / Balıkesir)

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : D.boğazı / Balıkesir
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.497 / 2.7	**Pr / 2.7**	: 2.542 / 2.7
Weight	: 0.925 kg	**Weight**	: 0.941 kg
1.Flow Time	: 31.17	1.Flow Time	: -
2.Flow Time	: 30.39	2.Flow Time	: 17.82
3.Flow Time	: 30.35	3.Flow Time	: 17.88
4.Flow Time	: 30.36	4.Flow Time	: 17.96
5.Flow Time	: 30.48	5.Flow Time	: 17.78
		6.Flow Time	: 17.64
Average	: 30.55 ≅ 31	Average	: 17.82 ≅ 18

Table 7.11 Specific Gravities of the Fine Aggregate Samples (Yeniköy/Balıkesir)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Yeniköy / Balıkesir
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	495	497
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	1088	
P+W	B	778	
BULK SSD W_2+B-A	V_1	190	
BULK DRY W_1+B-A	V_2	185	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		1092
P+W	B		778
BULK SSD W_2+B-A	V_1		186
BULK DRY W_1+B-A	V_2		183

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.605	2.672
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.632	2.688
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.676	2.716

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.010	0.600

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.12 Flow Rates of the Fine Aggregate Samples (Yeniköy / Balıkesir)

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Yeniköy / Balıkesir
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.605 / 2.7	**Pr / 2.7**	: 2.672 / 2.7
Weight	: 0.965 kg	**Weight**	: 0.989 kg
1.Flow Time	: 30.51	1.Flow Time	: 17.93
2.Flow Time	: 30.11	2.Flow Time	: 18.29
3.Flow Time	: 29.86	3.Flow Time	: 17.84
4.Flow Time	: 29.86	4.Flow Time	: 18.18
5.Flow Time	: 30.30	5.Flow Time	: 18.02
Average	: 30.13 ≅ 30	Average	: 18.05 ≅ 18

Table 7.13 Specific Gravities of the Fine Aggregate Samples (Erdoğanköy1/Bursa).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000
QUARRY&REGION : Erdoğanköy / Bursa
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	495	492.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	945	
P+W	B	634	
BULK SSD W_2+B-A	V_1	189	
BULK DRY W_1+B-A	V_2	184	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		959.8
P+W	B		647
BULK SSD W_2+B-A	V_1		187.2
BULK DRY W_1+B-A	V_2		179.7

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.619	2.631
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.646	2.671
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.690	2.741

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.010	1.522

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.14 Flow Rates of the Fine Aggregate Samples (Erdoğanköy1 / Bursa).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Erdoğanköy / Bursa
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.619 / 2.7	**Pr / 2.7**	**:** 2.631 / 2.7
Weight	**:** 0.970 kg	**Weight**	**:** 0.974 kg
1.Flow Time	: 28.90	1.Flow Time	: 16.75
2.Flow Time	: 29.03	2.Flow Time	: 16.61
3.Flow Time	: 29.10	3.Flow Time	: 16.48
4.Flow Time	: 29.20	4.Flow Time	: 16.52
5.Flow Time	: 28.90	5.Flow Time	: 16.70
Average	: 29.03 ≅ 29	Average	: 16.61 ≅ 17

Table 7.15 Specific Gravities of the Fine Aggregate Samples (Erdoğanköy2/Bursa)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Erdoğanköy2 / Bursa
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	490.7	492.8
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	946	
P+W	B	634	
BULK SSD W_2+B-A	V_1	188	
BULK DRY W_1+B-A	V_2	178.7	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		960.6
P+W	B		647
BULK SSD W_2+B-A	V_1		186.4
BULK DRY W_1+B-A	V_2		179.2

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.610	2.644
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.660	2.682
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.746	2.750

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.895	1.461

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.16 Flow Rates of the Fine Aggregate Samples (Erdoğanköy2/Bursa).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Erdoğanköy 2 / Bursa
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.610 / 2.7	**Pr / 2.7**	2.644 / 2.7
Weight	0.967 kg	**Weight**	0.979 kg
1.Flow Time	28.78	1.Flow Time	15.07
2.Flow Time	28.88	2.Flow Time	15.09
3.Flow Time	28.90	3.Flow Time	15.14
4.Flow Time	28.72	4.Flow Time	15.01
5.Flow Time	28.44	5.Flow Time	14.97
Average	28.74 ≅ 29	Average	15.06 ≅ 15

Table 7.17 Specific Gravities of the Fine Aggregate Samples (Pabuçcu / Bursa).

SPECIFIC GRAVITY TEST

TESTED BY	: A.Topal	QUARRY&REGION	: Pabuçcu / Bursa
DATE	: ../../2000	MINERAL AGGREGATE	: Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	495	494
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	1091	
P+W	B	778	
BULK SSD W_2+B-A	V_1	187	
BULK DRY W_1+B-A	V_2	182	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		1090
P+W	B		778
BULK SSD W_2+B-A	V_1		188
BULK DRY W_1+B-A	V_2		176

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.647	2.628
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.674	2.660
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.720	2.714

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.010	1.210

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.18 Flow Rates of the Fine Aggregate Samples (Pabuçcu / Bursa).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Pabuçcu / Bursa
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.647 / 2.7	**Pr / 2.7**	: 2.628 / 2.7
Weight	: 0.980 kg	**Weight**	: 0.973 kg
1.Flow Time	: 35.51	1.Flow Time	: 20.22
2.Flow Time	: 35.29	2.Flow Time	: 19.88
3.Flow Time	: 35.75	3.Flow Time	: 20.24
4.Flow Time	: 35.55	4.Flow Time	: 20.09
5.Flow Time	: 35.67	5.Flow Time	: 20.41
Average	: 35.55 ≅ 36	Average	: 20.17 ≅ 20

