A STUDY ON ABRASION RESISTANCE OF CONCRETE PAVING BLOCKS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

DECEMBER 2004

Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

A STUDY ON ABRASION RESISTANCE OF CONCRETE PAVING BLOCKS

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December 2004, 93 Pages

Concrete block pavement (CBP) can be an alternative pavement to asphalt and concrete pavements. CBP is formed from individual concrete paving blocks (CPBs) that fit next to one another on a suitable sub base leaving a specific joint space among them to be filled with jointing sand.

CBP differ from other pavements according to their mechanical behavior, manufacturing technique, structural design, installation technique and structural behavior. For a serviceable pavement all of these subjects have to be studied. The literature about the mechanical behavior of CPBs is not adequate. This study aims to determine the performance of CPBs formed from different mixes prepared with a white portland cement.

For this purpose, 10 mixes with different cement contents and W/C ratios and 2 mixes from a commercial CPB manufacturer were tested. The compressive strength, tensile splitting strength, abrasion resistance, density and % water absorption tests were performed on each mix at 7, 14, 28 days.

It was concluded that, the cement content in the mix, optimum water volume for a given cement content, the way the manufacturing equipment is operated and their interaction was effective on the mechanical properties of CPBs. It was also observed that there was no handicap to stop the abrasion resistance test at 8*22 revolutions instead of 16*22 revolutions given in TS 2824.

Keywords: Concrete paving block, concrete block pavement, abrasion resistance, white portland cement

ÖZ

BETON PARKE TAŞLARININ AŞINMA DİRENCİ ÜZERİNE BİR ÇALIŞMA

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Tez Yöneticisi: Yrd. Doç. Dr. İ. Özgür Yaman

Aralık 2004, 93 Sayfa

Parke taşı yol döşemesi asfalt ve beton yol döşemelerine alternatif olabilir. Parke taşı yol döşemeleri, uygun alt taban üzerine birbiri yanına aralarında ek kumu ile doldurulmak üzere belirli ek mesafeleri bırakılmış tekil parke taşlarından oluşur.

Parke taşları mekanik davranışı, üretim tekniği, yapısal dizaynı, yerleştirme tekniği ve yapısal davranışı bakımından diğer yol döşemelerinden ayrılır. Kullanılabilir bir yol döşemesi için bütün bu konuların çalışılması gerekir. Parke taşlarının mekanik davranışı ile ilgili yazın yeterli değildir. Bu çalışma beyaz portland çimentosu ile hazırlanan farklı karışımlardan oluşturulmuş parke taşlarının performansını belirlemeyi amaçlamaktadır.

Bu amaçla, farklı çimento miktarları ve su çimento oranlarında 10 karışım ve ticari bir parke taşı üreticisinin 2 karışımı test edildi. Basınç dayanımı, yarma

dayanımı, aşınmaya karşı direnç, yoğunluk ve % su emme testleri bütün karışımlarda 7, 14, 28 günlerinde yapıldı.

Sonuç olarak karışımdaki çimento miktarı, belirli bir çimento miktarı için en uygun su hacmi, üretim aletinin nasıl işletildiği ve bunlar arasındaki etkileşimin parke taşlarının mekanik özellikleri üzerinde etkili olduğu gözlenmiştir. Ayrıca aşınmaya karşı direnç testinin TS 2824' te belirtilen 16*22 devir yerine 8*22 devirde durdurulmasında hiçbir dezavantaj olmadığı da gözlemlenmiştir.

Anahtar Kelimeler: Parke taşları, parke taşı yol döşemesi, aşınma direnci, beyaz portland çimentosu

To My Parents,

Mehmet & Cevriye ASLANTAŞ

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Asst.Prof.Dr. İ. Özgür YAMAN for his valuable supervision, precious help, invaluable suggestions and continuous support throughout the research.

I would like to thank ÇİMSA for supplying the Böhme Abrasion Equipment. I also would like to thank Mr. Önder KIRCA from ÇİMSA for his kind help, technical assistance and support.

I would like to thank Özkul Beton Elemanları San. ve Tic. LTD. ŞTİ. managers Suat ÖZKUL and Ahmet ÖZKUL for their support and kind helps. I am especially thankful to Özkul Beton Elemanları San. ve Tic. LTD. ŞTİ. staff Hüseyin OLGUN, İsmail DAĞAŞAR, İsa PINAR and Mehmet CEYHAN for their kind helps during manufacturing and post manufacturing process of concrete blocks.

I would like to expand my thanks to Mustafa ŞAHMARAN and Materials of Construction staff for their close and friendly assistance.

Finally, special thanks go to my friends that all of whom couldn't be mentioned here.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete block pavements (CBPs) are formed from individual solid blocks that fit closely next to one another to form a pavement surface. A typical CBP is placed on a thin bed of sand overlaying a sub base. CBP can be placed with a variety of shapes and patterns. There are joint spaces between blocks. These spaces are filled with sand having suitable grading. The blocks are restrained from two sides by edge restraints.

CPBs are manufactured from semi-dry mixes. During manufacturing process vibration and pressure is applied to the mix. By this process dense and strong CPB can be achieved to form strong and durable paving surfaces. Moreover interlocking behavior of CBP gives the ability of spreading loads to larger areas.

CBP has several advantages over asphalt and concrete pavements in their structural, aesthetics, construction and maintenance, operational and economical characteristics which will be presented in detail in Chapter 2.

Like other pavement surfaces, the design of CBP is based upon environmental, traffic, sub grade support and pavement materials conditions and their interactive effect. Therefore, CBP needs an in depth design process to achieve good performance.

1.2. Object and Scope

The performance of CBP depends on mechanical properties of concrete blocks and structural design of the pavement, for a serviceable CBP, both factors have to be studied. CBP in our country shows some performance problems that can be grouped into two: structural design and mechanical deficiencies of concrete blocks. Inadequate sub layers thicknesses and material properties, inadequate drainage, incorrect joint sand gradation and joint spacing are items that can be count in structural design deficiencies. Mechanical deficiencies are: inadequate abrasion resistance, compressive strength, and indirect tensile strength, freezing-thawing and de-icing chemical resistance.

Concrete blocks are manufactured by dry mixes that are exposed to vibration and pressure during the manufacturing process. The literature about mix design of concrete blocks which are produced by this special manufacturing technique with different cement types is quite inadequate.

The objective of this research is to form the background knowledge about CBP to exterminate the performance problems and to evaluate the abrasion and mechanical properties of Concrete Blocks (CBs) produced by a white portland cement.

For this purpose, in Chapter 2 detailed knowledge about structural design of CBP and mechanical properties of concrete blocks will be given. Than the research will concentrate on the mechanical properties of concrete blocks which will be discussed in Chapter 3. Mix designs with different W/C ratios and cement contents will be prepared to form most appropriate mix design for CBs. White Portland cement will be used for mix designs. Abrasion resistance, compressive strength, tensile splitting strength, unit weight and % absorption will be the performance criteria's to be tested. The designed specimens will be compared with concrete blocks in use which were produced by concrete paving blocks producers. In Chapter 4 detailed discussions about the findings of this research will be presented. Chapter 5 will present a summary, conclusion and suggestions for possible future research.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1 History of Concrete Block Pavement

Road paving with tightly fitted stones resting on a flexible granular base dates back to the Roman Empire. Even though, stones are still being used as paving material the modern version of this road technique utilizes concrete blocks instead. [Rada et. al. 1990]. The use of CBP for roads began in the Netherlands after the Second World War. Brick paving was the traditional surface material in the Netherlands before the Second World War. Because of the coal shortages brick had been unavailable as a result CBP had been used as a substitute. The substitution became hugely successful. After the war, the roads of Rotterdam were almost entirely constructed from concrete block paving [Pritchard and Dawson 1999]. This technology quickly spread to Germany and Western Europe as a practical and attractive method useful for both pedestrian and vehicular pavement [Rada et. al. 1990]. Over the past 40 years CBP has gained rapid popularity as an alternative to conventional concrete and asphalt pavements. The CBP is now a standard paving surface in Europe where over 100,000,000 m^2 are placed annually [Ghafoori and Mathis 1998].

2.2 Features of Concrete Block Pavements

Concrete paving blocks are utilized in a variety of commercial, municipal and industrial applications. The primary reasons for selecting CBP over other paving surfaces are low maintenance, ease of placement and removal, reusage of original blocks, aesthetics appeal, and immediate usage after installation or repair [Ghafoori and Mathis 1998]. A comparison of the advantages and disadvantages of CBP over rigid and flexible pavements is given in Table 2.1. As seen in that table CBPs are able to withstand heavy loads and resists aggressive environments as good as a rigid concrete pavement. Beside that, with its wide range of colors, textures and patterns, CBPs provide excellent aesthetic appearance opportunities.

2.2.1 Aesthetic Appeal

Concrete block paving is available in a constantly expanding variety of colors, shapes and textures and can be installed in numerous bonds and laying patterns [Interpave 2003]. Concrete pavers offer unique aesthetic benefits when compared to other forms of pavement in their ability to integrate and harmonize with both the built and natural environment [Concrete Masonry Association of Australia 1997a]. In Figure 2.1 some applications of paving blocks are provided [Interpave 2003].

Table 2.1 Comparison of Concrete Paving Block with Asphalt and Rigid Concrete [Aeon's Construction Products Limited 2003].

ATTRIBUTE	*SEGMENTAL PAVERS*	*ASPHALT*	*RIGID CONCRETE*
STRUCTURAL FEATURES			
Strength	Good compressive strength. Can be controlled as required	Poor	Good
Resistance to weathering	Good	Poor	Good
Load transfer	Good	Poor	Good
CONSTRUCTİON AND MAINTENANCE			
Speed of construction	Fast	Fast	Slow (Requires curing)
Trenching and reinstatement	Readily excavated by hand methods	Requires use of jackhammer	Difficult and expensive to excavate and restore
Recycling	Easily accomplished without reprocessing	Materials requires to be reprocessed	Expensive, material requires reprocessing
AESTHETICS			
Appearance	Very good	Poor	Moderate-only limited control of colour and texture
OPERATIONAL			
Durability	Good	Moderate	Good
Resistance to heavy axle loads	Very good	Good	Very good
Concentrated wheel loads	Very good	Poor	Very good
Fuel and oil skidding	Good; Satisfactory up to 60 Km/h	Poor; Satisfactory	Good; Good
ECONOMY			
Inıtial cost	Moderate	Low	High
Maintenance cost	Low	High	High
Salvage volue	High, easily recycled	Medium	Low

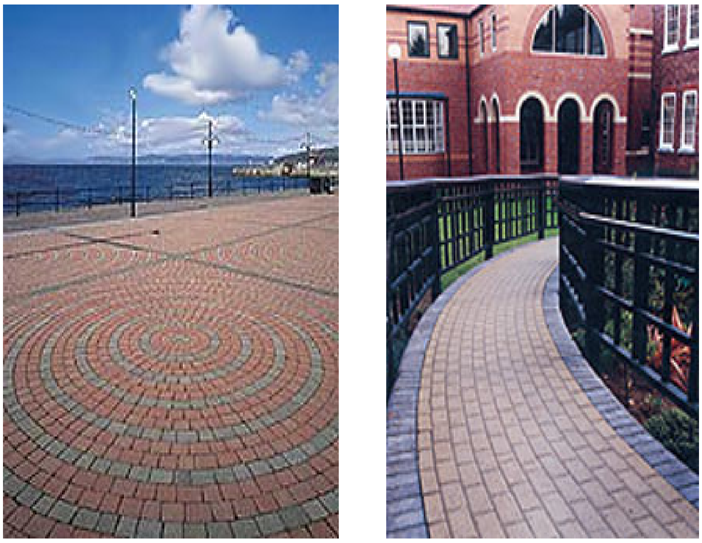


Figure 2.1. Paving Block Applications [Interpave 2003]

CBPs offer numerous opportunities in residential and pedestrian areas by their, light reflection, water absorption, noise generation features and are often used for traffic management (Figure 2.2.) [Concrete Masonry Association of Australia 1997a, Interpave 2003].

Figure 2.2. Paving Block Applications for Traffic Management [Interpave 2003].

2.2.2 Construction and Maintenance

Maintenance cost can be kept low as it is possible to rehabilitate areas of concrete segmental pavement without heaving to purchase a new surface [Concrete Masonry Association of Australia 1997a]. Repair to underground utilities or local deformations in the base materials can be accessed by simply removing and replacing the concrete blocks (pavers). Pavement materials are not wasted and jackhammers or heavy equipment are not required [Ackerstone 2003].

2.2.3 Structural and Operational Characteristics

The uniquely flexible surface course of concrete block paving, with its characteristic interlock, prevents the block from moving in isolation and dissipates applied loads sideways and diagonally downwards through the sub-base to the foundations. Combined with the high compressive strengths of the blocks, this provides a working surface with remarkably high load bearing capacity. Plate-bearing tests have shown that block paving with its bedding sand performs significantly better than a similar thickness of bituminous surface [Interpave 2003].

Concrete block paving is extremely durable. It withstands severe frost attack and repeated freeze-thaw cycles and can be used in harsh environments. It can be laid on airfields or highways where temperatures fall below –30 degrees centigrade [Interpave 2003]. Physical requirements of CPB as specified by TS, ASTM and BS are given in Table 2.2.

Table 2.2. TS, ASTM and BS Physical Requirements for CPB [TS 2824, ASTM C 936, BS 6717]

	TS 2824	ASTM C 936	BS 6717 Part 1
Dimensional Requirements	Length/Thickness<4	Length/Thickness<4 Surface Area<0.065m^2 t_{min}>60mm	Surface Area<295 mm^2
Compressive Strength	——	Average Str>55MPa Individual Str.>50MPa	——
Indirect Tensile Str.	Average Str.>3.5 MPa Individual Str.>2.8MPa (Tensile Splitting Str.)	——	Average Str.>3.9 MPa Individual Str.>2.9MPa (Three Point Bending)
Abrasion Resistance	V. Loss< 15cm^3/50cm^2 (Exp. to Severe Abr.)	V. Loss<15cm^3/50cm^2 Average Thick. Loss<3mm	For A_2 Abrasion Class: Dgr. of Abr.< 23mm
Resistance to Frz-Thw.	Weight Loss< 0.5kg/m^2	Weight Loss< %1 (Subject to 50 cycles)	W_2 Weathering Class: Mass Loss < 1kg/m^2 Ind. Loss<1.5 kg/m^2
Absorption	Individual Unit Abs<%6	Average Absorption<%5 Individual unit<%7	——
Skid Resistance	——	——	For S_2 Class C scale units>35 For S_3>45

Note: A_2 abrasion class is for areas to be subject to vehicular traffic exceeding 1.5 msa. S_2 skid resistance class is suitable for use in pedestrian areas and paving blocks of class S_3 are suitable for use in vehicular areas [BS 6717].

Concrete block pavements are highly resistant to the effects of braking, swelling or acceleration of vehicles. Because of these features and their immunity to softening by fuel and oil spillages, concrete segmental pavements are suited for use at bus stops, bus depots and terminals, intersections, pedestrian cross-walks, in heavy duty pavements and aircraft aprons [Concrete Masonry Association of Australia 1997a].

2.3 Concrete Flag Paving

In British Standards, a concrete paving block is defined as a precast concrete element whose work size fits within a (295mm) square. Any larger precast paving unit is named as flag [Pritchard and Dawson 1999]. In Turkish Standards concrete paving blocks referenced to TS 2824. In this standard there is not an area limit. But, the length/thickness ratio is limited. This ratio must be equal to or smaller than 4. The concrete blocks out of this range are referenced to TS 213. Typical flag paving applications can be seen from Figure 2.3.

Figure 2.3. Concrete Flag Paving Applications [Interpave 2003].

The standard dimensions of concrete flags are given in Table 2.3. Flag paving has similar usage, design and construction properties with block paving. The main difference is flag paving has larger dimensions. Three point bending becomes important for flag paving as opposed to tensile splitting strength. The required transverse strength of British Standard flags tested in three point bending to BS 7263 Part 1 is given in Table 2.4.

Table 2.3. Standard Dimensions of Flags [Pritchard and Dawson 1999].

Flag Type	Nominal size (mm)	Work size (mm)	Thickness (mm)
A	600 x 450	598 x 448	50 or 63
B	600 x 600	598 x 598	50 or 63
C	600 x 750	598 x 748	50 or 63
D	600 x 900	598 x 898	50 or 63
E	450 x 450	448 x 448	50 or 70
F	400 x 400	398 x 398	50 or 65
G	300 x 300	298 x 298	50 or 60

Table 2.4. The Required Transverse Strengths of Flags [Pritchard and Dawson 1999].

Flag type	Minimum failing load (kN)				
	50 mm	60 mm	63 mm	65 mm	70 mm
A	8.3		12.7		
B	11.1		16.9		
C	11.1				
D	11.1				
E	9.6				18.8
F	9.1			15.4	
G	9.6	13.8			

A flag paved area is primarily designed for pedestrian use. However by careful selection of the appropriate flag in conjunction with the correct method of bedding, certain sizes of flags can sustain trafficking by light vehicles and frequent overrun by commercial vehicles. For lighter trafficked, mainly pedestrian areas a mortar laying course is sufficient but for areas subject to regular vehicular overrun small element flags bedded on a sand laying course, with sand joints, are necessary. It is essential to maintain the structural integrity of the surface course to prevent water penetration leading to deterioration of the sub-layers and sub grade or loss of interlock resulting in direct wheel loading to the underlying sub-layers [Pritchard 2001].

2.4 Production of Concrete Blocks

There are two common methods of producing precast concrete: a) Wet mix, b) Dry mix. In wet mix fresh concrete is placed and compacted into moulds, stripping the moulds when adequate strength has been reached. However in a dry mix, a semi-dry cohesive concrete mix is placed in the mould, which is later, compacted and extruded (pushed out) from the mould, right after compaction. (Figure 2.4). The units are then cured and stored. This latter process is commonly used in the manufacture of concrete masonry and paving units as it is the most economic way of producing large volumes of bricks, blocks and pavers [Concrete Manufacturers Association Publication 2002].

Figure 2.4 Production of CB by the Dry-Mixing Method

2.4.1 Material Properties

The materials used in the production are Portland Cement as the binder, coarse aggregate and water as the other mix ingredients. In this section requirements for these material preparation will be briefly discussed.

