USE OF PERLITE AS A POZZOLANIC ADDITION IN BLENDED CEMENT PRODUCTION

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USE OF PERLITE AS A POZZOLANIC ADDITION
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ABSTRACT

USE OF PERLITE AS A POZZOLANIC ADDITION IN BLENDED CEMENT PRODUCTION

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Perlite is a volcanic glass which has high amount of silica and alumina. Those properties make it a candidate, if finely ground, for being used as a pozzolan. The studies on the pozzolanic properties of perlite are very limited, and none of them has dealt with the use of perlite in the blended cement production.

The aim of this study is to investigate the pozzolanic properties of perlite, and if appropriate to investigate perlite's usability in blended cement production.

For this purpose, perlites from two different sources – Izmir and Erzincan - are used as replacement of portland cement clinker with two different percentages: 20% and 30% by weight of total cement. Then for each different composition, materials are ground with some gypsum in order obtain grinding curves for the resultant cements.

After obtaining the grinding curves, a total of 22 cements with two different finenesses are produced by intergrinding and separately grinding the materials for each composition. The obtained cements are used in paste and mortar production so that normal consistencies, setting times, autoclave expansions, and compressive strengths are determined.

Keywords: Perlite, Intergrinding, Pozzolan, Blended Cement

ÖZ

PERLITIN KATKILI ÇIMENTO ÜRETIMINDE PUZOLAN OLARAK KULLANILMASI

Meral, Çagla
Yüksek Lisans, Insaat Mühendisligi Bölümü
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Perlit yüksek oranda silika ve alumina içeren camsı özelikli volkanik bir tastır. Bu özeliklerinden dolayı, ince ögütülmüs perlitin puzolanik özelik gösterebilecegi beklenmektedir. Perlitin puzolanik özelikleri ile ilgili çalısmalar oldukça sınırlı olup hiçbiri perlitin katkılı çimento üretiminde kullanımını incelememistir.

Bu çalısmanın amacı perlitin puzolanik özeliklerini arastırmak, ve eger uygunsa perlitin katkılı çimento üretiminde kullanılabilirligini arastırmaktır.

Bu amaçla, çimento üretiminde kullanılan klinker miktarı agırlıkça %20 ve %30 oranında azaltılarak azaltılan malzemenin yerine iki degisik yöreden – Izmir ve Erzincan ‘dan - temin edilen perlit eklenmistir. Olusturulan her farklı kompozisyon bir miktar alçıtası ile ögütülerek elde edilen çimentolar için ögünme egrileri hazırlanmıstır.

Ögünme egrilerinin elde edilmesinden sonra çalısmaların devamı için iki farklı Blaine inceligi belirlenmistir. Her kompozisyon için, bu inceliklerde, beraber ve ya ayrı olarak ögtülmüs çimento hazırlanmıstır. Elde edilen 22 çimentonun tane dagılımları bulunmus, ve çimentolardan çimento hamurları ve harçları hazırlanıp normal kıvam, priz baslangıçı ve priz sonu süreleri, otoklav genlesmeleri, ve basınç dayanımları bulunmustur.

Anahtar Kelimeler: Perlit, Ögütme, Puzolan, Katkılı Çimento

To My Parents…
To My Brother …

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LIST OF ABBREVIATIONS

PC	Portland Cement
PI	Izmir Perlite
PE	Erzincan Perlite
I	Interground
S	Separately Ground
BC	Blended Cement

CHAPTER 1

INTRODUCTION

1.1. General

Concrete - made from cement, aggregate, and water - is leading among the construction materials used in civil engineering projects around the world. The reasons for concrete's domination are diverse, but among the most critical are flexibility and adaptability as proved by various types of construction in which concrete is used; low maintenance requirements during service; and the economic and widespread accessibility of concrete's constituents.

Besides cement, aggregate, and water; concrete admixtures are also incorporated into concrete mixtures to improve the behavior of concrete under a variety of conditions or to reduce the energy and materials used.

Concrete admixtures are of two main types: chemical and mineral. The chemical admixture substitution level is low. However, mineral admixture substitution level may rise up to 50% by weight of cement, or even more. Generally, pozzolanic materials that are fine or will be fine after grinding are used as mineral admixtures.