Table 7.19 Specific Gravities of the Fine Aggregate Samples (Karatepe / Çorlu)

SPECIFIC GRAVITY TEST

TESTED BY	: A.Topal	QUARRY&REGION	: Karatepe / Çorlu
DATE	: ../../2000	MINERAL AGGREGATE	: Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	495	493
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	958.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	175	
BULK DRY W_1+B-A	V_2	170	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		972.5
P+W	B		646.5
BULK SSD W_2+B-A	V_1		174
BULK DRY W_1+B-A	V_2		167

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.829	2.833
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.857	2.870
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.910	2.950

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.048	1.420

P	: Weight of Picnometer	SSD	: Saturated Surface Dry
W	: Weight of Water	M	: Weight of Material

Table 7.20 Flow Rates of the Fine Aggregate Samples (Karatepe /Çorlu)

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Karatepe / Çorlu
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Impact Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.829 / 2.7	**Pr / 2.7**	: 2.883 / 2.7
Weight	: 1.048 kg	**Weight**	: 1.049 kg
1.Flow Time	: 40.64	1.Flow Time	: 22.99
2.Flow Time	: 40.46	2.Flow Time	: 23.25
3.Flow Time	: 40.54	3.Flow Time	: 23.04
4.Flow Time	: 40.50	4.Flow Time	: 23.16
5.Flow Time	: 40.59	5.Flow Time	: 23.11
Average	: 40.55 ≅ 41	Average	: 23.11 ≅ 23

Table 7.21 Specific Gravities of the Fine Aggregate Samples (Mecidiye / Keşan)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : 06/05/2000

QUARRY&REGION : Mecidiye / Keşan
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	498.5	498.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	942.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	191	
BULK DRY W_1+B-A	V_2	189.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		956.5
P+W	B		646.5
BULK SSD W_2+B-A	V_1		190
BULK DRY W_1+B-A	V_2		188.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.610	2.620
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.620	2.630
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.630	2.640

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.300	0.300

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.22 Flow Rates of the Fine Aggregate Samples (Mecidiye / Keşan).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Mecidiye / Keşan
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.610 / 2.7	**Pr / 2.7**	2.620 / 2.7
Weight	0.966 kg	**Weight**	0.970 kg
1.Flow Time	33.94	1.Flow Time	18.94
2.Flow Time	33.86	2.Flow Time	19.12
3.Flow Time	33.72	3.Flow Time	18.91
4.Flow Time	33.51	4.Flow Time	19.20
5.Flow Time	33.65	5.Flow Time	18.85
Average	33.71 ≅ 34	Average	19.00 ≅ 19

Table 7.23 Specific Gravities of the Fine Aggregate Samples (Betonsa / Gebze).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Betonsa / Gebze
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	498	498
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	962.5	
P+W	B	646.5	
BULK SSD W_2+B-A	V_1	184	
BULK DRY W_1+B-A	V_2	182	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		961.6
P+W	B		646
BULK SSD W_2+B-A	V_1		184.4
BULK DRY W_1+B-A	V_2		182.4

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.707	2.700
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.710	2.711
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.736	2.730

ABSORPTION

% ABSORPTION	$100\frac{W_2 - W_1}{W_1}$	0.400	0.400

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.24 Flow Rates of the Fine Aggregate Samples (Betonsa / Gebze).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION	:	Betonsa / Gebze
MINERAL AGGREGATE	:	Limestone
CRUSHER TYPE	:	Vertical Shaft Impact (VSI) Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.707 / 2.7	**Pr / 2.7**	: 2.700 / 2.7
Weight	: 1.003 kg	**Weight**	: 1.000 kg
1.Flow Time	: 48.66	1.Flow Time	: 24.94
2.Flow Time	: 48.42	2.Flow Time	: 25.69
3.Flow Time	: 48.53	3.Flow Time	: 25.72
4.Flow Time	: 48.51	4.Flow Time	: 25.70
5.Flow Time	: 48.50	5.Flow Time	: 25.25
Average	: 48.52 ≅ 49	Average	: 25.46 ≅ 25

Table 7.25 Specific Gravities of the Fine Aggregate Samples (Y.Hereke / Gebze).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Y.Hereke / Gebze
MINERAL AGGREGATE : Dolomite

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	493.5	494
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	965	
P+W	B	646.5	
BULK SSD W_2+B-A	V_1	181.5	
BULK DRY W_1+B-A	V_2	175	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		963
P+W	B		646
BULK SSD W_2+B-A	V_1		183
BULK DRY W_1+B-A	V_2		177

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.720	2.700
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.755	2.732
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.820	2.791

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.317	1,215

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.26 Flow Rates of the Fine Aggregate Samples (Y.Hereke / Gebze).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Y.Hereke / Gebze
MINERAL AGGREGATE : Dolomite
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.720 / 2.7	**Pr / 2.7**	2.700 / 2.7
Weight	1.007 kg	**Weight**	1.000 kg
1.Flow Time	35.44	1.Flow Time	17.81
2.Flow Time	34.72	2.Flow Time	18.12
3.Flow Time	35.10	3.Flow Time	18.04
4.Flow Time	35.02	4.Flow Time	17.99
5.Flow Time	34.88	5.Flow Time	17.72
Average	35.03 ≅ 35	Average	17.94 ≅ 18

Table 7.27 Specific Gravities of the Fine Aggregate Samples (Bayındır / Izmir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Bayındır / Izmir
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	495.7	495.8
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	956.5	
P+W	B	651.47	
BULK SSD W_2+B-A	V_1	188.9	
BULK DRY W_1+B-A	V_2	184.6	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		946
P+W	B		632
BULK SSD W_2+B-A	V_1		186
BULK DRY W_1+B-A	V_2		181.8

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.624	2.665
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.647	2.688
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.685	2.727