2.4.1.1 Portland Cement

Portland cement is the binder used for the production of concrete blocks just like any other concrete products. In choosing a portland cement for the manufacture of CBPs, rate of strength gain and sensitivity to curing should be considered [Concrete Manufacturers Association Publication 2002].

2.4.1.2 Aggregates

Aggregates form the bulk of CB. They significantly affect the cost and quality of the final product and the ease with which the products are manufactured and finished. Aggregates used are mostly derived from solid rock, which is crushed or has been broken down by weathering. Alternative aggregates or waste products such as furnace clinker and furnace bottom ash, fly ash, crushed burnt clay brick and slag are also used extensively in the manufacture of concrete masonry units, where available. All sources of these aggregates should be checked to see if they are of adequate quality. This might be done by testing the aggregates in a laboratory or by reference to the successful service performance of the aggregates in concrete, say over a 5-year period [Concrete Manufacturers Association Publication 2002].

The performance of aggregates at the molding stage and in the hardened block depends on the combined effects of particle size, grading, particle shape, and hardness. Each of these properties is discussed below [Cement and Concrete Institute 2001].

a) Size

The recommended maximum nominal size of aggregate is 13.2 mm. However, the maximum size generally used in practice is 9.5 mm. Smaller sizes (4.75 mm) may be specifically selected to obtain a particular surface texture. Generally, the use of coarse particles results in savings in binder provided the mix is properly proportioned. If coarse aggregate particles are too big, or if too much coarse aggregate is used in the mix, it may be difficult to achieve good compaction and acceptable surface texture [Cement and Concrete Institute 2001]. The size of stone should not exceed about one quarter of the thickness of the concrete item being precast [Concrete Manufacturers Association Publication 2002] . The minimum concrete thickness for various stone size is given in Table 2.5.

Table 2.5. Minimum Concrete Thickness for Various Stone Size [Concrete Manufacturers Association Publication 2002].

Stone size (mm)	6.7	9.5	13.2	19.0
Minimum concrete thickness (mm)	30	40	50	60

b) Grading

Continuous grading will facilitate compaction. Guidelines for grading are given in Table 2.6.

Table 2.6. Recommended Aggregate Grading for Making Paving Blocks [Cement and Concrete Institute 2001].

Sieve Size (mm)	Cumulative percentage passing
13.2	100
9.5	90-100
4.75	70-85
2.36	50-65
0.30	10-25
0.15	5-15
0.075	2-10

c) Particle Shape

Because paving blocks are manufactured from semi-dry mixes, chunky particle shape and smooth texture will facilitate compaction and increase consistency. This property is more likely to be found with natural sands. On the other hand, good green strength is required as the units are extruded and handled straight after compaction in the mould. Here crushed sand is suitable because of its elongated shape and rough surface texture. It may therefore be beneficial to use a blend of natural sand (for easy compaction) and crushed sand (for green strength) [Concrete Manufacturers Association Publication 2002, Cement and Concrete Institute 2001].

d) Hardness

Sands containing large amounts of unsound weathered material should be avoided. Natural sands with high silica content are suitable [Cement and Concrete Institute 2001].

There are many factors that abrasion resistance depends on. But the most important one is the degree of cementing of particles at the surface. Factors like surface texture, shape, cement content, compaction and curing are therefore important [Cement and Concrete Institute 2001].

Assuming that aggregate particles are well cemented at the surface of the block, the service life of concrete blocks can be extended by using the harder aggregate types for most modes of wear. To enhance wear resistance, selected aggregates may be used in a richer topping layer about 15mm thick molded simultaneously with the base concrete [Cement and Concrete Institute 2001].

2.4.1.3 Pigments

Quality pigments are commercially available to add color to paving blocks. Dosage, which will depend on the color selected and the natural color of the aggregate and cement being used, is generally 5%, but not more than 10%, by mass of the cement. Trial castings are required to determine the correct dosage because the color of the finished product in a dry state is influenced by density, curing and surface texture [Cement and Concrete Institute 2001].

2.4.1.4 Chemical Admixtures

Concrete paving blocks are manufactured from semi-dry mixtures which possess poor flow properties even under vibration. Using a water-reducing or plasticizing admixture to improve compactibility may be cost-effective [Cement and Concrete Institute 2001].

2.4.2 Proportioning CPB Mixes

Proportioning involves finding the best aggregate grading, aggregate: cement ratio and water content, for the specific block making equipment and the way in which it is operated. Each of these aspects is discussed in the following sections [Cement and Concrete Institute 2001].

2.4.2.1 Aggregates Grading

In general, the aggregate should be graded to permit full compaction of the mix with the least effort. If full compaction is not achieved, voids have a disproportionate effect on strength [Cement and Concrete Institute 2001]. Good compaction will be facilitated by using aggregates which are continuously graded (and have good particle shape). A grading envelope for aggregates which has been found suitable in South Africa was given in Table 2.6. The envelope should be used for guidance only as it does not take particle shape into account; materials having a grading outside the suggested envelope may give satisfactory results.

2.4.2.2 Cement Content

The cement content to achieve the required strength level will depend on the type of cement, rate of strength gain, degree of compaction [Cement and Concrete Institute 2001]. The only accurate method of establishing the optimum cement content is through a series of trials, using the machine intended for production, in which cement content is varied and the physical properties monitored [Cement and Concrete Institute 2001].

2.4.2.3 Water Content

The optimum moisture content (OMC) for molding depends on the materials being used, quality of vibration, and molding equipment. Generally, the coarser the particles are graded and the greater the compactive effort, the lower will be the OMC. Using moisture content below OMC will hamper good compaction and may necessitate longer periods of vibration which in turn will reduce output. Lack of compaction will reduce durability. Using too much water will result in a reduction of density and may cause units to stick in the mould and thus make extrusion difficult, or cause deformation of the units after extrusion. It must be noted that certain pigments, because of their particle shape, can have a significant effect on OMC [Cement and Concrete Institute 2001].

2.4.3 Manufacturing Equipment and Manufacture

2.4.3.1 Batching Equipment

Raw materials are first delivered to silos and bins. From here, cement and aggregates are weighed automatically to predetermined quantities (Figure 2.5).

Figure 2.5 Aggregate Silos and Weigh Batching

2.4.3.2 Mixer

Because a semi-dry mixture is used to mould concrete paving blocks, effective mixing can be done with pan and trough mixers. Drum-type mixers are unsuitable. The size of the pan mixer must be related to production so that batches are used up within a reasonable time, i.e. before workability is reduced by moisture loss or hydration of the cement [Cement and Concrete Institute 2001]. A pan mixer is shown in Figure 2.6.

Figure 2.6 Pan Type Mixer

2.4.3.3 Molding Equipment

Unlike bricks and blocks used for masonry, paving blocks must be dense (fullest possible compaction to be achieved). Equipment must be capable of a high degree of compaction and satisfactory output. Therefore, a combination of vibration and pressure is the most effective way of achieving compaction. Molding pressure should be 10 MPa or more. The optimum period of vibration must be determined experimentally in the plant but is usually 3 to 12 seconds. Frequency and amplitude of vibration should be optimized for the specific materials being used and the number of blocks being molded per cycle [Cement and Concrete Institute 2001]. Good compaction is more difficult to achieve in thicker blocks and those that have acute angles. For this reason concrete pavers with a thickness greater than 80 mm are seldom manufactured [Cement and Concrete Institute 2001]. Block making equipments can be classified into three: Stationary, egg-laying and manual.

A stationary equipment (Figure 2.7.) deposits its extruded units on a pallet, which is removed for subsequent curing. Stationary plants using the pallet system are almost exclusively used as they are capable of providing the necessary high levels of vibration and pressure [Concrete Manufacturers Association Publication 2002, Cement and Concrete Institute 2001].

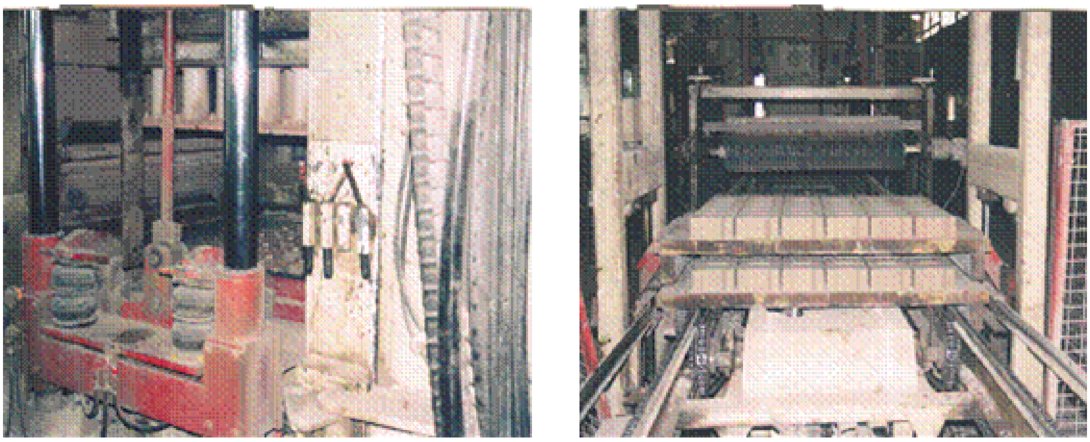


Figure 2.7. Stationary Equipment

An egg-laying type of equipment deposits its extruded units on a concrete slab, and then moves forward to "lay" the next set of units. Units are removed from the slab the next day, or, in cold weather, two days after manufacture unless richer mixes are used [Concrete Manufacturers Association Publication 2002]. Manual equipment works with the same principle as the stationary equipment (Figure 2.8). The volume of units produced is less than the stationary equipment.

Figure 2.8 Production with Manual Equipment

2.4.3.4 Curing Chamber

Newly molded blocks should be subjected to some form of curing. The form of curing ranges from the prevention of moisture loss to the use of elevated temperature and high humidity [Cement and Concrete Institute 2001].

Low-pressure steam curing was one of the earliest accelerated curing methods used. In this system, saturated steam, at atmospheric pressure and at temperatures above about 70°C, is introduced into insulated chambers containing racks of 'green' blocks (Figure 9). Hydration, the chemical reaction between cement and water which causes hardening, is accelerated at high temperature in a vapour-saturated atmosphere. About 70 to 80% of the 28-day atmospheric-temperature cured strength of the concrete is developed in 18 to 24 hours by this process. Units may thus be handled and packaged the day after molding [Concrete Masonry Association of Australia 2000]. However this curing process increases the cost of concrete blocks.

Figure 2.9 Curing Chamber

2.5 Mechanical Properties of Paving Blocks

CBP comprises of concrete blocks bedded and jointed in sand. Therefore, the overall load carrying capacity of a CBP depends on the properties of these two constituents, concrete blocks and sand, as well as the interaction between these two. The slope, size, thickness, laying patterns, etc., are important block parameters influencing the overall performance of the pavements [Bikasha and Ashok 2002]. However, load carrying capacity is not the only performance parameter of a CBP. Other serviceability requirements of CBPs can be listed as; skid resistance, abrasion resistance and resistance to weathering such as freezing-thawing and deicing chemicals [Dowson 1994]. The indicators of these performance requirements are: compressive strength, flexural strength, skid resistance, abrasion resistance, freezing-thawing and deicing chemical resistance.

The mechanical properties of concrete blocks are important for a serviceable CBP. But, it is very important to notice that just like other flexible pavements, deficiencies in the under laying layers can not be compensated for by the surface quality of the pavement [Hodgkinson 1986]. A brief review of literature on the performance requirements of CBPs, will now be presented.

2.5.1 Abrasion Resistance

Abrasion resistance of concrete pavements is a surface property that is mainly dependent on the quality of the surface layer characteristics [Ghafoori and Sukandar 1995, Humpola 1996]. The top 1-3 mm is the most important part for the abrasion resistance of the concrete product [Humpola 1996]. Cement content, water-cement ratio, cement type, aggregate type, the use of pigments and curing regime are the factors that influence abrasion resistance [Shackel 1994]. Common assumption is that a correlation exists between CPB strength and abrasion resistance. This indirect approach can be reasonable, but not always correct [Ghafoori and Sukandar 1995]. The strength of the whole unit can show differences with the top-layer-strength of CPB due to unequal curing conditions [Humpola 1996]. Humpola, et. al. (1996), studied the development of compressive strength of overnight mist cured followed by air cured concrete pavers. Modified version of ASTM C779 developed by The Concrete Masonry Association of Australia (CMAA) was used for their research. As a result, Humpola, et. al. (1996), found that the strength increased up to 7 days then became minimal when pavers void saturation level fell below the required level for hydration. But, abrasion index measured on units from the same lot of pavers continued to increase at ages above 180 days.

They concluded that abrasion resistance was not a function of compressive strength and they stated that abrasion resistance is probably affected by variables such as cement content, curing regime and carbonation, all of which influence the condition of the top surface layer [Humpola, et. al. 1996].

In another study by Humpola, the abrasion resistance of concrete blocks subjected to different initial curing schemes was determined by Ball Race Test. It was concluded that mist cured CBPs performed significantly better when compared to air cured ones [Humpola 1996].

Ghafoori and Sukandar (1995), studied on concrete blocks abrasion resistance by using ASTM C 779 (Procedure C, Ball bearings) method. An experimental program was performed to examine various aggregate-cement ratios on bulk and surface properties of concrete block pavers . Because of the large daily production and lack of indoor storage capacity nearly all pavers block manufacturers use air curing although air curing is not recommended for cement-based products. The specimens used for their experiments were also air cured after fabrication at room temperature 25 ± 1.7 C for 1 day and than placed outdoors [Ghafoori and Sukandar 1995].

According to this investigation:

- The abrasion resistance of concrete paving blocks is strongly affected by the aggregate-cement ratio of the matrix. The increase in cement content results in a more binder rich and dense block surface which in turn increases the surface quality and the resistance to abrasion. The change in aggregate-cement ratio has a much greater influence on abrasion resistance than compressive or splitting tensile strength of concrete pavers

• There is a correlation between depth of wear and bulk characteristics. The proposed quadratic equations are found to be an accurate representation of these relations.

• The testing condition of the specimen has impact on abrasion resistance. The abrasion resistance of concrete pavers is much better under air-dry conditions than under wet conditions. The difference is drastically reduced as the cement aggregate ratio of the mix is increased.

• Finally, as a result of their research, they concluded that for the worst case scenario (air-cured specimen and wet testing condition) concrete pavers with cement content of 223 kg/m^3 (11.11 percent of total dry mix) provide the surface properties that meet the maximum limit of 3 mm required by ASTM C 936. And, the minimum mean compressive strength of 55 MPa required by ASTM C 936 for pavers is adequate as an indirect measure of abrasion resistance. This cement content, however, is likely not to be sufficient for adequate freezing and thawing durability or resistance to deicing salts.

Shackel (1994), summarized the factors affecting the abrasion resistance of CBPs as follows:

• The abrasion resistance increases with increased cement in the mix.

• Increasing the water/cement ratio lead to a reduction in abrasion resistance.

• For pavers manufactured from off-white cements, the addition of up to a 7% pigment produced no significant change in abrasion resistance.

• Mixes with crushed aggregate tended to exhibit higher abrasion than those manufactured using river gravel.

• Some pigments significantly increase the abrasion resistance.

• Moist curing yielded higher abrasion resistance and compressive strength than air curing of specimens. Curing condition affected abrasion more than strength.

• Although it is possible to obtain weak correlations between abrasion resistance and compressive strength. In particular, compressive strength did not provide a reliable indicator of resistance to wear.

2.5.2 Resistance to Freezing and Thawing

The actions of freezing and thawing can result in severe deterioration of all cementitous products. As water in concrete freezes, hydraulic and osmotic pressures can develop in the pores of cement paste and aggregate. If these stresses exceed the tensile strength of the aggregate or cement paste deterioration will occur in the form of cracking , spalling, or surface scaling [Ghafoori and Mathis 1997; Powers 1975]. Concrete is further damaged by the application of deicing agents. Utilization of deicing chemicals like sodium chloride and calcium chloride to remove snow and ice from roads tends to magnify the hydraulic and osmotic pressures that develop in frozen concrete. Consequently, the potential for deterioration increases which is usually in the form of surface scaling [ACI 1991].

Current manufacturing practice (vibration and pressure) used in fabrication of concrete paving blocks can lead to a final product that has a low permeability which can keep the pore structure from becoming critically saturated. However, lack of sufficient amount of entrapped or entrained air still makes paving blocks vulnerable to freezing and thawing damage. Use of air entrainment is one possible solution, but the strong vibration used in the manufacturing process cause an undesirable loss of entrained air. Furthermore, the stiff consistency of the low water-cementitious ratio mixtures using in paving block inhibits the action of air entraining and makes measurement of the air content extremely difficult. As a result, specifying a minimum cementitious content or aggregate-cementitous ratio is the most appropriate method for assuring adequate freezing and thawing durability [Ghafoori and Mathis 1998].

There are various accelerated laboratory tests on freezing and thawing performance of concrete pavers. Ghafoori and Smith (1996) compared ASTM C 67, ASTM C 666, ASTM C 672 and CSA-A231.2 standards used for the evaluation of freezing and thawing durability.

For the whole testing program, Ghafoori and Smith (1996), kept the mass ratio of coarse to fine aggregate uniform at 1:2. In their experiment, the range of water-cement ratios was fairly narrow (0.21-0.34), governed by the moldability characteristics of the materials in relation to the needs of the molding process. 7 different aggregate-cement ratios used in this study are shown in Table 2.7.

Table 2.7 Bulk Characteristics of Concrete Pavers [Ghafoori and Smith 1996].