Pozzolans are defined as "Siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [1],". Volcanic tuffs, volcanic ashes and diatomaceous earths can be listed as examples of natural pozzolans; fly ashes, silica fumes, and granulated blast furnace slags may be counted as artificial materials which show pozzolanic properties.

Besides one way of obtaining pozzolanic concrete by using finely divided pozzolanic admixtures substituting some percentage of portland cement, another way to obtain such a concrete is to use blended cements, in which pozzolans are used as addition.

In producing portland - pozzolan type of cements, the amount of clinker used in producing ordinary cement is reduced and the reduced amount is substituted with pozzolan. In other words, portland – pozzolan cements are produced by intergrinding “clinker + gypsum + pozzolan” combination. These cements can also be obtained by adding some finely divided pozzolan to ordinary Portland cement and mixing them thoroughly.

1.2. Object and Scope

Perlite is a volcanic glass which has 70%-75% silica and 12%-18% alumina. Those properties make it - in finely divided form - a candidate for being used as a pozzolan. Until now, perlite has not been used commercially in the production of blended cement or pozzolan added concrete. On the other hand, Turkey has the highest amount of perlite reserves in the world (see Table 3.5).

The aim of this study was to investigate the pozzolanic properties of perlite from different places of Turkey and if appropriate, to investigate perlite’s usability in blended cement production.

For this purpose, perlites from two different sources – Izmir and Erzincan - were used as replacement of portland cement clinker with two different percentages: 20% and 30% by weight. Then for each different mix, materials were ground with some gypsum in order obtain grinding curves for the resultant cements.

After obtaining the grinding curves, cements with two different finenesses were produced by intergrinding and separately grinding the materials. A total of 22 cements were produced for paste and mortar specimens.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1. Portland Cement

Cement, for constructional purposes, can be described as the siliceous and calcareous material capable of bonding with stones, sand, bricks, or building blocks. The cements of interest in making concrete have the property of setting and hardening under water by virtue of a chemical reaction with it and are, therefore, called hydraulic cements [2].

Portland cement, whose name was originated from the resemblance of the color and quality of the hardened cement to portland stone - a limestone quarried in Dorset, England -, is described as a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulphate as an interground addition [3].

2.1.1. Manufacturing of Portland Cement Clinker and Portland Cement

The process of manufacture of portland cement clinker consists essentially of grinding the raw materials - calcareous and silica, alumina, and iron oxide bearing materials -, mixing them intimately in certain proportions and burning in a large rotary kiln at a temperature that reaches up to 1450°C where the material sinters and partially fuses into porous balls known as clinker. [4]

The temperature of the kiln should be regulated carefully; as too low temperatures cause insufficient sintering, while too high temperatures result in molten mass.

After clinkering, the hot portland cement clinker is cooled at a specially arranged rate, since the cooling rate affects the degree of crystallization and the amount of amorphous material present in the clinker. [2]

Portland cement is manufactured by intergrinding the cooled clinker, with some gypsum addition to regulate the setting time, ground to a fine powder of a particle size ranging from 1 mm to 200 μm. The resultant product has its specific gravity varying from 3.10 to 3.15. [4]

2.1.2. Chemical Composition of Portland Cement

Determining the exact chemical composition of a cement is a very complex procedure. However, a general idea of composition for portland cement can be obtained from its oxide analysis.

The amounts of oxides in PC (Portland cement) are limited within ranges; but a relatively small change in the analytical composition of cement alters the compound content in a great extend with consequent changes in the properties of cement. Table 2.1 gives typical oxide composition of portland cements.

Four compounds are typically considered as the major constituents of cements: they are listed in Table 2.2 together with their abbreviated symbols. It should not be forgotten that commercially available portland cements are rarely in pure forms.

Table 2.1. Typical Oxide Composition in Portland Cement [4]

Oxide	Content, Percent by Weight
CaO	63,6
SiO_2	20,7
Al_2O_3	6,0
Fe_2O_3	2,4
SO_3	2,1
MgO	2,6
Na_2O	0,1
K_2O	0,9

Table 2.2. Main Compounds of Portland Cement [2]

Name of compound	Chemical Formula	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium alumino ferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

2.1.3. Hydration of Portland Cement

The series of the reaction of cement with water that causes setting and hardening of concrete is referred as hydration. In these series of chemical reactions, the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products which in time produce a rigid and hard mass - the hardened cement paste -.