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.867	0.847

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.28 Flow Rates of the Fine Aggregate Samples (Bayındır / Izmir).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Bayındır / Izmir
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.624 / 2.7	**Pr / 2.7**	**:** 2.665 / 2.7
Weight	**:** 0.972 kg	**Weight**	**:** 0.987 kg
1.Flow Time	: 31.50	1.Flow Time	: 18.94
2.Flow Time	: 31.59	2.Flow Time	: 18.93
3.Flow Time	: 31.63	3.Flow Time	: 18.50
4.Flow Time	: 31.42	4.Flow Time	: 18.70
5.Flow Time	: 31.58	5.Flow Time	: 18.88
Average	: 31.54 ≅ 32	Average	: 18.79 ≅ 19

Table 7.29 Specific Gravities of the Fine Aggregate Samples (Işıkkent / Izmir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Işıkkent / Izmir
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	488	490
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	963.5	
P+W	B	655.5	
BULK SSD W_2+B-A	V_1	192	
BULK DRY W_1+B-A	V_2	180	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		952
P+W	B		633.5
BULK SSD W_2+B-A	V_1		188.5
BULK DRY W_1+B-A	V_2		171.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.631	2.700
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.695	2.755
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.813	2.857

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.459	2.020

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.30 Flow Rates of the Fine Aggregate Samples (Işıkkent / Izmir).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Işıkkent / Izmir
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.631 / 2.7	**Pr / 2.7**	**:** 2.700 / 2.7
Weight	**:** 0.974 kg	**Weight**	**:** 1.000 kg
1.Flow Time	: 33.23	1.Flow Time	: 20.29
2.Flow Time	: 33.06	2.Flow Time	: 20.45
3.Flow Time	: 33.93	3.Flow Time	: 20.35
4.Flow Time	: 33.12	4.Flow Time	: 20.49
5.Flow Time	: 33.06	5.Flow Time	: 20.39
Average	: 33.08 ≅ 33	Average	: 20.39 ≅ 20

Table 7.31 Specific Gravities of the Fine Aggregate Samples (Torbalı / Izmir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Torbalı / Izmir
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	490	483
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	944.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	189	
BULK DRY W_1+B-A	V_2	179	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		965.5
P+W	B		655.5
BULK SSD W_2+B-A	V_1		190
BULK DRY W_1+B-A	V_2		173

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.593	2.542
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.646	2.632
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.737	2.639

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.040	3.520

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.32 Flow Rates of the Fine Aggregate Samples (Torbalı / Izmir).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Torbalı / Izmir
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.593 / 2.7	**Pr / 2.7**	: 2.542 / 2.7
Weight	: 0.960 kg	**Weight**	: 0.942 kg
1.Flow Time	: 32.08	1.Flow Time	: 18.55
2.Flow Time	: 31.99	2.Flow Time	: 19.20
3.Flow Time	: 32.52	3.Flow Time	: 18.63
4.Flow Time	: 32.27	4.Flow Time	: 18.86
5.Flow Time	: 32.18	5.Flow Time	: 19.01
Average	: 32.21 ≅ 32	Average	: 18.85 ≅ 19

Table 7.33 Specific Gravities of the Fine Aggregate Samples (Akyapı / Izmit)

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Akyapı / Izmit
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	496.5	495.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	949.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	184	
BULK DRY W_1+B-A	V_2	180.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		961
P+W	B		646.5
BULK SSD W_2+B-A	V_1		185.5
BULK DRY W_1+B-A	V_2		181

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.698	2.671
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.720	2.695
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.751	2.738

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.705	0.908

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.34 Flow Rates of the Fine Aggregate Samples (Akyapı / Izmit)

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Akyapı / Izmit
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Impact Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.698 / 2.7	**Pr / 2.7**	**:** 2.671 / 2.7
Weight	**:** 0.999 kg	**Weight**	**:** 0.989 kg
1.Flow Time	: 36.94	1.Flow Time	: 21.34
2.Flow Time	: 37.07	2.Flow Time	: 21.05
3.Flow Time	: 36.99	3.Flow Time	: 21.14
4.Flow Time	: 37.02	4.Flow Time	: 21.02
5.Flow Time	: 36.88	5.Flow Time	: 21.18
Average	: 36.98 ≅ 37	Average	: 21.15 ≅ 21

Table 7.35 Specific Gravities of the Fine Aggregate Samples (Ema / Söke).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Ema / Söke
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	496	493.3
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	958	
P+W	B	641	
BULK SSD W_2+B-A	V_1	183	
BULK DRY W_1+B-A	V_2	179	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		1089
P+W	B		775
BULK SSD W_2+B-A	V_1		186
BULK DRY W_1+B-A	V_2		179.3

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.710	2.652
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.730	2.688
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.771	2.751

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.807	1.358

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.36 Flow Rates of the Fine Aggregate Samples (Ema / Söke).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Ema / Söke
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.710 / 2.7	**Pr / 2.7**	2.652 / 2.7
Weight	1.004 kg	**Weight**	0.982 kg
1.Flow Time	33.95	1.Flow Time	16.41
2.Flow Time	33.99	2.Flow Time	16.58
3.Flow Time	34.01	3.Flow Time	16.41
4.Flow Time	33.87	4.Flow Time	16.60
5.Flow Time	33.85	5.Flow Time	16.48
Average	33.93 ≅ 34	Average	16.50 ≅ 17

Table 7.37 Specific Gravities of the Fine Aggregate Samples (Karakaşlar/Söke).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000
QUARRY&REGION : Karakaşlar / Söke
MINERAL AGGREGATE : Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	490.5	491
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	947	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	186.5	
BULK DRY W_1+B-A	V_2	177	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		968.5
P+W	B		655.5
BULK SSD W_2+B-A	V_1		187
BULK DRY W_1+B-A	V_2		178