Specimen Code	A/C Ratio	Cement Cont. (kg/m3)	Density (kg/m3)	Absorption (%)	Comp. Str: (Mpa)	Sp. Tensile Str. (Mpa)
A	9:1	200	2101	5.86	40.32	3.365
B	8:1	223	2116	5.73	43.46	3.634
C	7:1	252	2184	4.72	51.00	4.254
D	6:1	295	2219	4.35	52.75	4.820
E	5:1	356	2255	4.09	61.23	5.667
F	4.5:1	395	2272	3.97	67.04	6.481
G	4:1	447	2317	3.76	75.00	6.688

One of the freezing thawing durability tests was conducted following the referred to ASTM C 67. The ASTM C 67 test method consists of placing the top of a brick (or a concrete pavers) unit in a tray with 13mm deep water. The unit is then subjected to 50 freezing and thawing cycles with one cycle consisting of 20 hours of freezing at -9° C and 4 hours of thawing at 24° +5.5° C. No more than 1% loss of material is allowed after 50 cycles in order to satisfy the test according to ASTM C 936 [Ghafoori and Smith 1996]. From the test results N. Ghafoori, D. R. Smith (1996), observed that keeping concrete pavers mass loss from exceeding the maximum %1 requirement was achieved with 223 kg/m3 cement content, corresponding to a compressive strength of approximately 43.5 MPa and an absorption of 5.7%.

The second test was conducted following the ASTM C 666 test method. In this test, concrete samples are exposed to continuous cycles of freezing and thawing [alternatively from 40 to 0^0F (4.4 to -17.8^{0}C)] with each cycle lasting only 2-5 h [Ghafoori and Mathis 1998]. Ghafoori and Smith (1996), concluded that to complete 300 rapid freezing and thawing cycles using no greater loss than 1% as a test criteria, pavers required at least 395 kg/m^3 cement content under ASTM C 666 conditions. This means an increase in cement content of 57% over that required under ASTM C 67. In other words, the exposure conditions of ASTM C 666 required a minimum compressive strength of 67 MPa and an absorption capacity of no more than 4% to satisfactorily ensure the requirements of rapid freezing and thawing durability.

Ghafoori and Smith (1996), also studied on CSA-A231.2-M85 which is a standard developed by Canadian Standard Association. As a result of their researches, Ghafoori and Smith (1996), concluded that under the exposure conditions of CSA-A231.2-M85, a minimum cement content of 395 kg/m^3 offers adequate resistance to freezing and thawing with deicing salts. This level of cement content also provides a compressive strength of 67 MPa and an absorption value of less than 4% like ASTM C 666 [Ghafoori and Smith 1996].

2.5.3 Resistance to Deicing Chemicals

Several standardized procedures have been developed in order to assess the deicer salt scaling resistance of concrete. These include ASTM C 672, , and CSA-A231.2-M85. In the ASTM only the top surface of the concrete specimens is exposed to deicing chemicals, whereas the Canadian test requires total immersion of test samples in salt solution. ASTM C 672, also known as ponding method is the most widely used deicer test procedure and it is a basis for several national and international standards [Ghafoori and Mathis 1997]. Ghafoori and Smith (1996) found that under ASTM C 672 conditions pavers with a minimum cement content of 356 kg/m^3 and 395 kg/m^3 did not display any sign of surface scaling after 50 and 200 cycles respectively. It is concluded that, minimum compressive strength of 61.3 MPa and a maximum absorption capacity of 4% ensure freezing and thawing durability with deicing chemicals [Ghafoori and Smith 1996].

Ghafoori and Mathis (1997) also investigated the relative performance of concrete block pavers subjected to repeated cycles of freezing and thawing with deicing chemicals using the specifications of ASTM C 672. Based on the experimental results Ghafoori and Mathis (1997), observed that the bulk properties of concrete pavers strongly influenced by the aggregate-cement properties of the matrix. A decrease in aggregate-cement ratio reduced the porosity and resulted in a denser, strong, and less permeable product.

2.5.4. Compressive Strength

Generally, concrete composes of three phases. Mortar matrix, aggregate and the interfacial transition zone (ITZ) between the two [Akçaoğlu et. al. 2003]. The strength of concrete is determined by the characteristics of these phases. In normal strength concrete, the strength of mortar and the bonding of mortar and coarse aggregate are limiting factors of strength [Özturan and Çeçen 1997].

In general, volume of all voids in concrete: entrapped air, capillary pores, gel pores and entrained air ,if present, influences strength of concrete [Neville 1981]. The compressive strength does not provide any direct measure of paver’s durability but does provide a simple method for deciding the overall quality of a paving unit [Concrete Masonry Association of Australia 1986].

Humpola (1996) studied on effect of type of curing and density on paver's compressive strength. Humpola (1996) found out that, density and compressive strength of air and steam cured CBs performed significantly worse as compared with mist curing ones.

Pavers must provide sufficient strength to resist handling, construction stresses and traffic. Most specifications require the pavers to exhibit compressive strengths in the order of 40 MPa. In some specifications the flexural strengths in the range of 3-4 MPa is also required. The test specimens (whole paver , or cube, or cylinder extracted from pavers), the definition of strength (single, mean, characteristic), the testing procedures, age and the number of specimens tested shows differences in different specifications. Because of that comparison of different specifications can be rather difficult and meaningless [Shackel 1994]. Nevertheless, a worldwide survey of specifications suggest that, once the influence of test procedures is eliminated, the minimum compressive strength of a single pavers should exceed 45 MPa to 50 MPa [Huber et. al. 1984].

2.5.5. Tensile Strength

The tensile strength of concrete is approximately % 10 of its compressive strength. The tensile strength of concrete can be measured by the direct tensile loading test. However the application of direct tensile load to the test specimens is rather difficult. For this reason tensile strength of concrete is usually measured by the flexural (bending) strength of concrete or by the indirect tension test like splitting test

[Erdoğan 2002]. Strength requirements for pavers in different standards are given in Table 2.8.

Table 2.8 Strength Requirements for Pavers [Bullen 1994].

Country	Compressive Strength	Flexural Strength
Canada	50 MPa min average 45 MPa absolute min	NA
GFR	60 MPa min average 50 MPa absolute min	NA
Japan	NA	4.9 Mpa
Netherlands	NA	5.9 Mpa min C_k
New Zealand	40 MPa	NA
South Africa	35 MPa min average 30 MPa absolute min	NA
USA	55 MPa min average 50 MPa absolute min	NA

2.5.6. Slip and Skid Resistance

A vehicle has to compensate the horizontal component of the forces formed with direction or speed change of vehicle. When the horizontal force is greater than that which can be resisted by the friction between tyre and road surface, skidding will occur. The capability of a road pavement surface to withstand skidding force components is known as the skid resistance. In-service skid resistance of the pavement can be measured by the Polished Pavers Value (BS 7932: 1998 Method for Determination of Polished Pavers Value) test. Concrete block paving with typical in-service Polished Pavers Values (PPV) of 50 are suitable for most roads. Higher skid-resistance blocks are available on request [Pritchard and Dawson 1999]. Normally spoken, a surface made of concrete has enough slip and skid resistance. [Jan 1994].

The property of skid is specifically for traffic and slip is specially related to pedestrian use [Dowson 1994]. Slipperiness can be described as a condition where there is inadequate friction between the foot and the walking surface for the pedestrian. A walking surface needs to provide sufficient friction to give the pedestrian confidence that his or her foot will not slide. The slip resistance of paving products can be determined in the laboratory by "pendulum" test [BS 7932:1998]. It is indicated that a pendulum value of 40 gives a safe and satisfactory walking surface [Pritchard and Dawson 1999]. Table 2.9 gives values for the pendulum apparatus.

Table 2.9 Pendulum Values [Pritchard and Dawson 1999].

Pendulum Value	Category
65 and above	Excellent
35-64	Satisfactory
25-34	Marginal
25 and below	Dangerous

2.6 Structural Design of Concrete Pavements

The design of CBP roads is based upon the evaluation of four primary factors and their interactive effect which are environment, traffic, sub grade soil, and pavement materials [Rada et. al. 1990].

a) Environment

Pavement performance is significantly influenced by environmental factors. Moisture adversely affects the load bearing capacity of the pavement by reducing the strength of unbound granular materials and sub grade soils. Moisture causes differential heaving and swelling of certain soils, too. Temperature can also affect the load bearing capacity of pavements, particularly those that have asphalt-stabilized layers. The combined effect of temperature and moisture can also lead to detrimental effects like frost action [Rada et. al. 1990].

b) Traffic

A key factor in the design of CBP is the anticipated traffic over its design life. In most design procedures, traffic related parameters such as vehicle mix, volumes, growth rate, directional split, and lane distributions are used to arrive at a single-value representation of traffic for direct input into the design procedure. Typically, traffic is represented in terms of the number of the equivalent 80-kN single axle load repetitions [Rada et. al. 1990].

c) Sub grade Support

One of the most significant factors in the design of pavements is the evaluation of the sub grade soil strength. Many procedures for establishing this design factor are available. For example, estimates made by the engineer based on experience, soil-type-to-strength correlations, laboratory tests, and in situ evaluation methods such as dynamic deflection tests [Rada et. al. 1990].

d) Pavement Materials

The last set of design variables that must be established is related to the pavement structure as depicted in Figure 2.10. First, all paving materials available for construction must be identified. Finally, all feasible material type and layer-thickness combinations that provide sufficient structural capacity must be developed [Rada and Smith 1990].

Although the use of concrete blocks in pavement design and construction is a rather new development, several CBP design methods are presently available (Eisenmann and Leykauf 1988; Houben et. al. 1984,1988; Livneh et. al. 1988; Miura et al. 1984; Rolling 1984; Shackel 1982,1988) [Rada and Smith 1990], LOCKPAVE (Computer software for thickness design of concrete segmental pavements developed in Australia) [Concrete Masonry Association of Australia 1997b], BS 7533 Part 1 (Guide for Structural Design of Pavements Constructed with Clay, Natural stone or Concrete pavers), and American Association of State Highway and Transportation Officials (AASHTO) flexible pavement design method and other Specifications for Highway Works can also be base for the design of CBP.

Generally, the performance of concrete block pavement depends on proper design, proper selection of materials and good workmanship. The performance of CBP are affected from concrete block properties, edge restraints, joints and joint sand properties, laying pattern of concrete blocks and the sub-layers.

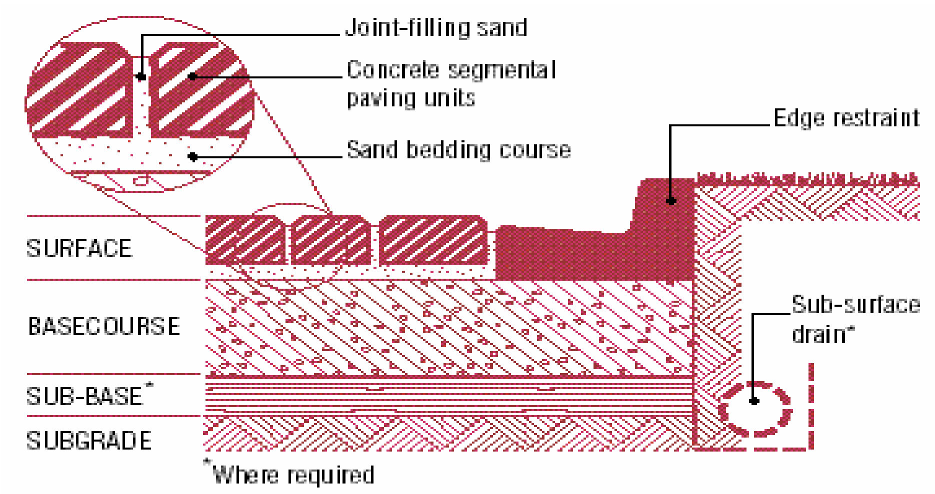


Figure 2.10 Typical Block Paving [Concrete Masonry Association of Australia 1997b].

2.6.1 Sub-Layers

In any paving assembly, the base is of prime importance. The pavers, sand and edge restraints must be placed on a properly prepared base. If the base is improperly designed or constructed, the entire system is prone to failure [Brick Industry Association 1992]. For the base design, attention must be given to local soils and drainage conditions, the expected traffic, and the availability of adequate base materials [Ackerstone 2003].

The paving surface receives the traffic wear, protects the base and transfers loads to the base. The base and sub base (if required) provide structural support to the paving system by distributing the load to the sub grade [Brick Industry Association 1992]. Low strength sub grade soils can present difficulties in achieving a firm and stable platform for the base course construction in their unmodified form using conventional compaction techniques. In that case, chemical stabilization by lime, fly ash, ground granulated slag or cement or some combination of these might be necessary [Concrete Masonry Association of Australia 1997b].

Paving assemblies are classified by the type of paving surface and the type of base supporting the surface. Typical base system for CBP is flexible base pavements. Flexible bases include crushed stone, gravel or coarse sand. Applications for flexible bases range from residential patios to city streets. Flexible paving systems are typically the most economical to install since less labor and fewer materials are involved. The thickness of each layer in a flexible pavement depends upon the imposed loads and the properties of each layer. A pavement subjected to heavy vehicular traffic requires a thicker base than a pavement subjected to pedestrian traffic. Only mortarless paving, CBP set on sand bedding course in which the joints are filled with sand, is suitable for this type of base [Brick Industry Association 1992]. In flexible base system unbound materials like crushed stone, gravel or coarse sand are to be used.

Other base systems, semi rigid & rigid base systems, have no regular use for CBP but will be explained below.

● Semi Rigid Base System: This type of base consists of asphalt concrete, commonly referred to as asphalt. Only mortarless paving is suitable over this type of base [Brick Industry Association 1992]. Typically, an asphalt base is supported by an aggregate sub base. Each material layer is compacted as placed. An asphalt or bituminous setting bed is placed over the base [Brick Industry Association 1993].

● Rigid Base System: A rigid base is defined as a reinforced or unreinforced concrete slab on grade [Brick Industry Association 1992]. Both mortarless and mortared paving systems may be laid over a rigid concrete base. Concrete bases may or may not be laid over an aggregate sub base depending upon the application and traffic. Typically, the concrete base should cure a minimum of seven days before installation of the setting bed and pavers [Brick Industry Association 1993].

2.6.2 Bedding Course

When the quality of bedding course material and the uniformity of the bedding course are not satisfactory localized differential settlement may occur early in the life of the pavements. Materials such as clean graded crushed quarry fines and good quality concreting sands have given good performance provided that the materials have good grading [Concrete Masonry Association of Australia 1997b]. The grading of the bedding course sand can be selected using Tables 2.10 and 2.11 depending on the CBP application [Pitchard 2001].

Table 2.10 Laying Course Material Categories [Pritchard 2001].

Laying Course Categories	Application
1A	Aircraft pavements, Bus stations, Pavements with severly channalized traffic
1B	Industrial pavements, Loading bays
2	Adopted highways, Roads, Petrol station forecourts, Pedestrian schemes with regular heavy traffic, Car parks with some heavy vehicles, Footways with frequent vehicle overrun
3	Pedestrianisation schemes with occasional heavy traffic, Car parks with no heavy vehicles
4	Private drives, Areas with only pedestrian traffic, Footways with occasional vehicle overrun

Table 2.11 Laying Course Material Grading [Pritchard 2001].

BS Sieve size	Percentage by Mass Passing				
	Category 1A	Category 1B	Category 2	Category 3	Category 4
5.00mm	90 to 100	90 to 100	90 to 100	89 to 100	89 to 100
2.36mm	75 to 100	75 to 100	75 to 100	65 to 100	65 to 100
1.18mm	55 to 90	55 to 90	55 to 90	45 to 100	45 to 100
600mm	35 to 65	35 to 65	35 to 65	25 to 80	25 to 80
300mm	10 to 45	10 to 45	10 to 45	5 to 48	5 to 48
150mm	0 to 10	0 to 10	0 to 10	0 to 15	0 to 15
75mm	0 to 0.3	0 to 0.5	0 to 1.5	0 to 3	0 to 5

Single-sized, gap-graded or material containing an excessive amount of fines will lead to reduced performance. The use of a cement-bound material is also not recommended. When placed on the base course, the material should have uniform moisture content. Moisture contents in the range 4–8% have been found to be suitable. The material should be washed free of soluble salts or other contaminants which can cause or contribute to efflorescence [Concrete Masonry Association of Australia 1997b].

2.6.3 Edge Restraint

Concrete segmental pavements derive much of their strength from horizontal forces developed between the pavers also called interlocking forces. These forces, which are generated by wedging action of the filler material between the pavers, must be restrained by installing edge restraints at the pavement perimeter [CMAA 1997b]. The paved area must be restrained at the edges to prevent movement, either of the whole paved area or of individual blocks. Edge restraint resists lateral movement, prevent rotation of the blocks under load and restrict the loss of laying course sand at boundaries. They should be suitable for their purpose and sufficiently robust to withstand damage if accidentally overrun by vehicles [Pritchard and Dawson 1999]. The following diagrams illustrate some typical edge restraints for various vehicular situations.

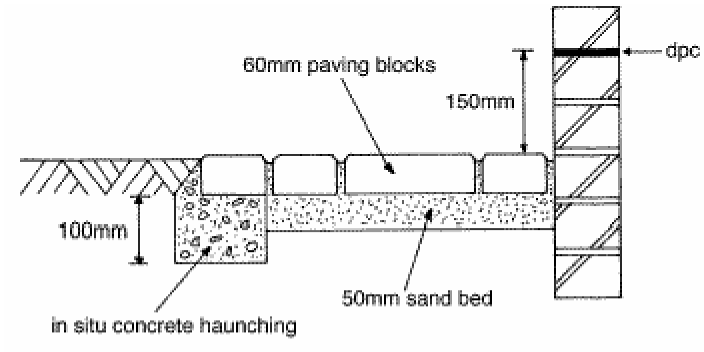


Figure 2.11 Domestic Light Traffic Areas - Adjacent to a Building [Pritchard and Dawson 1999].

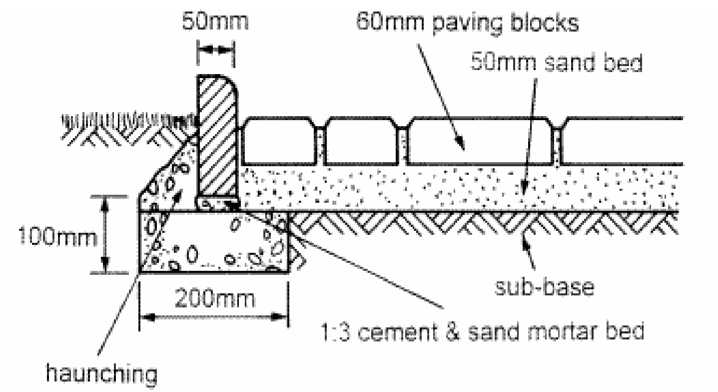


Figure 2.12 Light Vehicle and Pedestrian Traffic [Pritchard and Dawson 1999].