It is assumed that the hydration of each cement compound takes place independently of the others that are present in portland cement. This assumption is not completely valid due to the interactions between hydrating compounds, but in most cases reasonable [20]. A basic view of the behavior and hydration of the four major compounds are explained below to provide an idea about the composition of the hydrated products.

The key strength-giving compounds are the calcium silicates (C_3S and C_2S) which react with water to produce calcium silicate hydrate gel (archaically called tobermorite gel after a naturally occurring mineral), and calcium hydroxide (commercially known as lime). The hydration reaction of the two calcium silicates that make up the largest percent of PC, are similar. However, tricalcium silicate hydrates and hardens rapidly to provide high early strengths, while the reaction of dicalcium silicate is far slower, at ages beyond one week. Calcium silicates hydrate as follows [4]:

$$\underset{\substack{\text{Tricalcium}\\ \text{Silicate}}}{2C_3S} + \underset{\text{Water}}{6H} \rightarrow \underset{\text{C-S-H Gel}}{C_3S_2H_3} + \underset{\substack{\text{Calcium}\\ \text{Hydroxide}}}{3CH}$$

$$\underset{\substack{\text{Dicalcium}\\ \text{Silicate}}}{2C_2S} + \underset{\text{Water}}{4H} \rightarrow \underset{\text{C-S-H Gel}}{C_3S_2H_3} + \underset{\substack{\text{Calcium}\\ \text{Hydroxide}}}{CH}$$

The calcium silicate hydrate (C-S-H) gel represents a high percent of the total solids in a fully hydrated cement system. However, its exact chemical composition is variable. The ratio of C/S in the gel varies between 1.5 and 2, and depends on many factors such as temperature, water-cement ratio, and impurities. [2]

Due to its poorly crystalline structure, C-S-H develops tiny irregular particles and accordingly a very high surface area. The surface area of C-S-H which is far larger than the unhydrated cement greatly influences physical properties of the C-S-H. [2, 12]

In the hardened paste, the tiny C-S-H particles grow forcing the adjacent particles like the remaining unhydrated cement grains and aggregates to interlock to form dense, bonded aggregations. The development of this structure is the paste's cementing action and is responsible for the engineering properties of concrete –setting and hardening, and strength development –.

The calcium hydroxide (CH) - formed after the hydration reactions - has thin hexagonal crystalline plates, that later on merges into a massive deposit. CH adds little to the cementitious properties of the system. [2]

The next cement compound of particular importance is tricalcium aluminate. Although the average C_3A content is about 4-11%, it significantly influences the early reactions. The hydration reaction of C_3A with water is very rapid, but does not contribute to the ultimate strength of cement considerably. [2, 4, 21]

The hydration of C_3A occurs with sulfate ions supplied by the dissolved gypsum. The primary result of the reaction is called "ettringite" after a naturally occurring mineral of the same composition. The formation reaction for the hexagonally-shaped prism crystals of ettringite which causes great expansion in volume is shown below [4]:

$$\begin{array}{ccccccc} C_3A & + & 3C\overline{S}H_2 & + & 26H & \rightarrow & C_6A\overline{S}_3H_{32} \\ \text{Tricalcium} & & \text{Gypsum} & & \text{Water} & & \text{Ettringite} \\ \text{Aluminate} & & & & & & \end{array}$$

If the sulfate supply from the gypsum is consumed entirely before the C_3A is completely hydrated, a second reaction may occur to form another calcium sulfoaluminate hydrate containing fewer sulfates [4]:

$$\begin{array}{ccccccc}
2C_3A & + & C_6A\overline{S}_3H_{32} & + & 4H & \rightarrow & 3C_4A\overline{S}H_{12} \\
\text{Tricalcium} & & \text{Ettringite} & & \text{Water} & & \text{Calcium Alumino} \\
\text{Aluminate} & & & & & & \text{Monosulfo Hydrate}
\end{array}$$

The product of this reaction is calcium alumino monosulfo hydrate. This reaction may even occur before the formation of the ettringite, if the reaction of C_3A and the sulfate ions is faster than the gypsum will allow. The $C_4A\overline{S}H_{12}$ is not a stable product; and if exposed to another source of sulfate ions, a new reaction will occur forming more ettringite. [21] This new formation causes volume increase and leads to tensile cracking which brings about the reduction of the resistance to the sulfate attack of PC.