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.630	2.626
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.681	2.674
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.771	2.758

ABSORPTION

% ABSORPTION	$100\frac{W_2 - W_1}{W_1}$	1.937	1.833

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.38 Flow Rates of the Fine Aggregate Samples (Karakaşlar/Söke).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION	:	Karakaşlar / Söke
MINERAL AGGREGATE	:	Limestone
CRUSHER TYPE	:	Cone Crusher

<table>
<tr><th colspan="2">AGGREGATE CHARACTERISTICS</th></tr>
<tr><td>Gradation : No:10–No:200</td><td>Gradation : No:5–No:200</td></tr>
<tr><td>Pr / 2.7 : 2.630 / 2.7</td><td>Pr / 2.7 : 2.626 / 2.7</td></tr>
<tr><td>Weight : 0.974 kg</td><td>Weight : 0.973 kg</td></tr>
<tr><td>1.Flow Time : 32.28
2.Flow Time : 31.98
3.Flow Time : 32.12
4.Flow Time : 32.35
5.Flow Time : 32.22
Average : 32.19 ≅ 32</td><td>1.Flow Time : -
2.Flow Time : 20.73
3.Flow Time : 20.95
4.Flow Time : -
5.Flow Time : 21.07
6.Flow Time : 21.91
7.Flow Time :
8.Flow Time : -
9.Flow Time : 21.62
10.Flow Time : -
Average : 21.55 ≅ 22</td></tr>
</table>

Table 7.39 Specific Gravities of the Fine Aggregate Samples (Entegre / Şile)

SPECIFIC GRAVITY TEST

TESTED BY	: A.Topal	QUARRY&REGION	: Entegre / Şile
DATE	: ../../2000	MINERAL AGGREGATE	: Limestone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	498.5	499
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	955	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	178.5	
BULK DRY W_1+B-A	V_2	177	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		971
P+W	B		646.5
BULK SSD W_2+B-A	V_1		175.5
BULK DRY W_1+B-A	V_2		174.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.793	2.840
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.780	2.850
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.820	2.860

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.301	0.200

P	: Weight of Picnometer	SSD	: Saturated Surface Dry
W	: Weight of Water	M	: Weight of Material

Table 7.40 Flow Rates of the Fine Aggregate Samples (Entegre / Şile).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Entegre / Şile
MINERAL AGGREGATE : Limestone
CRUSHER TYPE : Cone Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.793 / 2.7	**Pr / 2.7**	: 2.840 / 2.7
Weight	: 1.034 kg	**Weight**	: 1.052 kg
1.Flow Time	: 35.38	1.Flow Time	: 19.60
2.Flow Time	: 35.56	2.Flow Time	: 20.32
3.Flow Time	: 35.44	3.Flow Time	: 20.12
4.Flow Time	: 35.50	4.Flow Time	: 19.96
5.Flow Time	: 35.42	5.Flow Time	: 20.04
Average	: 35.46 ≅ 35	Average	: 20.01 ≅ 20

Table 7.41 Specific Gravities of the Fine Aggregate Samples (Davutlar / Kuşadası).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Davutlar / Kuşadası
MINERAL AGGREGATE : Basalt

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	375.5	470.5
SSD WEIGHT	W_2	400	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	882.5	
P+W	B	646.5	
BULK SSD W_2+B-A	V_1	164	
BULK DRY W_1+B-A	V_2	139.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		929.5
P+W	B		633.5
BULK SSD W_2+B-A	V_1		204
BULK DRY W_1+B-A	V_2		174.5

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.290	2.306
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.430	2.450
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.690	2.690

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	6.520	6.270

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.42 Flow Rates of the Fine Aggregate Samples (Davutlar / Kuşadası).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION	:	Davutlar / Kuşadası
MINERAL AGGREGATE	:	Basalt
CRUSHER TYPE	:	Roll Crusher

AGGREGATE CHARACTERISTICS			
Gradation	**:** No:10–No:200	**Gradation**	**:** No:5–No:200
Pr / 2.7	**:** 2.29 / 2.7	**Pr / 2.7**	**:** 2.306 / 2.7
Weight	**:** 848 kg	**Weight**	**:** 0.854 kg
1.Flow Time	: 35.45	1.Flow Time	: 21.15
2.Flow Time	: 35.21	2.Flow Time	: 21.25
3.Flow Time	: 35.33	3.Flow Time	: 21.18
4.Flow Time	: 35.22	4.Flow Time	: 21.15
5.Flow Time	: 35.18	5.Flow Time	: 22.10
Average	: 35.28 ≅ 35	Average	: 21.19 ≅ 21

Table 7.43 Specific Gravities of the Fine Aggregate Samples (Madra/Ayvalık).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Madra / Ayvalık
MINERAL AGGREGATE : Andesite

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	437.5	487
SSD WEIGHT	W_2	450	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	918.5	
P+W	B	646.5	
BULK SSD W_2+B-A	V_1	178	
BULK DRY W_1+B-A	V_2	165.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		945.5
P+W	B		646.5
BULK SSD W_2+B-A	V_1		201
BULK DRY W_1+B-A	V_2		188

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.460	2.420
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.530	2.490
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.640	2.590

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.800	2.670

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.44 Flow Rates of the Fine Aggregate Samples (Madra/Ayvalık).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Madra / Ayvalık
MINERAL AGGREGATE : Andesite
CRUSHER TYPE : Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.460 / 2.7	**Pr / 2.7**	: 2.420 / 2.7
Weight	: 0.911 kg	**Weight**	: 0.896 kg
1.Flow Time	: 39.66	1.Flow Time	: 23.77
2.Flow Time	: 38.42	2.Flow Time	: 22.15
3.Flow Time	: 39.53	3.Flow Time	: 22.86
4.Flow Time	: 39.51	4.Flow Time	: 21.37
5.Flow Time	: 39.50	5.Flow Time	: 22.25
Average	: 39.32 ≅ 39	Average	: 22.48 ≅ 22