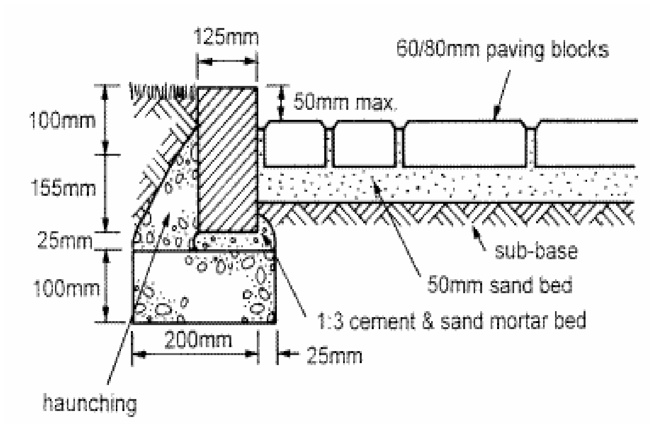


Figure 2.13 Estate Roadway - Light Industrial [Pritchard and Dawson 1999].

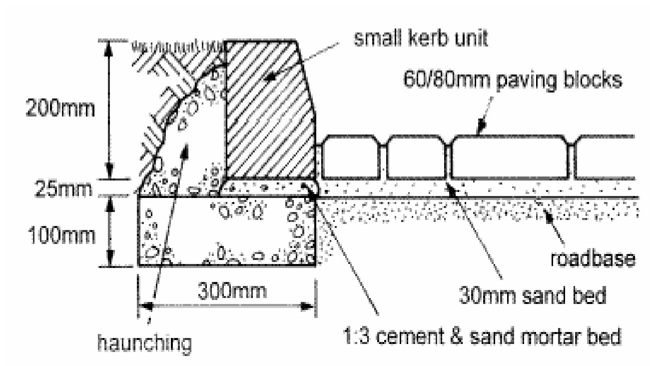


Figure 2.14 Estate Roadways - Parking Areas [Pritchard and Dawson 1999].

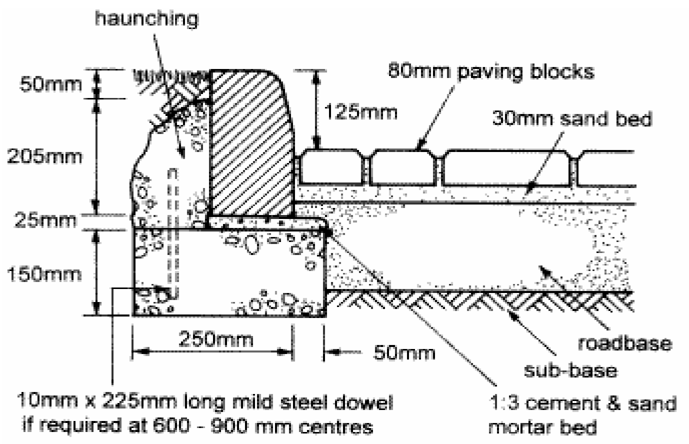


Figure 2.15 Heavy Industrial Traffic [Pritchard and Dawson 1999].

2.6.4 Concrete Blocks

Concrete block paving can be used for several applications. The use influences the thickness of block required [Pritchard and Dawson 1999]. Typical block thicknesses used for different applications are: 60 mm for residential roads and domestic drives and 80 mm for factory floors, industrial pavements and aircraft pavements [Pritchard and Dawson 1999].

The surface of CBP comprises concrete blocks bedded and jointed in sand. It transfers loads to the substructure of the pavement. The load bearing capacity of individual blocks layer depends on the interaction of individual blocks with jointing sand to build up resistance against applied load. Complex shape blocks have larger vertical surface areas than rectangular or square blocks of the same plan area. Consequently, shaped blocks have larger frictional areas for load transfer to adjacent blocks. It is reported that the shape of the block influences the performance of the block pavement under load [Bikasha and Ashok 2002].

The blocks can be classified according to interlocking characteristics. Typical shapes of blocks are shown in Figure 2.16 [Concrete Masonry Association of Australia 1997b].

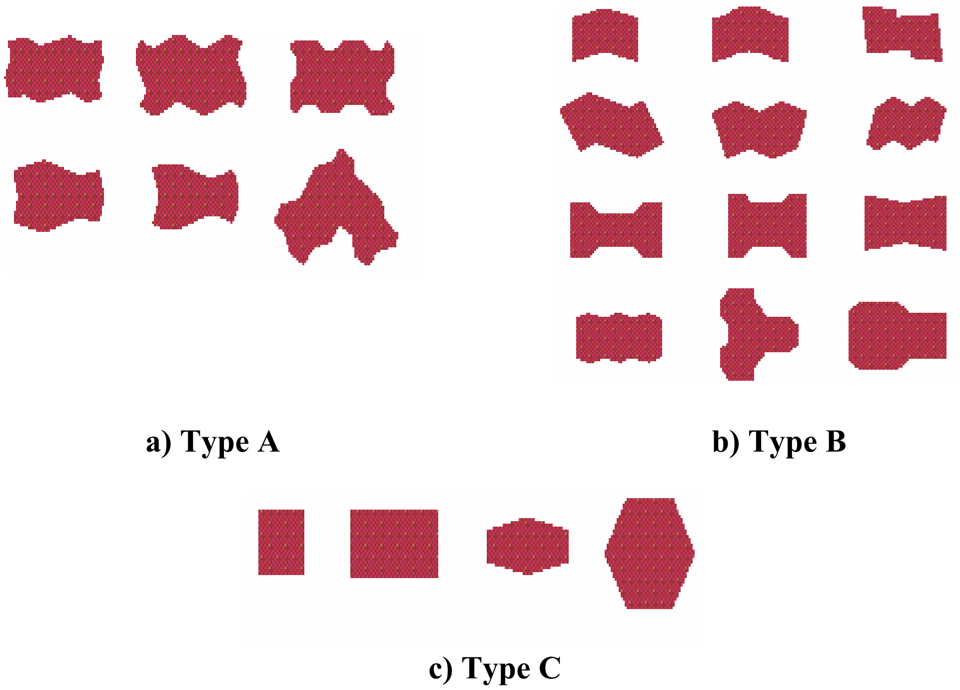


Figure 2.16 Typical Shapes of Paving Blocks [Concrete Masonry Association of Australia 1997b].

● Type A blocks are dentate units that key into each other and, by their plan geometry, interlock and resist the relative movement of joints parallel to both the longitudinal and transverse axes of the unit [Concrete Masonry Association of Australia 1997b].

● Type B blocks are dentate units that key into each other and, by their plan geometry, interlock and resist the relative movement of joints parallel to one axis [Concrete Masonry Association of Australia 1997b].

● Type C blocks are units that do not interlock.

Several researchers indicate that the performance of CBP depends also on the interlocking of the individual units and, to a lesser degree, on the shape and the thickness of the blocks. The interlocking of the pavers blocks is, in turn, influenced by the laying pattern and the thickness of the bedding sand [Rada and Smith1990; Bikasha and Ashok 2002].

The most important factor in choosing a bond or pattern is the use of the pavement [Pritchard and Dawson 1999]. Typical block paving patterns is given in Figure 2.17. In vehicular areas, either rectangular blocks in a 90^0 or 45^0 herringbone patterns, or shaped blocks which conform to a rectangular format, should be used. This reduces the incidence of creep and disturbance wheel loads better to the underlying pavement construction. Stretcher (Running) bond may be used in very lightly trafficked areas where vehicles are unlikely to make regular turns or to brake or accelerate frequently. Basket weave bond should not be used in areas used by vehicle [Pritchard and Dawson 1999]. The recommended paving unit shape, thickness and laying pattern by Concrete Masonry Association of Australia (CMAA) is given in Table 2.12

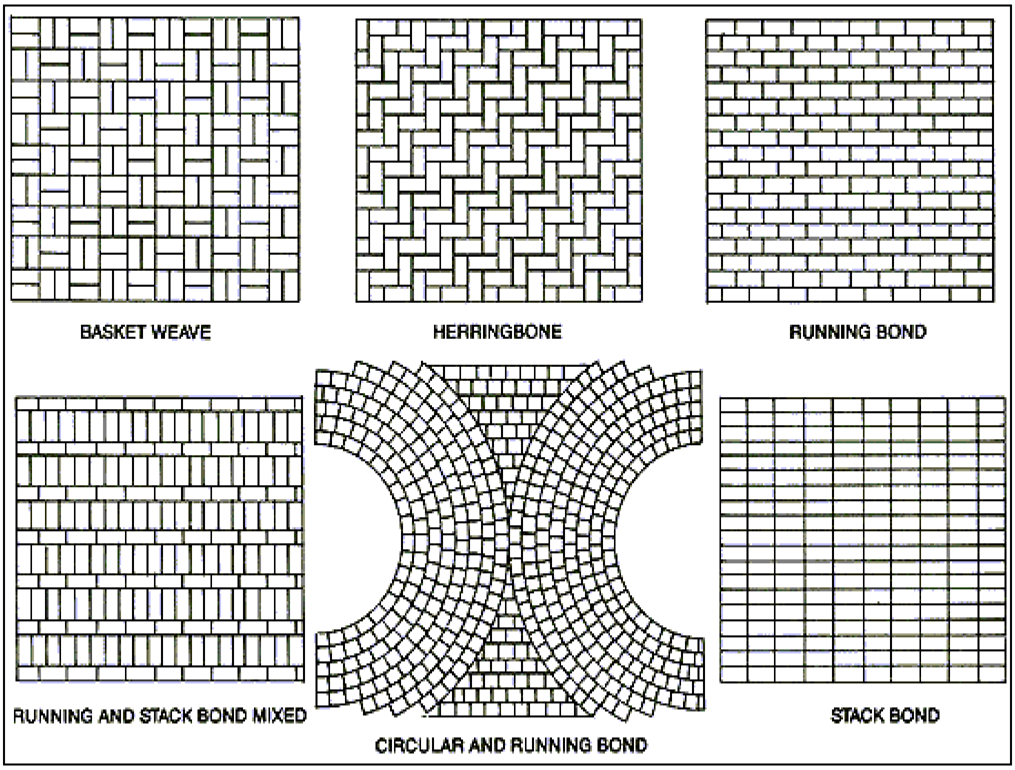


Figure 2.17 Block Paving Patterns [Brick Industry Association 1992].

Table 2.12 Paving Unit Shape, Thickness and Laying Pattern [Concrete Masonry Association of Australia 1997b].

Estimated traffic*(Commercial vehicles exceeding 3t gross)	Recommended surface layer		
	Shape type	Thickness (mm)	Laying Pattern
Up to 10^3	A,B or C	60	H,B or S
10^3 to 10^4	A A,B or C	60 80	H only H,B or S
Over 10^4	A only	80	H only
* Including building construction traffic			
H = Herringbone, B = Basketweave, S = Stretcher			

2.6.5 Drainage

Good surface and sub-surface drainage is essential for satisfactory pavement performance. Drainage needs to be considered during the design, specification and construction phases of a project [Concrete Masonry Association of Australia 1997b]. Adequate drainage of flexible and rigid paving systems is an extremely important design consideration for successful performance and durability. Ponding water can cause deterioration of the paving in areas of repeated freeze-thaw and cause slippery conditions. Continued saturation of the base, sub base and sub grade can reduce load capacity due to weakening of the soil and cause deformations or rutting of the pavement [Brick Industry Association 1992].

In mortared paving, concrete blocks are set on mortar bedding course. Drainage in mortared paving systems is restricted to the surface by full mortar joints and good bond between the brick paving units and the mortar. A drainage system should be designed so standing water is kept to a minimum [Brick Industry Association 1992]. The best way to obtain drainage of the pavement is to slope the paving surface to provide as much surface drainage as possible. A slope of 1 to 2 mm per 100 mm is suggested. Large paved areas and vehicular traffic areas may require a slope greater than 2 mm per 100 mm. The paving system should be sloped away from buildings, retaining walls and other elements capable of collecting or restricting surface runoff. To improve surface drainage, the direction of continuous mortar joints should run parallel to the desired direction of surface runoff [Brick Industry Association 1992]. Drainage of surface runoff is shown in Figure 2.18

Figure 2.18 Pavement Edge Drainage (Curb Gutter and Drain) [Interpave 2003].

Mortarless paving requires both surface and subsurface drainage. The majority of drainage should occur on the surface. However, some water will penetrate downward until it reaches an impervious layer. This layer may be a concrete or asphalt base, a flexible base compacted to high density, an impervious soil such as clay or an impervious membrane used to separate pavement layers. Water not drained off the pavement surface will percolate to the top of this impervious layer, possibly causing pending of the water. Due to these conditions, subsurface drainage is required [Brick Industry Association 1992]. An Examples of sub-surface drainage is given in Figure 2.19.

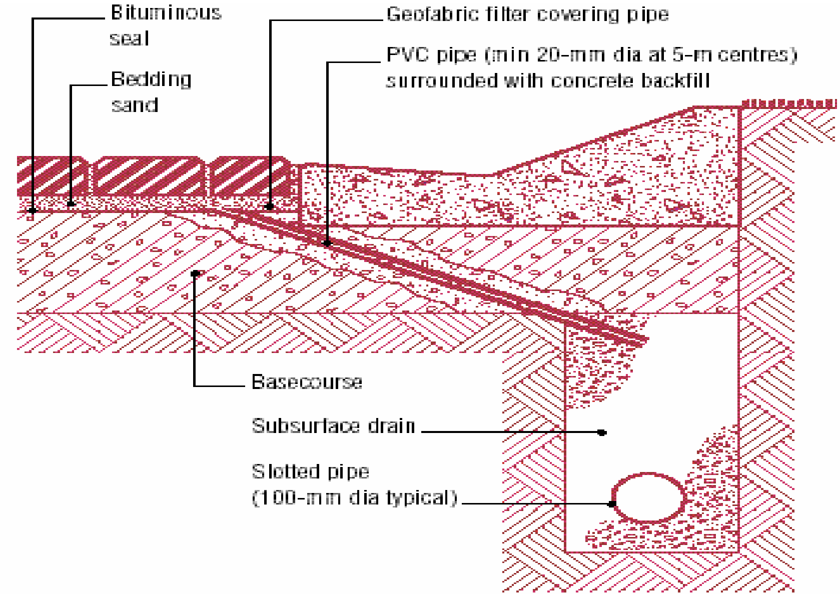


Figure 2.19 Draining directly into Subsurface [Concrete Masonry Association of Australia 1997c].

2.7 Installation of Concrete Block Pavements

There are three main operations for a successful installation of a concrete block pavement; preparation, detailing and compaction [Pritchard 2001]. Workmanship is a critical factor which has a great impact on the performance of pavements. Proper preparation and compaction of the base is absolutely critical [Brick Industry Association 1993].

2.7.1 Sub grade Preparation

One element common to all paving assemblies is the soil or sub grade. Excavation of the sub grade to the proper elevation, removing deleterious materials, and the sub grade compaction are preparations for the base or sub base [Brick Industry Association 1993]. It may also be necessary to introduce drainage into the sub-grade to lower the water table and improve the bearing capacity of sub-grade [Pritchard 2001]. The entire sub grade should be compacted to 90-95% maximum density [Brick Industry Association 1993].

2.7.2 Sub base and Base Preparation

The sub base and base materials should be spread and compacted in layers. The thickness of these layers must be consistent with the capabilities of the compaction equipment. Heavy compaction equipment such as vibratory rollers may be necessary when constructing a street with crushed stone, whereas a plate vibrator may be used when constructing a sand base for a residential areas. Each material should be placed and compacted in layers no greater than 100 mm. The pavers can be placed on a uniform thickness of bedding sand without difficulty so it is essential that the indented surface profile of pavement is formed by the base. The final surface of the sub base should not be open textured and may require the addition of fine material to provide a close textured surface and therefore prevent downward migration of the laying course, when it is laid immediately above the sub base [Pritchard 2001].

2.7.3 Preparation of Restraints

Edge restraints are vital for proper placing and full strength development of the paving units. Before commencement of the laying operation, all permanent edge restraints should be installed rigidly in position to resist possible displacement of the paving units induced by vibration of the plate compactor during construction or the subsequent traffic loads [Highway Department, Hong Kong 1999].

2.7.4 Bedding Course Preparation

The bedding course (setting bed) material should be spread over the base in a uniform thickness. A screed board is often used to spread the sand. The setting bed should not be used to fill in low spots and its thickness should not be adjusted to bring the pavement to the correct grade. Any changes in thickness or undulations in the sand will reflect on the pavement surface [Brick Industry Association 1993]. Nominal compacted thickness of laying course should be 50mm with a thickness tolerance +15mm and –20mm when laid on sub base [Pritchard 2001]. To prevent disturbance of the sand it should not be spread too far in front of the laying face of the pavers. Prepared setting bed materials left overnight should be properly protected from disturbance and moisture. The moisture content of the sand during installation should be as uniform as possible, with the material moist but not saturated. Stockpiled sand should be kept covered to prevent contamination [Brick Industry Association 1993]. Stages of setting bed preparation and block installation can be seen from Figure 2.20.

Figure 2.20. Setting Bed Preparation and Installation of Blocks

2.7.5 Pavers Installation

The last step for the Concrete block is the installation over the bedding course. Pavers could be installed either manually or by means of mechanical apparatus. Mechanical laying by its nature is more suited to large areas with minimum obstructions such as trees and manhole covers [Highway Department, Hong Kong 1999].

Pavers should be laid in the desired bond pattern with a 2 to 3 mm average joint width. The joint width should not exceed 6 mm. For the pavers installation process the following items should be considered [Brick Industry Association 1993, Highway Department, Hong Kong 1999]:

Measures shall be taken to prevent water draining across or through the paving area during laying, bedding and compaction of the units.

- Lay paving units so that the surface levels are within tolerances.
- Make minor adjustments to maintain the bond pattern and ensure that the joints remain wide enough for sand filling if required.

- The first row of units should be aligned against the edge restraints or by using a straightedge or string line. Check the alignment of units periodically and make adjustments where necessary.
- Trim paving units to shape and size to form boundaries. Do not insert pieces of a size less than one-third of a full unit as far as possible.
- To work round any obstructions such as tree planting pits, surround the obstruction with concrete strips to form a more regular shape first, and then cut paving units to abut the surround .