Table 7.45 Specific Gravities of the Fine Aggregate Samples (Ikitelli / Istanbul).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Ikitelli / Istanbul
MINERAL AGGREGATE : Gritstone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	485.6	487.5
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	955.5	
P+W	B	647	
BULK SSD W_2+B-A	V_1	191.5	
BULK DRY W_1+B-A	V_2	177.1	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		946.5
P+W	B		634
BULK SSD W_2+B-A	V_1		187.5
BULK DRY W_1+B-A	V_2		175

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.536	2.600
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.611	2.667
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.742	2.786

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.965	2.564

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.46 Flow Rates of the Fine Aggregate Samples

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION	:	Ikitelli / Istanbul
MINERAL AGGREGATE	:	Gritstone
CRUSHER TYPE	:	Jaw Crusher

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.536 / 2.7	**Pr / 2.7**	2.600 / 2.7
Weight	0.939 kg	**Weight**	0.963 kg
1.Flow Time	29.95	1.Flow Time	17.77
2.Flow Time	29.43	2.Flow Time	17.54
3.Flow Time	29.82	3.Flow Time	17.91
4.Flow Time	29.69	4.Flow Time	17.52
5.Flow Time	29.90	5.Flow Time	17.39
Average	29.76 ≅ 30	Average	17.63 ≅ 18

Table 7.47 Specific Gravities of the Fine Aggregate Samples (Ikitelli 2/ Istanbul).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Ikitelli 2 / Istanbul
MINERAL AGGREGATE : Gritstone

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	453	492.6
SSD WEIGHT	W_2	465	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	924.5	
P+W	B	634	
BULK SSD W_2+B-A	V_1	174.5	
BULK DRY W_1+B-A	V_2	162.5	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		961.5
P+W	B		647
BULK SSD W_2+B-A	V_1		185.5
BULK DRY W_1+B-A	V_2		178.1

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.596	2.656
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.665	2.695
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.788	2.766

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.649	1.502

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.48 Flow Rates of the Fine Aggregate Samples (Ikitelli 2/ Istanbul).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Ikitelli 2 / Istanbul
MINERAL AGGREGATE : Gritstone
CRUSHER TYPE : Impact Crusher

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.596 / 2.7	**Pr / 2.7**	: 2.655 / 2.7
Weight	: 0.961 kg	**Weight**	: 0.983 kg
1.Flow Time	: 33.95	1.Flow Time	: 19.01
2.Flow Time	: 32.43	2.Flow Time	: 18.74
3.Flow Time	: 33.82	3.Flow Time	: 18.43
4.Flow Time	: 33.69	4.Flow Time	: 19.00
5.Flow Time	: 32.92	5.Flow Time	: 18.82
Average	: 33.10 ≅ 33	Average	: 18.80 ≅ 19

Table 7.49 Specific Gravities of the Fine Aggregate Samples (Kepsut / Balıkesir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Kepsut / Balıkesir
MINERAL AGGREGATE : Natural

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	496	487
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	955.5	
P+W	B	655.5	
BULK SSD W_2+B-A	V_1	200	
BULK DRY W_1+B-A	V_2	186	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		936.5
P+W	B		633.5
BULK SSD W_2+B-A	V_1		197
BULK DRY W_1+B-A	V_2		184

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.430	2.472
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.500	2.538
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.613	2.647

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	0.900	2.669

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.50 Flow Rates of the Fine Aggregate Samples (Kepsut / Balıkesir).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Kepsut / Balıkesir
MINERAL AGGREGATE : Natural
CRUSHER TYPE : -

AGGREGATE CHARACTERISTICS			
Gradation	No:10–No:200	**Gradation**	No:5–No:200
Pr / 2.7	2.430 / 2.7	**Pr / 2.7**	2.472 / 2.7
Weight	0.900 kg	**Weight**	0.916 kg
1.Flow Time	27.70	1.Flow Time	15.13
2.Flow Time	27.31	2.Flow Time	14.96
3.Flow Time	27.36	3.Flow Time	15.08
4.Flow Time	27.42	4.Flow Time	15.22
5.Flow Time	27.15	5.Flow Time	15.16
Average	27.39 ≅ 27	Average	15.11 ≅ 15

Table 7.51 Specific Gravities of the Fine Aggregate Samples (Salihli / Manisa).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Salihli / Manisa
MINERAL AGGREGATE : Natural

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	486.6	437.1
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	935.5	
P+W	B	634	
BULK SSD W_2+B-A	V_1	198.5	
BULK DRY W_1+B-A	V_2	185.1	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		922.5
P+W	B		647
BULK SSD W_2+B-A	V_1		174.5
BULK DRY W_1+B-A	V_2		161.6

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.451	2.505
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.519	2.579
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.629	2.705

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	2.754	2.951

P : Weight of Picnometer
W : Weight of Water

SSD : Saturated Surface Dry
M : Weight of Material

Table 7.52 Flow Rates of the Fine Aggregate Samples (Salihli / Manisa).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Salihli / Manisa
MINERAL AGGREGATE : Natural
CRUSHER TYPE : -

AGGREGATE CHARACTERISTICS	
Gradation : No:10–No:200	**Gradation** : No:5–No:200
Pr / 2.7 : 2.451 / 2.7	**Pr / 2.7** : 2.505 / 2.7
Weight : 0.908 kg	**Weight** : 0.928 kg
1.Flow Time : 26.23 2.Flow Time : 26.33 3.Flow Time : 25.99 4.Flow Time : 26.09 5.Flow Time : 25.95	1.Flow Time : 13.48 2.Flow Time : 13.54 3.Flow Time : 13.47 4.Flow Time : 13.42 5.Flow Time : 13.45
Average : 26.12 ≅ 26	Average : 13.47 ≅ 13

Table 7.53 Specific Gravities of the Fine Aggregate Samples (Çine /Aydın).