After the pavers are installed, the laying course material and blocks should be compacted using a vibrating plate compactor. The block paved area should be fully compacted as soon as possible after the full blocks and cut blocks have been laid. Blocks should not be left uncompacted overnight other than within 1.0m of an unrestrained edge. After compaction, fine dry (preferably kiln dried) free flowing silica sand in accordance with Table 2.13 should be brushed into the joints between the blocks, fully filling the joints, followed by two or more applications of the vibrating plate compactor. Additional sand should be added to top up the joint as necessary after compaction and during the early life of the pavement.

Table 2.13. Jointing Course Sand Grading [Pritchard 2001].

BS Sieve Size	% Passing (by mass)
2.36mm	100
1.18mm	95 to 100
600mm	50 to 100
300mm	15 to 60
150mm	0 to 15
75mm	0 to 3

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Experimental Program

In order to find the most appropriate mix for the abrasion and strength properties of CB fifteen different mixes were designed. Five different cement content and three different w/c ratios were planned keeping the aggregate grading constant. The planned CB mix designs of the experimental program are given in Table 3.1.

Table 3.1 Mix Proportions to be Used for the Tests

Mix No	Cement C. (kg/m^3)	Water C. (kg/m^3)	Agg. C. (kg/m^3)	W/C Ratio
Mix 1	200	50	2306	0,25
Mix 2	200	60	2280	0,30
Mix 3	200	70	2254	0,35
Mix 4	250	63	2233	0,25
Mix 5	250	75	2201	0,30
Mix 6	250	88	2168	0,35
Mix 7	300	75	2160	0,25
Mix 8	300	90	2121	0,30
Mix 9	300	105	2082	0,35
Mix 10	350	88	2086	0,25
Mix 11	350	105	2041	0,30
Mix 12	350	123	1995	0,35
Mix 13	400	100	2013	0,25
Mix 14	400	120	1961	0,30
Mix 15	400	140	1909	0,35

As seen in Table 3.1, the amount of water increases with increasing cement content and w/c ratio. As vibration and pressure was used during the production process, some of the mixes have shown stability and surface problems after demoulding because of high water content in the mix. As a result, the production of the mixes: 9, 11,12,14,15 could not be performed.

In addition to the mixes given in Table 3.1, two commercially produced CBs were also tested. The first one was a regular concrete block (RCB) and the second one had a iron oxide pigment to obtain a red abrasion layer color (CB-P).

Mixes are produced at a commercial concrete block plant [Özkul Beton Elemanları San. ve Tic. LTD. ŞTİ]. Weighing and batching were done automatically.

The specimens were tested for their abrasion resistance, compressive strength , tensile splitting strength, absorption and density at 7,14 and 28 days of age.

3.2 Materials Used

Before the mix design process, the general properties of the materials used in the mixes were determined. These ingredients were the aggregates and the cement.

3.2.1 White Portland Cement

White Portland Cement that corresponds to TS 21 BPÇ 52.5N cement manufactured by Çimsa was used for all mixes. The chemical and physical properties of this cement were provided by the manufacturer. The chemical and physical properties of the cement are shown in Table 3.2 and 3.3.

Table 3.2 The Chemical Properties of Cement

Oxides and Other Values	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	IR	Free CaO	LOI
Pecentage by Weight (%)	21,48	4,17	0,18	65,16	1,33	0,48	0,21	3,85	0,14	1,50	3,09

Table 3.3 The Physical and Mechanical Properties of Cement

Density (g/cm^3)	Spec. Surface Area (cm^2/g)	Initial Set (min)	Final Set (min)	Compressive Strength (MPa)		
				2 days	7 days	28 days
3,05	4550	120	162	41,2	52,3	62,7

3.2.2 Aggregates

Four different aggregates were used in the mix design. The specific gravity, moisture content and absorption capacity of each aggregate was determined following the ASTM C 127 and 128 standards. The results of these tests are given in Table 3.4.

Table 3.4 Properties of Aggregates

Aggregate Sizes	*River Sand*	*0-3*	*3-7*	*7-15*
SSD Specific Gravity	2,51	2,49	2,66	2,67
% Absorbtion	2,5	1,3	0,62	0,6
% Moisture Content	2,8	1,5	0,28	0,18

Sieve analysis tests were also performed according to ASTM C 136 and the results are given in Table 3.5. Los Angeles weight loss as determined by ASTM C 131 was % 24,1.

Table 3.5 Aggregate Grading

Sieve Size	River Sand % Passing	0-3 Crushed Stone % Passing	3-7 Crushed Stone % Passing	7-15 Crushed Stone % Passing
3/8" (9.5 mm)	100	100	100	68,8
No.4 (4.75 mm)	99,9	99,6	67,1	4,7
No.8 (2.38 mm)	99,3	75,8	5,2	-
No.16 (1.19 mm)	85,5	44,3	1,7	-
No.30 (0.59 mm)	51,2	27,1	1,5	-
No.50 (0.297 mm)	14,3	17,9	1,3	-
No.100 (0.149 mm)	2,4	12,8	1,2	-
Pan	0	0	0	0

The aggregates were combined in proper volumetric percentages according to the results of sieve analysis tests as given in Table 3.6

Table 3.6 Volumetric Percentages for Combined Grading

Aggregate Type	*River Sand*	*0-3*	*3-7*	*7-15*	*Total*
Volumetric Portion in Combined Grading	2	8	2	1,5	13,5

While proportioning the aggregates the particle size distribution have been tried to be kept within the limiting curves of TS 706 for 8mm maximum aggregate size and recommended aggregate grading given in Table 2.6. The gradation curves of combined aggregate grading are given in Figure 3.1, and 3.2 The gradation between the A-B is accepted 'very good' in TS 706.

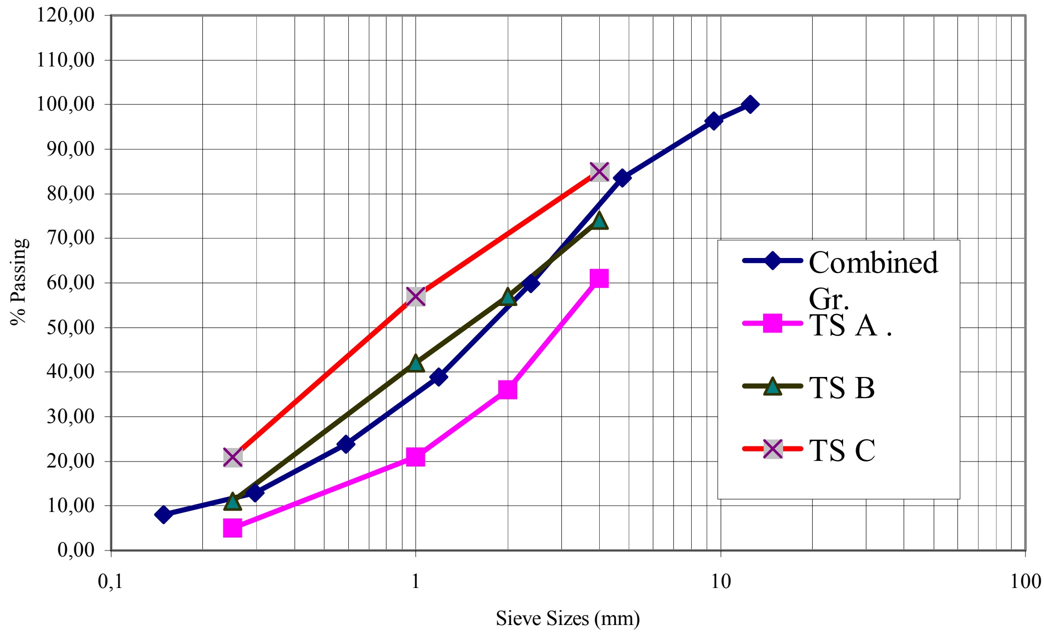


Figure 3.1 Combined Aggregate Grading and TS 706 Limits

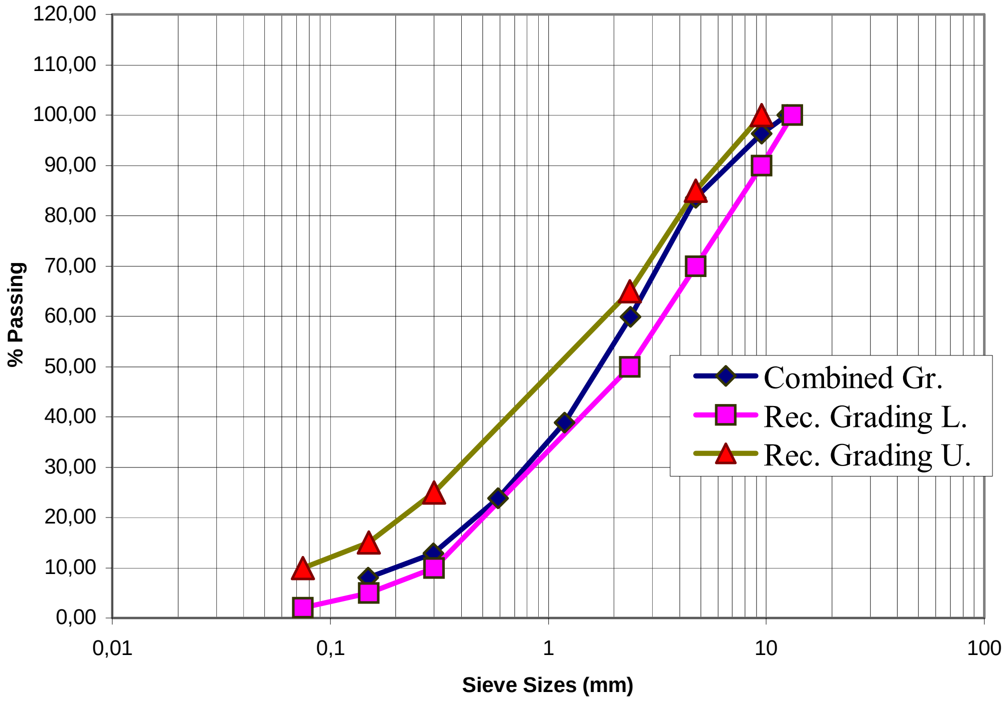


Figure 3.2 Combined Aggregate Grading and Recommended Aggregate Grading

3.2.3 Mixing Water

Groundwater which was assumed to be free from oil, organic matter and alkalis was used for the preparation of concrete mixes.

3.3 Experimental Procedures and Data

The production of all CBs were performed at the construction site of Özkul Beton Elemanları San. ve Tic. LTD. ŞTİ on 3 October 2004. The manufacturing equipment was stationary equipment which applies constant pressure under a vibration frequency. The total time of vibration and pressure was determined through the determined thickness of the CB. In other words, vibration and pressure was applied until the CBs reach the predetermined 80mm thickness. After demolding the CBs were stored for a day in the warehouse under a tent. The next day all the CBs were stored outside and were watered in the mornings for three days. At the end of three days, the specimens were brought to METU Civil Engineering Department Materials of Construction Laboratory. The specimens were later stored in lab conditions until the time of test.

3.3.1 Compressive Strength Tests

The compressive strength of the specimens was determined at 7, 14, 28 days of age after capping the CB surfaces by a gypsum plaster. At each date six specimens were tested in compression using a universal testing machine of 200 t capacity (Figure 3.3).

Figure 3.3 Compressive Strength Test

The Compressive strength test results are given in Table 3.7

Table 3.7 Compressive Strength Test Results

MIX NO	Compressive Strength (MPa)							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 6	COV (%)	Mean of 6	COV (%)	Mean of 6	COV (%)
RCB			36,3	13,0	37,5	7,5	45,9	9,7
CB-P			39,0	3,9	40,0	3,9	41,2	8,8
Mix 1	200	0,25	20,1	11,1	26,9	4,1	26,9	17,4
Mix 2	200	0,30	33,8	15,6	33,6	4,5	33,5	7,7
Mix 3	200	0,35	33,5	5,2	33,8	3,9	35,3	5,8
Mix 4	250	0,25	32,9	6,7	38,4	6,2	44,6	5,0
Mix 5	250	0,30	35,7	2,3	39,2	2,7	39,2	10,0
Mix 6	250	0,35	29,6	6,2	32,6	10,7	34,1	13,4
Mix 7	300	0,25	39,9	10,5	44,8	7,0	42,5	7,0
Mix 8	300	0,30	35,0	2,9	39,4	10,0	40,2	4,6
Mix 10	350	0,25	40,7	3,4	43,7	2,4	46,5	2,5
Mix 13	400	0,25	38,9	8,5	42,8	2,7	46,1	3,3

3.3.2 Tensile Splitting Strength Tests

Tensile splitting strength tests of concrete block specimens were determined at 7, 14, 28 days of age. For every age six specimens were tested. Thicknesses of the specimens were determined from two points before the application of load. The load was applied from the middle of the specimen with the apparatus shown in Figure 3.4

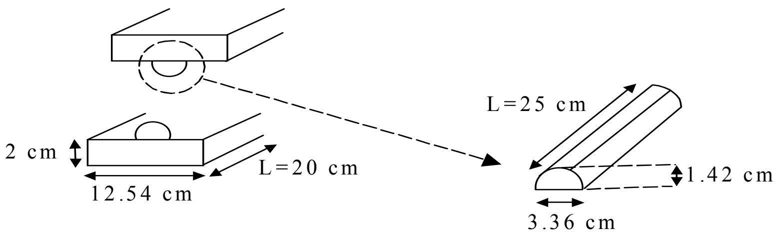


Figure 3.4 Splitting Aparatus

The splitting forces were applied with a universal testing machine of 200 t capacity as shown in Figure 3.5.

Figure 3.5 Tensile Splitting Strength Test

The splitting strengths of the specimens were calculated according to formula:

$T= 0.637*k*P/S$

$k= 1.3-30*(0.18-t/1000)^2$

T= Splitting Strength (MPa)

P= Load at Failure (N)

S= Area of Failure (mm^2)

t= Thickness

Tensile splitting test results are given in Table 3.8.

Table 3.8 Tensile Splitting Test Results

MIX NO	Applied Max Splitting Strength (Mpa)							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 6	COV (%)	Mean of 6	COV (%)	Mean of 6	COV (%)
RCB			1,9	9,1	1,7	10,8	1,7	11,6
CB-P			1,6	10,9	2,3	14,6	2,1	20,5
Mix 1	200	0,25	1,3	6,7	1,4	9,1	1,8	9,0
Mix 2	200	0,30	1,7	25,7	1,8	7,5	1,8	8,8
Mix 3	200	0,35	2,1	5,0	2,1	5,1	2,2	13,4
Mix 4	250	0,25	2,8	4,1	2,3	8,0	2,2	14,5
Mix 5	250	0,30	2,8	2,0	1,9	11,9	2,5	4,8
Mix 6	250	0,35	2,0	4,9	2,4	9,5	2,6	6,6
Mix 7	300	0,25	2,7	12,8	3,0	18,2	3,0	7,8
Mix 8	300	0,30	1,8	8,4	2,2	9,0	2,7	6,4
Mix 10	350	0,25	2,7	18,1	2,4	7,8	2,2	21,6
Mix 13	400	0,25	2,3	15,6	3,1	4,5	2,2	10,5

3.3.3 Abrasion Resistance Tests

Abrasion resistance of concrete block specimens were determined again at 7,14,28 days of age. At every age two specimens were tested. Before the day of test the test specimens for abrasion were cut from the whole CBs. The cut specimens were square with an abrasion layer dimension of 7cm. After cutting, the specimens were put into oven (110 ± $5C^0$) for 24 hours before testing. The abrasion resistances of specimens were tested by Böhme experimental method according to TS 2824. The bottom faces of the mixes were tested. Initially, the specimens were fixed and 294 ± 3 N vertical load is applied. 20 g standard abrasive dust is placed into the rotating table as shown in Figure 3.6

Figure 3.6 Böhme Testing Apparatus

After every 22 revolutions the path and the specimens were cleaned and new 20 g standard abrasive dust is placed and the specimens were rotated 90^0 in the horizontal axis. The specimens were weighed initially and at every 4*22 revolutions. Thickness measurements of the specimens also have been done from three points. Unlike from TS 2824 the total revolutions were increased to 32*22 rather than 16*22. According to TS 2824, total volume of abrasion must be smaller than $15cm^3$ for 50 cm^2 abrasion area. The abrasion volume can be controlled from:

$\Delta V = \Delta m/\rho$ where;

ΔV = Change in Volume (cm^3)

ρr = Density of Specimen (gr/cm3)

Δm=Mass change

Abrasion resistance test results are given in Table 3.9

Table 3.9 Abrasion Resistance Test Results

MIX NO	Abrasion Layer Loss After 16*22 Revolutions (cm^3)							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 2	COV (%)	Mean of 2	COV (%)	Mean of 2	COV (%)
RCB			13,4	7,3	17,2	2,9	20,5	3,5
CB-P			16,6	25,1	13,6	21,1	18,0	0,9
Mix 1	200	0,25	24,1	8,3	27,6	0,9	31,2	1,7
Mix 2	200	0,30	18,8	3,4	27,0	3,4	28,0	9,6
Mix 3	200	0,35	22,7	33,7	27,3	5,5	30,8	6,0
Mix 4	250	0,25	20,5	9,3	26,5	19,5	25,9	6,0
Mix 5	250	0,30	28,2	20,5	22,9	14,1	25,0	0,2
Mix 6	250	0,35	22,6	22,0	28,1	7,5	28,3	3,6
Mix 7	300	0,25	24,3	22,9	20,3	35,9	25,2	0,0
Mix 8	300	0,30	16,5	0,7	22,4	22,7	21,8	14,6
Mix 10	350	0,35	23,8	0,3	23,5	9,6	23,1	4,5
Mix 13	400	0,25	24,3	10,7	21,1	4,3	24,0	0,3

3.3.4 Water Absorption, Unit Weight and Compressive Strength Tests

After abrasion determination, same specimens were used in absorption and unit weight determination. Immediately after absorption and unit weight determination, the specimens were caped and tested under compression in saturated surface dry condition (Figure 3.7). By this Procedure, the SSD mixes were tested in compression a week later than the compressive tests for whole specimens.

Figure 3.7 Compressive Strength Determination after Abrasion

For the calculations; dry mass of the specimens, SSD mass of the specimens and mass of the specimens in water were determined. The calculations were made according to the given formulas:

% Absorption = (A-B)/B*100

Dry Density = B/ (A-C)

A = Mass of SSD Specimen

B = Mass of dry specimen

C= Mass of specimen in water

Density, % Absorption and SSD Compressive strength test Results are given in Table 3.10, Table 3.11 and Table 3.12.

Table 3.10 Dry Density Test Results

MIX NO	Dry Densiy (gr/cm^3)							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 2	COV (%)	Mean of 2	COV (%)	Mean of 2	COV (%)
RCB			2,26	0,35	2,26	2,19	2,24	1,00
CB-P			2,27	0,07	2,27	0,15	2,21	1,17
Mix 1	200	0,25	2,16	0,86	2,16	0,02	2,18	1,57
Mix 2	200	0,30	2,26	2,06	2,26	1,11	2,20	1,10
Mix 3	200	0,35	2,27	0,86	2,27	1,49	2,25	2,43
Mix 4	250	0,25	2,23	1,78	2,23	1,60	2,26	1,28
Mix 5	250	0,30	2,29	0,36	2,29	0,92	2,29	1,08
Mix 6	250	0,35	2,24	0,49	2,24	1,90	2,23	0,85
Mix 7	300	0,25	2,28	0,49	2,28	1,78	2,29	0,91
Mix 8	300	0,30	2,26	0,19	2,26	1,37	2,29	1,49
Mix 10	350	0,35	2,27	0,20	2,27	0,96	2,29	1,76
Mix 13	400	0,25	2,23	0,97	2,23	0,09	2,26	1,40

Table 3.11 % Absorption Test Results

MIX NO	% Absorption							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 2	COV (%)	Mean of 2	COV (%)	Mean of 2	COV (%)
RCB			3,70	0,01	3,77	3,13	3,81	0,38
CB-P			3,70	1,52	3,42	4,03	3,74	2,27
Mix 1	200	0,25	5,09	6,26	4,25	0,15	4,18	2,39
Mix 2	200	0,30	4,27	13,14	4,35	0,58	4,21	2,18
Mix 3	200	0,35	4,47	6,37	4,26	4,14	4,16	2,03
Mix 4	250	0,25	4,17	15,34	4,03	2,68	3,87	2,75
Mix 5	250	0,30	4,05	3,13	4,00	3,82	3,90	1,28
Mix 6	250	0,35	4,97	5,80	4,38	8,92	4,18	1,02
Mix 7	300	0,25	4,32	0,51	3,45	6,36	3,58	5,15
Mix 8	300	0,30	4,05	6,12	3,59	4,21	3,44	2,68
Mix 10	350	0,35	4,20	3,36	3,42	3,33	3,39	3,75
Mix 13	400	0,25	4,26	0,19	3,51	8,10	3,52	9,01

Table 3.12 SSD Compressive Strength Test Results

MIX NO	SSD Compressive Strength (Mpa)							
	Cement Content	W/C ratio	*7 Days*		*14 Days*		*28 Days*	
			Mean of 2	COV (%)	Mean of 2	COV (%)	Mean of 2	COV (%)
RCB			23,0	8,1	20,1	2,1	20,1	0,5
CB-P			21,7	5,9	21,7	16,2	24,7	4,5
Mix 1	200	0,25	16,4	1,8	17,6	12,3	19,1	3,6
Mix 2	200	0,30	24,9	15,9	20,1	16,8	23,2	7,8
Mix 3	200	0,35	20,4	2,7	18,8	1,3	20,0	26,3
Mix 4	250	0,25	26,9	8,3	24,7	8,6	26,0	15,2
Mix 5	250	0,30	25,7	15,5	26,1	15,6	25,6	3,3
Mix 6	250	0,35	21,6	4,8	22,0	23,3	20,0	0,4
Mix 7	300	0,25	28,3	3,9	29,7	4,4	33,3	3,3
Mix 8	300	0,30	30,4	0,0	29,2	24,3	25,7	6,3
Mix 10	350	0,35	25,5	18,0	32,4	5,1	30,3	10,4
Mix 13	400	0,25	25,6	17,5	30,6	27,1	29,9	15,6

CHAPTER 4

DISCUSSION OF RESULTS

4.1 Effects of Cement Content on the Properties of CBs

The effects of ingredients, water and cement content on the properties for each performance parameter of CBs will now be discussed. These parameters include: compressive strength, tensile splitting strength, unit weight and absorption. It can be observed from the following figures that for W/C= 0,30 and for W/C=0,35, the production of some mixes were eliminated because of their higher water content than the mixes which caused stability and surface problems during production.

4.1.1 Compressive Strength

The effects of cement content and W/C ratio on the strength properties of the CB are shown in Figure 4.1. In that figure it can be seen that, for W/C=0,25, the increase in strength was very rapid as the cement content was increased from 200 kg/m^3 to 250 kg/m^3. After 250 kg/m^3 cement content, the increase in strength was very small and even lower for 300 kg/m^3 cement content. It can be concluded that, for a given W/C ratio after an optimum cement content the increase in cement content was unnecessary. The trend was similar for W/C=0,30. And, increasing cement content caused decrease in strength for W/C=0,35.

It can be also observed from Figure 4.1 that for a given 200 kg/m^3 cement content, the strengths increased as W/C ratio of the mixes was increased. This behaviour was not observed for 250 kg/m^3 and 300 kg/m^3 cement contents. Increasing W/C ratio caused decreases in strength for these cement contents. This behaviour was related with the optimum moisture content (OMC). For a given cement content, the compactibility of the mixes was highest at OMC. In other words, for a given cement content the maximum strength can be achieved at OMC. And with increasing cement content, the W/C ratio should be lowered to reach OMC.

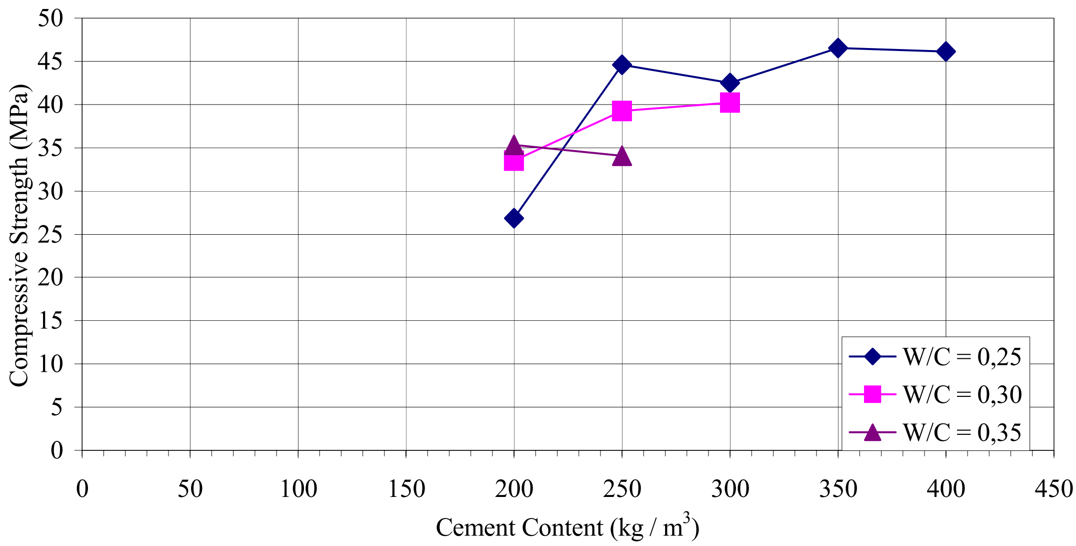


Figure 4.1 Compressive Strength Test Results

These behaviours were closely related with the operation of the CB manufacturing machine. In manufacturing process, as the mixes cast into moulds, the vibration continued until a target thickness was reached. If the target thickness could not reached, the vibration was continued to its adjusted maximum limit (9,99 seconds). As the water content in the mix increased, the mix cast in the mould also increased with increasing mobility. When the mix amount in the mould passed an amount that the machine could not compact to an adjust thickness the vibration duration were continued to its maximum limit (9,99 seconds). This powerful vibration might cause segregation in the mixes that were passed OMC. As a result, the expected increase in strengths with increasing cement content were not observed.

4.1.2 Abrasion Resistance

The Figure 4.2 represents the results of cement content versus abrasion loss relation. It can be observed from Figure 4.2 that for a given W/C ratio, the abrasion losses decreased with increasing cement content.. It can be also observed from Figure 4.2 that for a given 200 kg/m^3 cement content, the abrasion losses were decreased when the W/C ratio increased from 0,25 to 0,30. This condition was also the same for 250 kg/m^3 and 300 kg/m^3 cement contents. But as the W/C ratio was increased to 0,35 from 0,30, abrasion losses increased for both 200 kg/m^3 and 250 kg/m^3 cement contents. This condition reveals that the degree of cementing particles at the surface of the CBs were decreased after W/C=0,30 was exceeded.

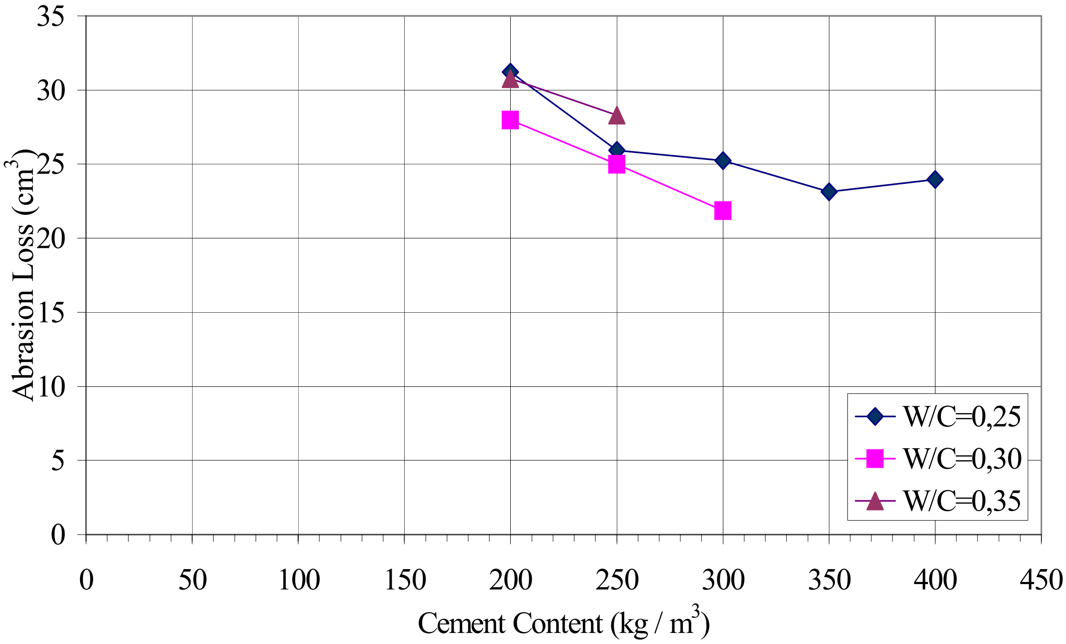


Figure 4.2 Abrasion Resistance Test Results

4.1.3 Other Performance Parameters

The effects of cement and W/C ratio on the tensile splitting strength and % absorption is shown in Figure 4.3, 4.4. As can be seen from figures, similar trends with compressive strength described in 4.1.1 were observed for tensile splitting strength and density at different optimum moisture content levels.

The Figure 4.5 represents the results of cement content versus absorption relation. It can be observed from Figure 4.5 that absorption values were affected from cement content values rather than W/C ratio. The general trend for all water cement ratios were decrease in % absorption as cement content have been increased. The decrease trend only have been disturbed for 400 kg/m^3 cement content at W/C=0,25.

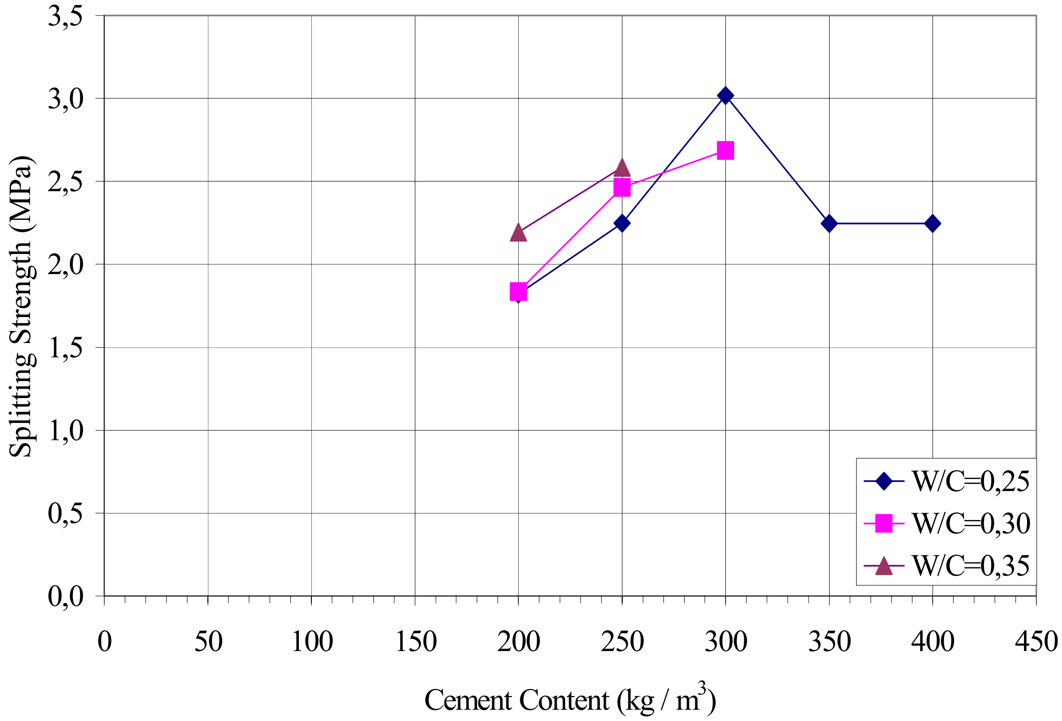


Figure 4.3 Tensile Splitting Strength Test Results

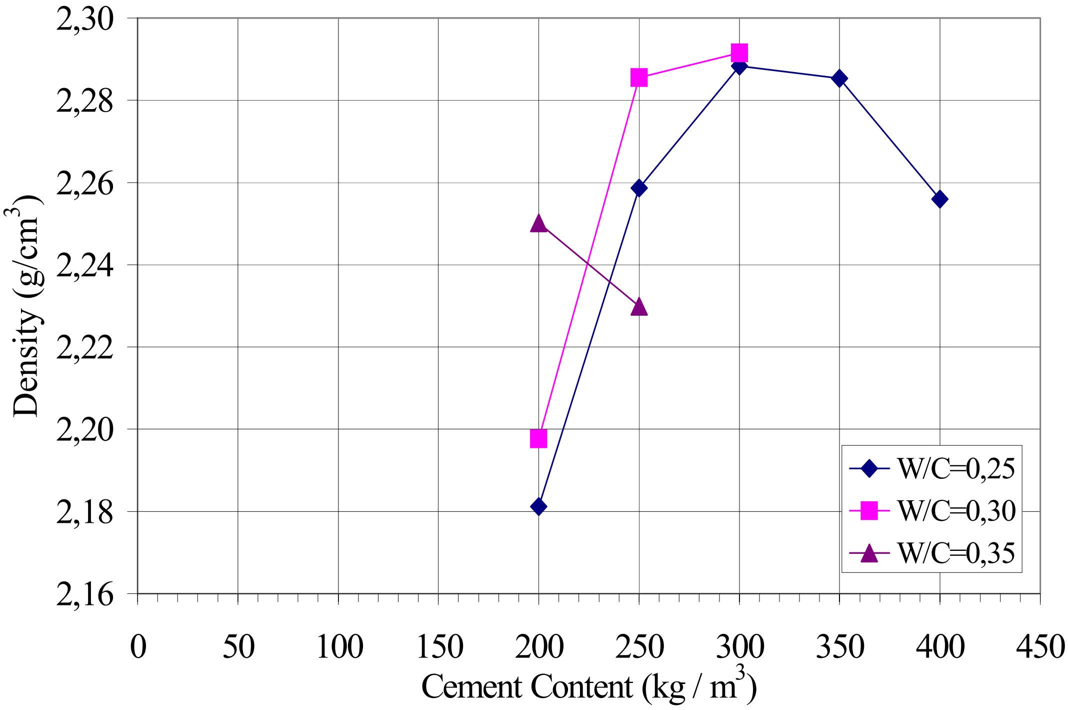


Figure 4.4 Density Test Results

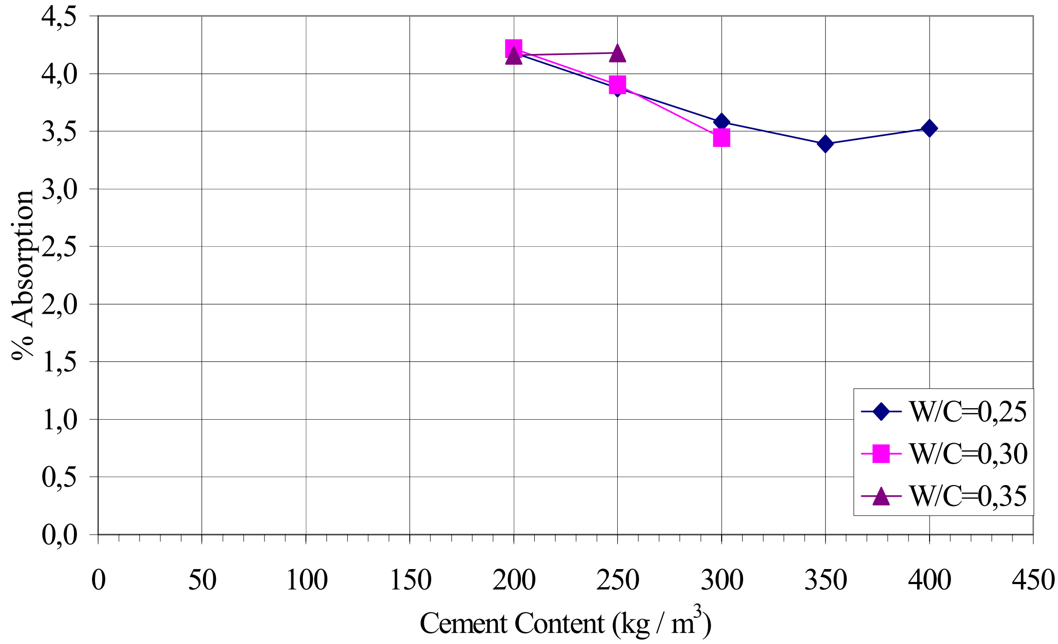


Figure 4.5. Absorption Test Results

4.2 Correlations between Performance Tests

The correlation between compressive strength-abrasion is given in Figure 4.6. As seen in that figure as the compressive strength increases abrasion loss decreases (abrasion resistance increases). The relation between abrasion resistance and compressive strength could be presented by linear regression with a satisfactory correlation.