SPECIFIC GRAVITY TEST

TESTED BY	: A.Topal	QUARRY&REGION	: Çine & Aydın
DATE	: ../../2000	MINERAL AGGREGATE	: Natural

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	494	494
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	943.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	190	
BULK DRY W_1+B-A	V_2	184	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		964.5
P+W	B		655.5
BULK SSD W_2+B-A	V_1		191
BULK DRY W_1+B-A	V_2		185

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.600	2.586
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.630	2.618
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.685	2.670

ABSORPTION

% ABSORPTION	$100\frac{W_2-W_1}{W_1}$	1.220	1.220

P	: Weight of Picnometer	SSD	: Saturated Surface Dry
W	: Weight of Water	M	: Weight of Material

Table 7.54 Flow Rates of the Fine Aggregate Samples (Çine /Aydın).

FLOW RATE TEST (AFNOR P18-564)

QUARRY & REGION : Çine & Aydın
MINERAL AGGREGATE : Natural
CRUSHER TYPE : -

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.600 / 2.7	**Pr / 2.7**	: 2.586 / 2.7
Weight	: 0.963 kg	**Weight**	: 0.958 kg
1.Flow Time	: 29.96	1.Flow Time	: 14.91
2.Flow Time	: 29.79	2.Flow Time	: 14.78
3.Flow Time	: 29.77	3.Flow Time	: 14.84
4.Flow Time	: 29.87	4.Flow Time	: 14.90
5.Flow Time	: 30.01	5.Flow Time	: 14.81
Average	: 29.88 ≅ 30	Average	: 14.85 ≅ 15

Table 7.55 Specific Gravities of the Fine Aggregate Samples (Ödemiş / Izmir).

SPECIFIC GRAVITY TEST

TESTED BY : A.Topal
DATE : ../../2000

QUARRY&REGION : Ödemiş / Izmir
MINERAL AGGREGATE : Natural

MATERIAL

AGGREGATE SIZE		No:10-No:200	No:5-No:200
DRY WEIGHT	W_1	494	495
SSD WEIGHT	W_2	500	500

BULK DEFINE OF FINE AGGREGATE (No:10-No:200)

P+W+M	A	945.5	
P+W	B	633.5	
BULK SSD W_2+B-A	V_1	188	
BULK DRY W_1+B-A	V_2	182	

BULK DEFINE OF COARSER FINE AGGREGATE (No:5-No:200)

P+W+M	A		965.5
P+W	B		655,5
BULK SSD W_2+B-A	V_1		188.5
BULK DRY W_1+B-A	V_2		185

SPECIFIC GRAVITIES

DRY SPECIFIC GRAVITY	$\frac{W_1}{V_1}$	2.628	2.626
SDS SPECIFIC GRAVITY	$\frac{W_2}{V_1}$	2.660	2.653
APPEARENT SPECIFIC GRAVITY	$\frac{W_1}{V_2}$	2.714	2.676

ABSORPTION

% ABSORPTION	$100\frac{W_2 - W_1}{W_1}$	1.215	1.010

P : Weight of Picnometer
W : Weight of Water
SSD : Saturated Surface Dry
M : Weight of Material

Table 7.56 Flow Rates of the Fine Aggregate Samples (Ödemiş / Izmir).

QUARRY & REGION : Ödemiş / Izmir
MINERAL AGGREGATE : Natural
CRUSHER TYPE : -

AGGREGATE CHARACTERISTICS			
Gradation	: No:10–No:200	**Gradation**	: No:5–No:200
Pr / 2.7	: 2.628 / 2.7	**Pr / 2.7**	: 2.626 / 2.7
Weight	: 0.973 kg	**Weight**	: 0.972 kg
1.Flow Time	: 30.39	1.Flow Time	: 15.08
2.Flow Time	: 30.38	2.Flow Time	: 15.47
3.Flow Time	: 30.42	3.Flow Time	: 15.32
4.Flow Time	: 30.29	4.Flow Time	: 15.50
5.Flow Time	: 30.44	5.Flow Time	: 15.12
Average	: 30.38 ≅ 30	Average	: 15.30 ≅ 15

CHAPTER EIGHT

CONCLUSIONS AND SUGGESTIONS

The recent studies of Strategic Highway Research Program (SHRP) identify fine aggregate angularity as one of the important aggregate properties contributing to the stability and permanent deformation resistance of hot mix asphalts (HMA). Therefore, fine aggregate angularity is critical for the rutting resistance of flexible pavements. Rutting observed in wearing and binder courses of asphalt pavements continues to be a major problem for highway engineers.

In the past dense-graded mixes were believed to be the best especially for high stability and durability, but the recently research work has shown that they are not resistant to rutting under the prevailing traffic conditions. At the present, mixtures that have not high workability (difficulty to compact) are preferred. FAA plans an important role in the difficulty of compaction.

Aggregate particle shape, size and gradation impact the performance of bituminous mixtures. In bituminous mixtures, the shape of aggregate particles has been related to permanent deformation, fatigue resistance and skid resistance of pavement. Additionally, it affects the workability and optimum bitumen content of the mixture. Bituminous mixture properties that are affected by the shape of aggregates include stiffness, stability, durability, permeability, resistance to moisture damage and air voids in the mixture. The aggregates must have the proper gradation and shape to design bituminous mixtures with long and satisfactory service life. Fine aggregate is a primary constituent of bituminous mixtures and the angularity of fine aggregate angularity is one of the most important factors affecting the performance of HMA mixtures

For this study, fine aggregate is defined as that part of the aggregate, which passes a 4.00 mm (No.5) sieve. There are two general types of fine aggregate that are used in bituminous mixtures; manufactured and natural. Natural fine aggregates generally tend to be more rounded than manufactured (crushed) fine aggregate (Figure 7.2)

There is no specification for FAA in Turkey. It would be preferable to use AFNOR P18 564 "Determination of Flow Rate of Fine Aggregate" provisional specification, which is one of the indirect methods of measuring fine aggregate angularity rather than an American specification since Turkey is a candidate country to enter European Community.