Moreover, correlations between density and other performance parameters were also investigated. It can be concluded from those relations shown in Figures (4.6, 4.7, 4.8, 4.9, 4.10) that density was closely related with all other performance parameters with satisfactory correlation. Therefore, density, which is the easiest parameter to determine, can be used as a quality control parameter.

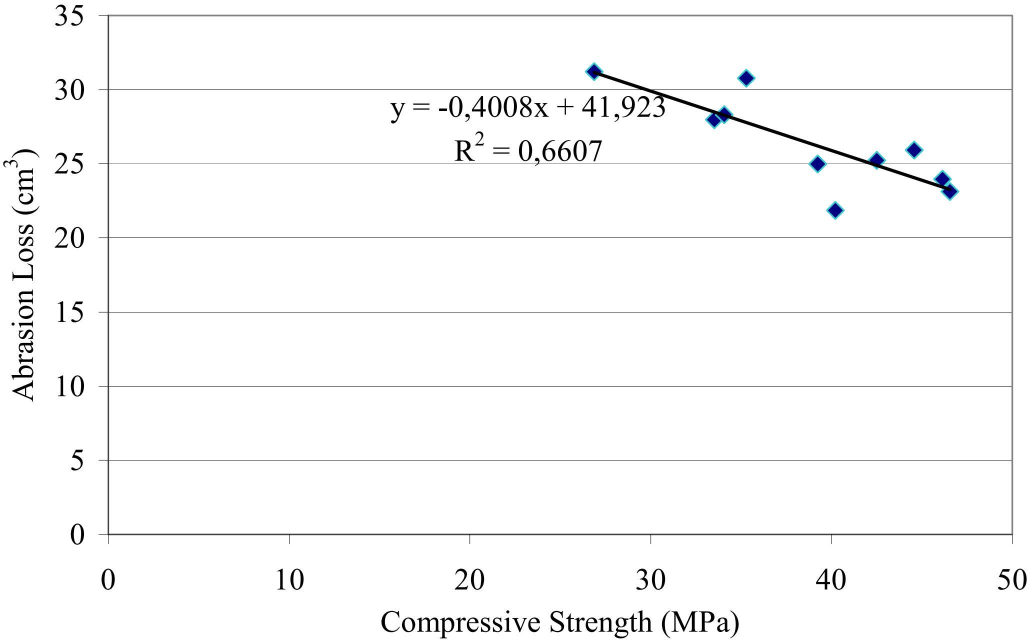


Figure 4.6 Compressive Strength-Abrasion Loss Relation

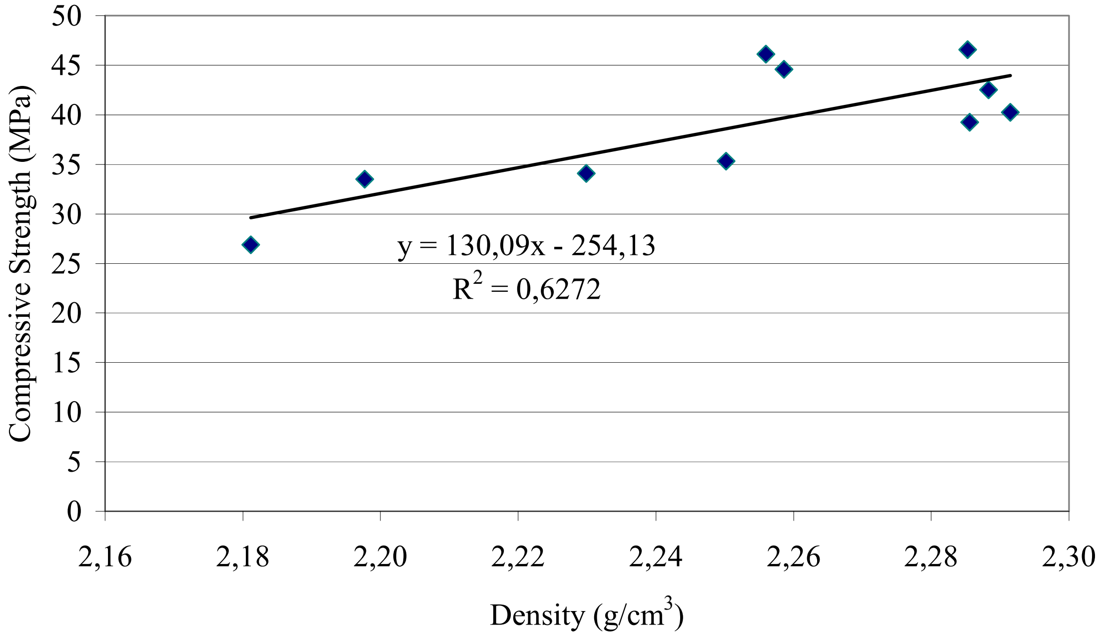


Figure 4.7 Density-Compressive Strength Relation

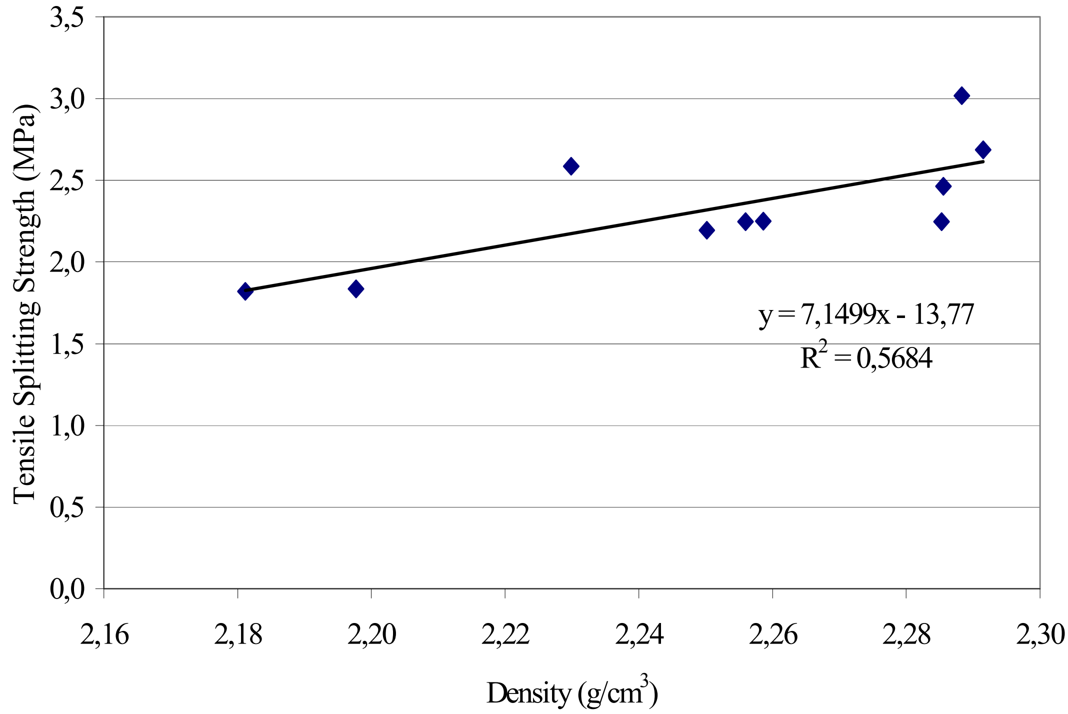


Figure 4.8 Density-Tensile Splitting Strength Relation

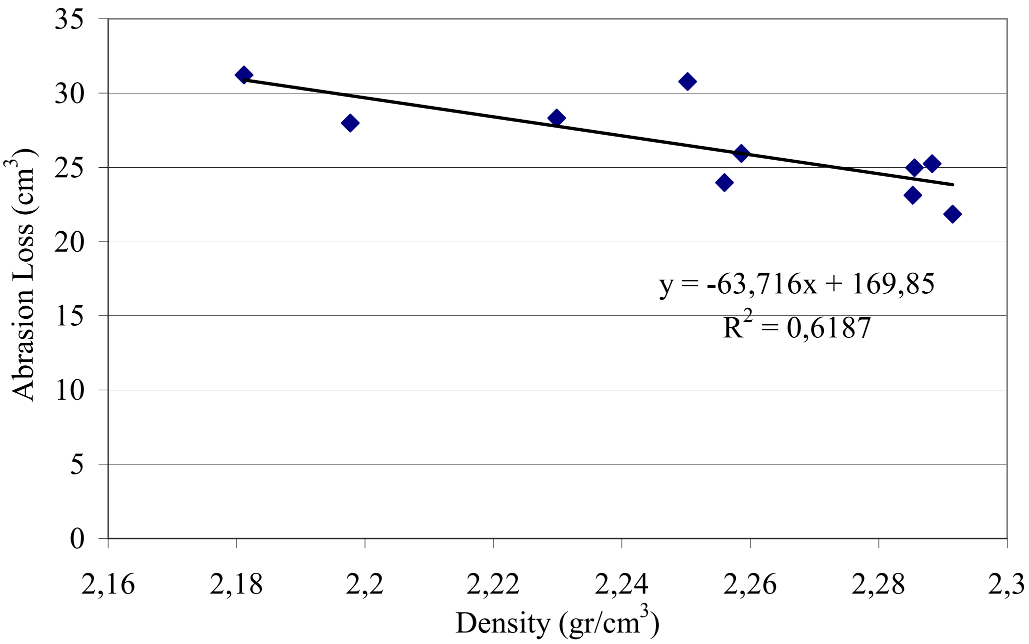


Figure 4.9 Density-Abrasion Loss Relation

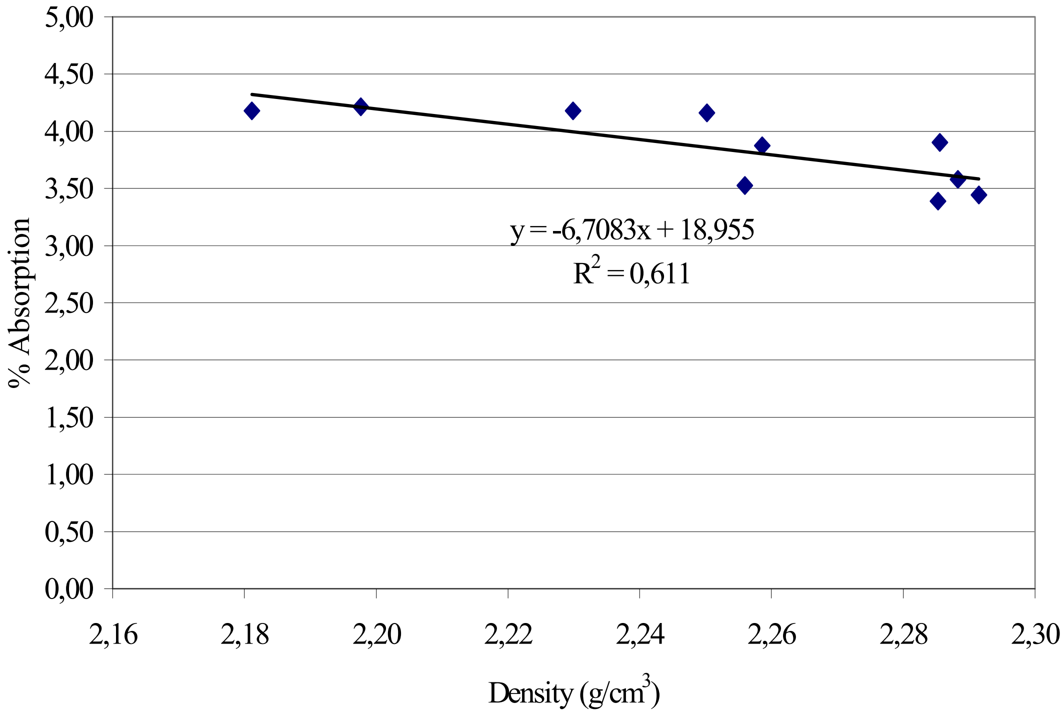
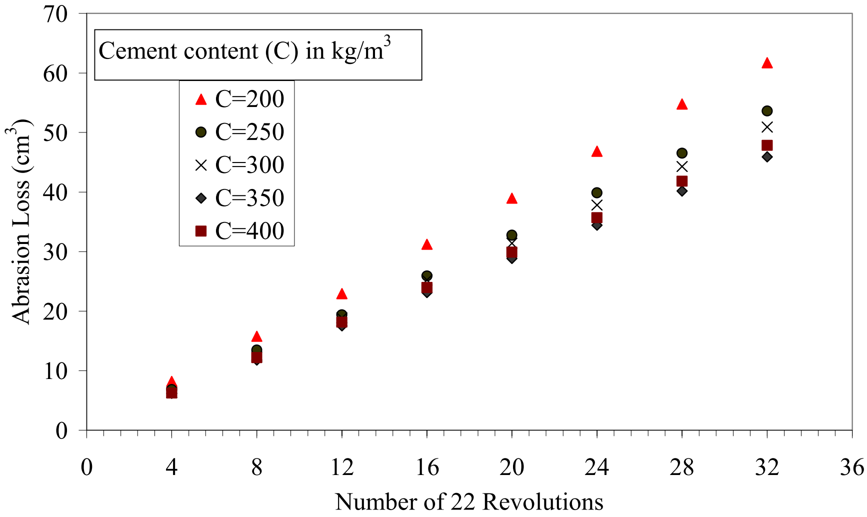


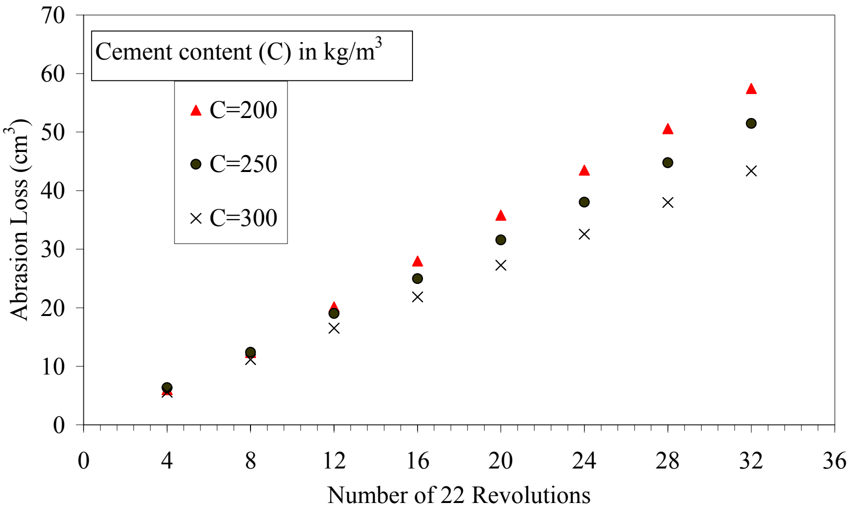
Figure 4.10 Density-% Absorption Relation

4.3 Evaluation of the Abrasion Test

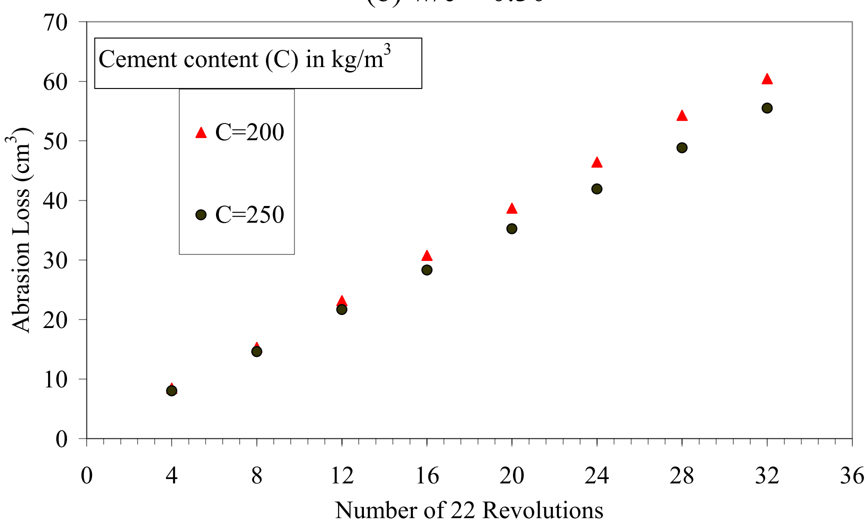
The abrasion test was performed by the Böhme equipment and procedure described in TS 2824, details of which was described in Chapter 3. In the standards the test was told to be stopped after 16*22 revolutions and the corresponding volume loss in the concrete block was to be measured at every 4*22 revolutions. However, each number of revolutions increase the time and cost of the test. In this part of the experimental program the test was continued for a total of 32*22 revolutions and the abrasion loss at every 4*22 revolutions was determined. The results of these abrasion losses are presented in Figure 4.11 for each w/c ratio group tested. As seen from Figure 4.11, the slope of the abrasion loss-number of 22 revolutions curve decreases as the cement content in the mixture increases. In other words, as the cement content increases, abrasion loss decreases (abrasion resistance increased) for each w/c ratio considered. This tendency is only disturbed by mix 13. Although, mix 13 had a higher cement content than mix 10, it showed a decrease in the abrasion resistance. It should be noted here that mix 13 had the highest water content among all the mixes cast. This reveals that, for a given w/c ratio increasing the cement content after a certain level will lead to decrease in abrasion resistance. The decrease in abrasion resistance is also closely related with the operation of the CB manufacturing equipment. Excessive increase in the water content with increasing cement content for a given w/c ratio may lead to accumulation of undesirable water at the surface with powerful vibration. This situation may reduce the degree of cementing at the surface which in turn reduces the abrasion resistance.



(a) w/c = 0.25



(b) w/c = 0.30



(c) w/c = 0.35

Figure 4.11 Abrasion Resistance Test Results of Concrete Blocks

It can also be seen from Figure 4.11 that, higher decrease in slope were observed between mix 1 and mix 4 as the cement content was increased to 250 kg/m^3 from 200 kg/m^3. As the mix was really a dry mix at 200 kg cement content level, the increase in water content associated with increase in cement content lead to rapid increase in abrasion resistance for W/C=0,25. The tendency (increase in abrasion resistance with increasing cement content) seen at W/C=0,25 was also observed for W/C=0,30 and W/C=0,35. For all mixes, the 15 cm^3 loss limit in TS 2824 after 16*22 revolutions was exceeded. It reveals that, upper surface of the CBs should be separately designed with an optimum water volume and the aggregates used at the surface should be also more abrasion resistant.

Abrasion results of commercially produced concrete blocks (RCB, CB-P) are presented in Figure 4.12. These concrete blocks were cast in two layers. The upper layer can be termed as the abrasion layer. The abrasion layer thicknesses of these concrete blocks were about 1.0 cm. As can be seen from Figure, the abrasion layer did not wear down until a predescribed 16*22 revolutions in TS 2824. As the abrasion layer wear down, the abrasion amount increased with a noticeable slope change. The pigmented mix showed a better performance than the unpigmented mix. This confirms that pigments used in the mixes may affect the abrasion resistance noticeably.

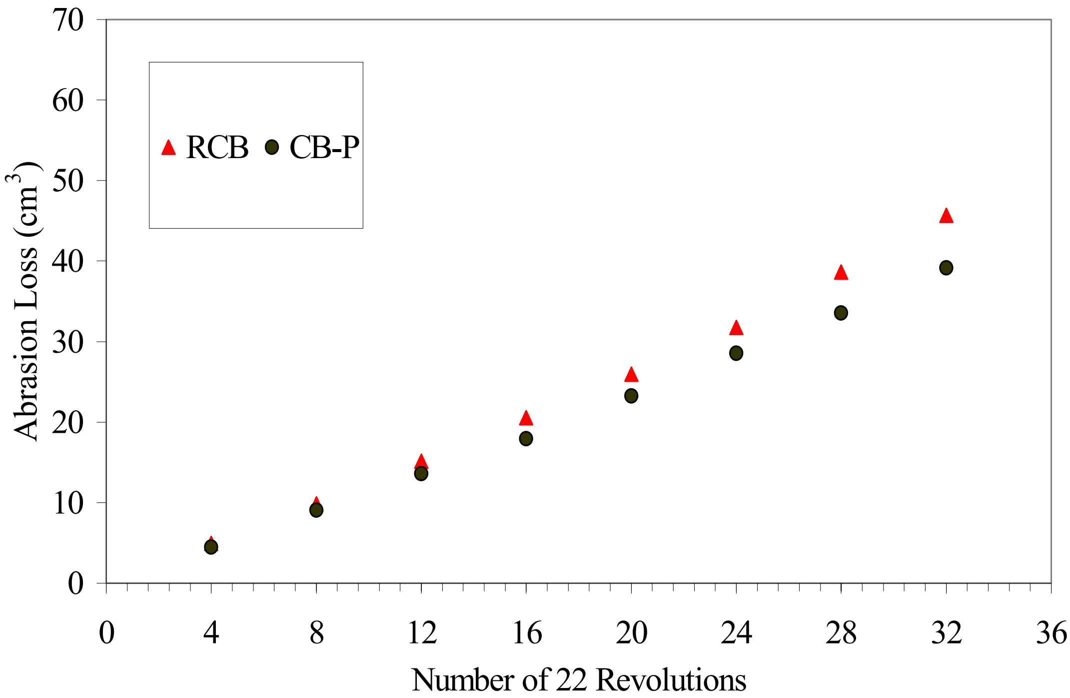


Figure 4.12 Abrasion Resistance Test Results of RCB and CB-P

As seen from the above Figures, for all the concrete blocks tested the abrasion loss linearly increased with increasing number of revolutions.

This part of the experimental study investigated the feasibility of reducing the number of revolutions of the abrasion test. In order to do this statistical analysis was performed for the abrasion loss and number of 22 revolutions test data given above such that, the slope of the linear regression line was calculated for 4, 8, 12, 16, 20, 24, 28, and 32 number of revolutions. The correlation coefficients between the number of revolutions and abrasion loss was in excess of 0.99 for all the blocks tested. As an example, the regression lines for the RCB mix are presented in Figure 4.13.

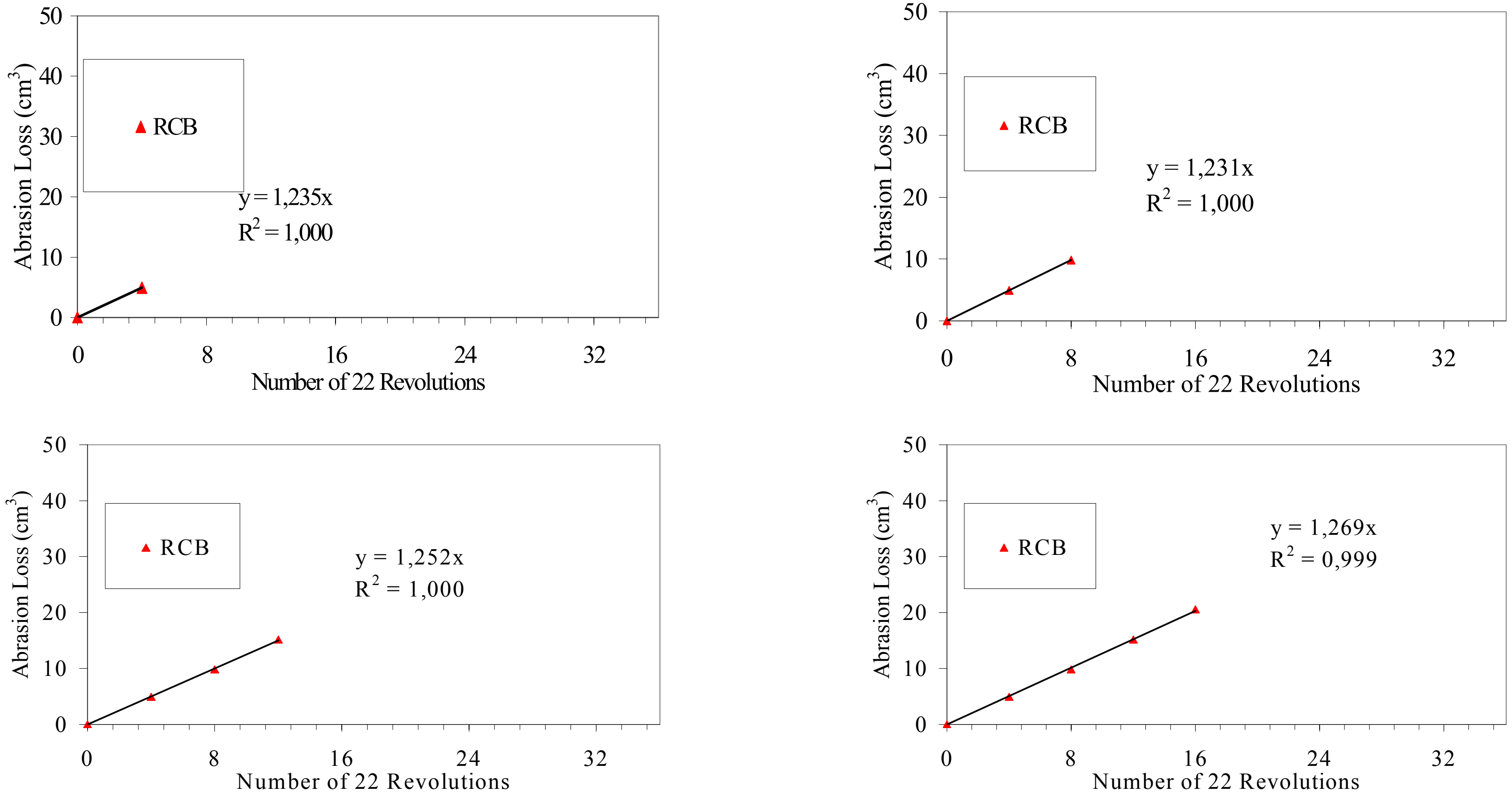


Figure 4.13 Change in Slope with Change in Number of 22 Revolutions

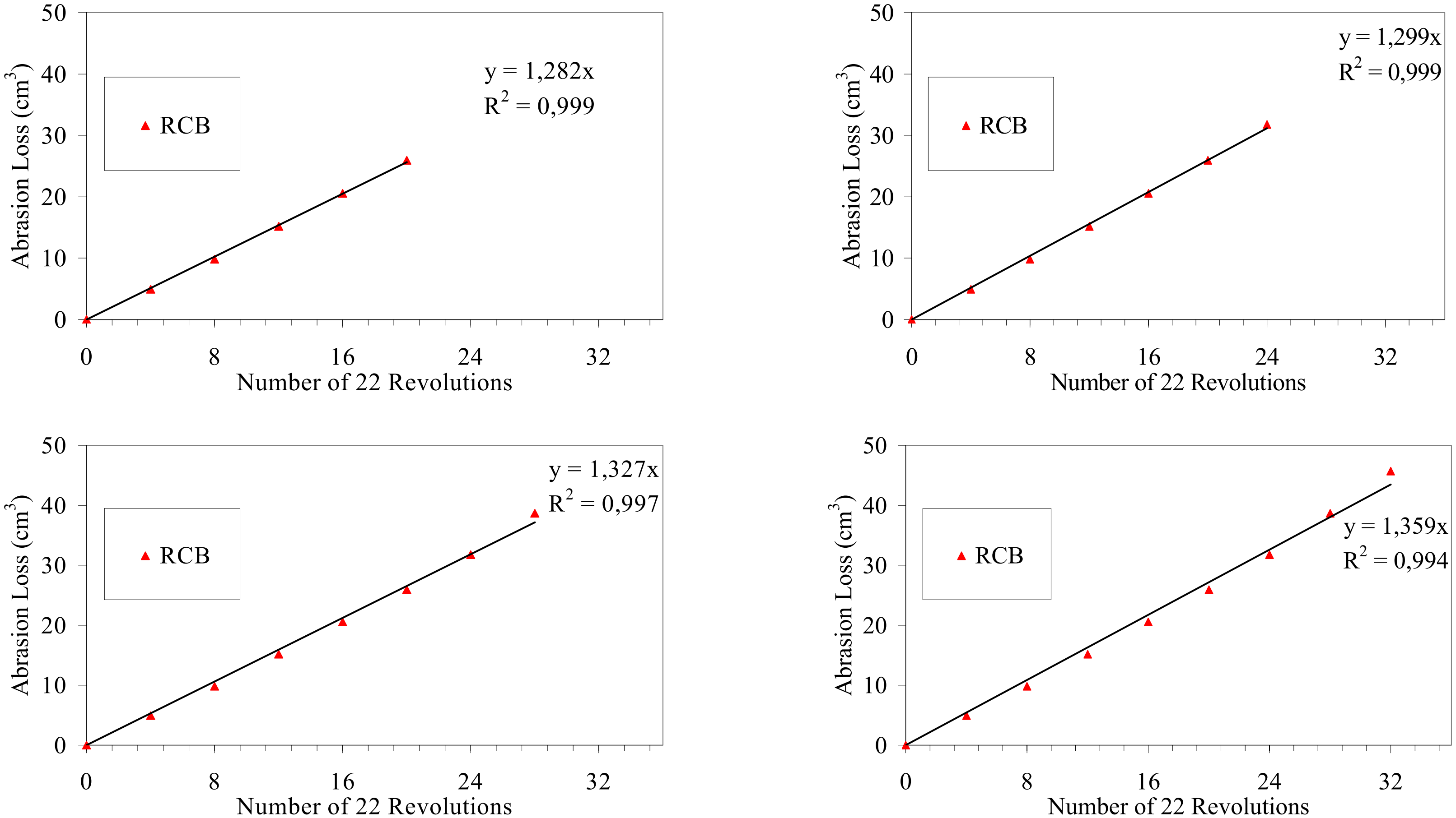


Figure 4.13 Change in Slope with Change in Number of 22 Revolutions (continued)

The calculated slopes of the regression lines for each concrete block tested is presented in Table 4.1. As seen from that table the slopes are nearly constant except for the first row. This was an indication of a soft layer formed at the surface of the concrete blocks, which might have formed by the accumulation of excessive water at the surface by powerful vibration during manufacturing. Therefore, this top layer will not represent the quality of the concrete block. However, after 8*22 revolutions the change in slope is observed to be rather small. Therefore, the relative change of slope with respect to 8*22 revolutions is calculated as shown in Table 4.2. From that table, it can be seen that the relative change of slopes was rather small in all mixes other than the deficiencies in mix 2 which might be because of an experimental error. Therefore, it can be concluded that, the test could be stopped after 8*22 revolutions. And the standard TS limit can be adjusted for 8*22 revolutions. By this change the testing time could be shortened and the cost of the testing could be reduced.

Table 4.1 Slopes of Regression Lines after Each Number of 22 Revolutions

Revolution	*Slope*											
	RCB	**CB-P**	**Mix1**	**Mix2**	**Mix3**	**Mix4**	**Mix5**	**Mix6**	**Mix7**	**Mix8**	**Mix10**	**Mix13**
After 4	1,24	1,12	2,05	1,50	2,12	1,71	1,59	2,01	1,58	1,40	1,55	1,56
After 8	1,23	1,14	1,97	1,54	1,91	1,68	1,55	1,83	1,54	1,39	1,47	1,52
After 12	1,25	1,13	1,91	1,67	1,91	1,62	1,58	1,79	1,57	1,38	1,45	1,51
After 16	1,27	1,13	1,93	1,75	1,91	1,61	1,57	1,76	1,58	1,37	1,44	1,50
After 20	1,28	1,15	1,94	1,80	1,92	1,62	1,57	1,74	1,57	1,36	1,43	1,49
After 24	1,30	1,18	1,94	1,84	1,92	1,64	1,58	1,73	1,58	1,35	1,43	1,48
After 28	1,33	1,20	1,95	1,84	1,93	1,65	1,59	1,73	1,58	1,35	1,43	1,49
After 32	1,36	1,22	1,94	1,84	1,90	1,67	1,60	1,72	1,59	1,35	1,43	1,49

Table 4.2 Relative Change of Slope with Respect to 8*22 Revolutions

Revolution	*Relative Slope*											
	RCB	**CB-P**	**Mix1**	**Mix2**	**Mix3**	**Mix4**	**Mix5**	**Mix6**	**Mix7**	**Mix8**	**Mix10**	**Mix13**
After 8	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
After 12	1,02	1,00	0,97	1,08	1,00	0,96	1,02	0,98	1,02	0,99	0,99	0,99
After 16	1,03	0,99	0,98	1,14	1,00	0,96	1,01	0,96	1,02	0,98	0,98	0,98
After 20	1,04	1,01	0,98	1,17	1,00	0,96	1,01	0,95	1,02	0,98	0,97	0,98
After 24	1,06	1,04	0,98	1,19	1,00	0,98	1,02	0,95	1,02	0,97	0,97	0,97
After 28	1,08	1,05	0,99	1,19	1,01	0,98	1,03	0,95	1,03	0,97	0,97	0,97
After 32	1,10	1,07	0,98	1,19	0,99	0,99	1,03	0,94	1,03	0,97	0,97	0,98

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

CPBs differ from other pavement materials according to their mechanical behavior. In this study, 10 mixes with different cement contents and W/C ratios and 2 mixes from a commercial CPB manufacturer were tested. The compressive strength, tensile splitting strength, abrasion resistance, density and % water absorption tests were performed on each mix at 7, 14, 28 days.

5.2 Conclusions

From the results of this study, the following conclusions can be drawn:

● For a given cement content CBs showed best performance at a specific water content called optimum moisture content. The above and below variations from that level caused decreases in strengths and density of CBs. This behavior is closely related with the way the concrete block equipment operates. As the cement content in a mix increases to obtain higher strengths, the W/C ratio should be lowered as higher water contents cause some stability and segregation problems.

● The cement content has an important role on the abrasion resistance and absorption. The abrasion losses and % Absorption generally decreased with increasing cement content for a given W/C ratio.

● The compressive strength and abrasion loss have correlation between each other. Increasing strengths have caused decrease in abrasion losses.

● From the linear regression analysis of the abrasion results, the obtained regression line showed a perfect correlation with a correlation coefficient (R^2) equal to one. And the slopes of the regression line have not showed change in slope after 8*22 revolutions. This situation has confirmed that there was no drawback to stop the test at 8*22 revolutions. The abrasion test might be stopped at 8*22 revolutions and the TS 2824 limit can be adjusted for 8*22 revolutions. Since, the abrasion test is a long time process by this change the gained time can be used to test more specimens to increase reliability of the results.

● CBs should be cast in two layers. The mix design of abrasion layer should be done separately. Higher cement contents with low W/C ratios might be needed to achieve required performance limit given in TS 2824. Furthermore, the aggregates with higher abrasion resistance might be used. The abrasion layer mix should be a rather dry mix than the lower part of the block.

● Density ,the easily determined property, seem to correlate well with all the performance parameters. Therefore it can be used as a rapid quality control parameter.

5.3 Recommendations for Future Studies

- Mix Proportioning of the CBs should be done according to block making machine intended to be used and the way it is operated.

- The consistency of such dry or semi-dry mixes can be determined by a Vebe Apparatus. This will facilitate the production of more uniform and consistent mixes.

- In this study a white portland cement (BPÇ 52.5N) were used. The effects of other cement types can also be studied.

- Savings in cement content can be achieved by studying the curing effect on CBs.

- As the pigments used for the upper part of the mix has an effect on the abrasion resistance noticeably. The effects of pigments on abrasion resistance prepared with white portland cement can be studied.

- The properties of CBs produced by other manufacturers can be determined and compared with natural stones.

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