In this study the angularity was evaluated for 28 aggregate samples which represent quiet a wide range of materials used in Turkey. Twenty-four samples of crushed rocks, which are crushed by different crusher types, four samples of washed natural sand (river deposits) were evaluated. ASTM C128 "Specific Gravity Test of Fine Aggregate" and AFNOR P18 564 "Determination of Flow Rate of Fine Aggregate" tests were performed on each sample.

"Vertical Shaft Impact (VSI) crushers tend to produce more cubical particles than the other" (Huber&McGennis,1996)(Hanf,2001). This statement was verified by the test performed in this study. Also, test results show that impact crushers and gyratory crushers tend to produce more cubical particles than the other. Generally, natural fine aggregates tend to be rounded whereas manufactured fine aggregates tend to be angular. However, some crushed fine aggregates are not angular (Erdoğanköy 1-2, Figure 7.6) and some natural fine aggregates are subangular (Çine/Ödemiş, Figure 7.8).

Basalt and andesite mineral aggregates have more angular shape than the limestone, even basalt is crushed by a roll-crusher (Figure 7.1).

Fine aggregates to be used in bituminous mixtures especially in HMA should be cubical and angular in shape (measured by AFNOR P18 564). Aggregates should be very rough or rough, should have low porosity and should be resistant to polishing (Measured by accelerated polishing test).

FAA is varies depending on mineralogy of rock and type of crusher. Crushers are of very different type, and technologies changing and developing. Therefore, the approach taken in identifying and selecting fine aggregates for use in this study was to select aggregates with varying values of FAA. Also included within the selection criteria were mineralogical composition of the fine aggregates and type of crusher. Maximization of these three criteria will ensure using fine aggregates with a wide range of properties.

FAA test results bring to light that FAA depends on so many agents, which have to be considered. It is clear that we need reliable data and it is emphasized that angularity tests must be made in situ. It is necessary to control if it is in specification limit or not.

REFERENCES

AASHTO. (1993). AASHTO Provisional Standard TP33, Standard Test Method for Uncompacted Void Content of Fine Aggregate, American Assoc. of State Highway and Transportation Officials, Washington, D.C.

AASHTO. (1993). Guide for Design of Pavement Structures 1993 American Assoc. of State Highway and Transportation Officials, Washington, D.C.

AFNOR. (1990). Normalisation Française P18-564 Determination du Coefficient d'e'coulement des Sables. PR Industrie, Paris.

Ağar, E., Sütaş, İ., & Öztaş, G. (1998). Beton Yollar- Rijit Yol Üstyapıları. İTÜ, İstanbul. pp.51-67.

Anderson, R.M. & Bahia, H.U. (1997). Evaluation and Selection Of Aggregate Gradations for Asphalt Mixtures Using Superpave. Transportation Research Record 1583, National Academy Press, Washington, D.C. pp.91-97.

Asphalt Institute. (1993). Filler in Asphalt Mixtures. Research Report No.69-2, Maryland.

Asphalt Institute. (1995). SUPERPAVE Performance Graded Asphalt Binder Specification and Testing. Superpave Series No.1 (SP-1) Lexington, KY.

Asphalt Institute. (1996). SUPERPAVE Level 1 Mix Design. Superpave Series No.2 (SP-2) Lexington, KY.

ASTM. (1981). Annual Book of ASTM Standards, Designation D3398 Standard Test Method for Index of Aggregate Particle Shape And Texture. American Society for Testing and Materials. Printed in Easton, Md., USA.

ASTM. (1982). Annual Book of ASTM Standards, Designation C136. Standard Method for Sieve Analysis of Fine and Coarse Aggregates. American Society for Testing and Materials, Printed in Easton, Md., USA.

ASTM. (1982). Annual Book of ASTM Standards, Designation C138. Standard Test Method for Specific Gravity of Fine Aggregates. American Society for Testing and Materials, Printed in Easton, Md., USA.

ASTM. (1982). Annual Book of ASTM Standards, Designation C75. Standard Practice for Sampling Aggregates. American Society for Testing and Materials, Printed in Easton, Md., USA.

Baradan, B. (1998). Yapı Malzemesi II-Bağlayıcı Maddeler, Agrega, Beton. Dokuz Eylül Üniversitesi Mühendislik Fakültesi Yayınları, Bölüm 2: Agregalar. İzmir. pp.2.1-2.26.

Blankenship, P.B. (1997). Experiences with Superpave Volumetric Mix Designs. UTAH Department of Transportation (UDOT) Engineer's conference, November 20-22, Snowbird, UT.

CHEN, W.F. (1995). The Civil Engineering Handbook. CRC Press, Florida.

Collis, L., & Fox, R.A. (1985). Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes, Engineering Geology Special Publication No:1, The Geological Society of London.

Cominsky, R.J., Huber, G.A., Kennedy, T.W. & Anderson, M. (1994). The Superpave Mix Design Manual for New Construction and Overlays. SHRP-407 National Research Council, Washington, D.C.

D'Angelo, J.A. (1997). Superpave Mix Design Tests, Methods and Requirements APWA International Public Works Congress NRCC/CPWA Seminar Series.

Freeman, R.B. & Kuo, C-Y. (1999) Quality Control for Natural Sand Content of Asphalt Concrete. Journal of Transportation Engineering, November/December, ASCE.

Gardiner, M.S., Newcomb, D., Kussman,W., & Olson, R. (1997) Characteristics of Typical Minnesota Aggregates. Transportation Research Record 1583, National Academy Press, Washington, D.C. pp.1-10.

Hanf, K. (2001). Using Sand and Gravel in Superpave Mixtures. International Centre for Aggregates Research 8th Annual Symposium, in Denver, Colorado, April 12-14.

Hossain, M.S., Parker, F.Jr., & Kandhal, P.S. (1999). Tests for Evaluating Fine Aggregate Particle Shape, Angularity and Surface Texture. Transportation Research Record 1673, National Academy Press, Washington, D.C. pp.64.

Hossain, M.S., Parker F.Jr., & Kandhal P.S. (2000). Uncompacted Voids and Particle Index Tests for Evaluating Coarse Aggregate. Transportation Research Record 1721, National Academy Press, Washington, D.C. pp.100.

Huber, A.G., Jones, J.C., Messersmith, P.E., & Jackson, N.M. (1998). Contribution of Fine Aggregate Angularity and Particle Shape to Superpave Mixture Performance. Transportation Research Record 1609, National Academy Press, Washington, D.C. pp.28-35.

Introduction to Transportation Engineering. (1998). University of Illinois Department of Civil and Environmental Engineering, CE 220 Block V, Section III A-C Physical Properties.

İpekoğlu, Ü. & Tanrıverdi, M. (1994). Cevher Hazırlama.(2nd Edition). DEÜ, İzmir.

Kandhal, P.S., Malick, R. B., & Huner, M. (2000). Measuring Bulk Specific Gravity of Fine Aggregates; Development of New Test Method. Transportation Research Record 1721, National Academy Press, Washington, D.C. pp.81.

Kennedy, T.W., Huber, G.A., Harrigan, E.T., Cominsky, R.J., Hughes, C.S., Quintus, H.V., & Moulthrop, J.S. (1994). Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program. SHRP-A-410. National Research Council, Washington, D.C.

Kuo, C.Y., & Freeman, R.B. (2000). Imaging Indices for Quantification of Shape, Angularity and Surface Texture of Aggregates. Transportation Research Record 1721, National Academy Press, Washington, D.C. pp.57.

Lai, J.S. & Lee T-M. (1990). Use of Loaded-Whell Testing Machine to Evaluate Rutting of asphalt Mixes. Transportation Research Record 1269, National Academy Press, Washington, D.C. pp.116-124.

Lee, C.J., Pan, C., & White, T.D. (1998). Review of Fine Aggregate Angularity Requirements in Superpave. Purdue University, West Lafayette IN.

Martin, J.R., & Wallace, H.A. (1958). Design and Construction of Asphalt Pavements. McGraw-Hill Book Company, Inc. New York, Toronto, London. p.211.

Monismith, C.L. (1961). Asphalt Paving Mixtures, Properties, Design and Performance. Course Notes. University of California, Berkeley, Los Angeles.

Neville, A.M. (1997) Properties of Concrete.(Third Edition) Longman ltd, England. pp.108-176

Oduroh, K.P., Mahboub, K.C., & Anderson, R.M. (2000). Flat and Elongated Aggregates in Superpave Regime. Journal of Materials in Civil Engineering, May.

Önal, M.A., Kahramangil, M. (1993). Bitümlü Malzemeler Laboratuvar El Kitabı. KGM, Ankara.

Page, G.C., Musselman, J.A., & Romano, D.C. (1997). Effect of Aggregate Degradation on Air Voids of Structural Asphalt Mixture in Florida. Transportation Research Record 1583, National Academy Press, Washington, D.C. pp.19-27.

Pike, D.C. (1990). Standards for Aggregates. Ellis Horwood ltd.Publ., p.280.

Takallau, B.H., Hussain U.B., Perdimo, D., & Schwartz, R. (1997). Use of Superpave technology for Design and Construction of Rubberized Asphalt Mixtures. Transportation Research Record 1583, National Academy Press, Washington, D.C. pp.71-81.

Topal, A., & Şengöz, B. (2000). Bitümlü Karışımlarda Kullanılan İnce Taneli Agregaların Köşeliğinin Belirlenmesi ve Kullanılabilirliğinin Saptanması. 3. Ulusal Asfalt Sempozyumu ve Sergisi,16-17 Kasım, KGM, Ankara, pp.184-194

Uluçaylı, M. (1976). The Identification of Failures in Asphaltic Concrete Pavements. Cento Seminar on the Maintenance and Improvement of Highways, Islamabad, Pakistan, May 2-16.

Uluçaylı, M. (1997). Bitümlü Karışımların Tasarımında Yeni Gelişmeler-Yoğurmalı Pres, YTMK, Ankara.

Uluçaylı, M. (2001). Highway Materials. Course Notes, (Not Published). DEÜ, İzmir.

UNPG LA NORME XP P18-540. (1990). Spécifications des Granulats Pour Chaussées et Bétons Hydrauliques, Paris.

Verstraeten, J. (1994). Bituminous Materials with a High Resistance to Flow Rutting. PIARC Technical Committee on Flexible Roads, TC 8, Belgium.

U.S. Army Corps of Engineers.(1991). Hot Mix Asphalt Paving Handbook .Pub.Un-13. Washington, D.C.

Wang, J-N., Kennedy, T.W. & McGennis, R.B. (2000). Volumetric and Mechanical Performance Properties of Superpave Mixtures. Journal of Materials in Civil Engineering. August.

Wills, B.A. (1984). Mineral Processing Technology (2nd Edition). NewYork.

Yağız, F., Işıksalan, C., Keçeciler, A.F. & Akkol, G. (1967). Bitümlü Malzemeler. KGM, Ankara.