In the absence of sulfates, C_3A reacts with water to form two unstable calcium hydrates which later convert to hydrogarnet that can lead to flash set.

$$\begin{array}{ccccccc}
C_3A & + & 21H & \rightarrow & C_4AH_{13} & + & C_2AH_8 \\
\text{Tricalcium} & & \text{Water} & & \multicolumn{3}{c}{\text{Calcium Alumino Hydrates}} \\
\text{Aluminate} & & & & & &
\end{array}$$

$$\begin{array}{ccccccc}
C_4AH_{13} & + & C_2AH_8 & \rightarrow & 2C_3AH_6 & + & 9H \\
\multicolumn{3}{c}{\text{Calcium Hydrates}} & & \text{Hydrogarnet} & & \text{Water}
\end{array}$$

The hydration of C_4AF yields the same sequence of products as the hydration of C_3A; however, the reactions are much slower in the presence of gypsum. In other words, gypsum retards the hydration of C_4AF more efficiently than it does C_3A. During hydration, iron oxide substitutes partially for alumina in the crystal structure of ettringite and $C_4A\overline{S}H_{12}$:

$$\underset{\substack{\text{Tetracalcium}\\ \text{Aluminoferrite}}}{C_4AF} + \underset{\text{Gypsum}}{3C\overline{S}H_2} + \underset{\text{Water}}{21H} \rightarrow \underset{\substack{\text{Calcium}\\ \text{Trisulfo}\\ \text{Aluminate}}}{C_6(A,F)\overline{S}_3H_{32}} + \underset{\substack{\text{(Iron,Aluminium)}\\ \text{Hydroxide}}}{(A,F)H_3}$$

If the sulfate is all consumed:

$$\underset{\substack{\text{Tetracalicum}\\ \text{Aluminoferrite}}}{C_4AF} + \underset{\substack{\text{Calcium}\\ \text{Trisulfo}\\ \text{Aluminate}}}{C_6(A,F)\overline{S}_3H_{32}} + \underset{\text{Water}}{7H} \rightarrow \underset{\substack{\text{Calcium}\\ \text{Monosulfo}\\ \text{Aluminate}}}{3C_4(A,F)\overline{S}H_{12}} + \underset{\substack{\text{(Iron,Aluminium)}\\ \text{Hydroxide}}}{(A,F)H_3}$$

2.1.4. Properties of Portland Cement

2.1.4.1. Fineness

Fineness is a measure of particle size of cement. There are several methods to measure cement fineness:

- ASTM C 115: Standard Test Method for Fineness of portland Cement by the Turbidimeter [7]
- ASTM C 786: Standard Test Method for Fineness of Hydraulic Cement and Raw Materials by the 300-µm (No. 50), 150-µm (No. 100), and 75-µm (No. 200) Sieves by Wet Methods [8]
- ASTM C 204: Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus [9]
- ASTM C 430: Standard Test Method for Fineness of Hydraulic Cement by the 45-µm (No. 325) Sieve [10]

Fineness of the produced cements are generally evaluated by Blaine surface area, amount retained on 45-µm sieve or by determining particle size distribution with laser diffraction. Blaine air permeability method may cause misleading values especially for porous materials [56]. Moreover, in this method, only the continuous paths through the bed of cement contribute to the measured surface area [2].

On the other hand, determination of the amount material retained on 45-µm sieve may be insufficient to evaluate the fineness since this method provides only a single value and supplies no information on the size of grains smaller than 45-µm [2]. A more informative method is the determination of particle size distribution by laser diffraction. However, this technique is based on volumetric measurements and it is difficult to compare the data with conventional sieve analysis.

Fineness of PC affects the rate of hydration and thus the rate of strength gain. The surface area-to-volume ratio, and therefore the area available for water-cement interaction per unit volume rise with the increase in the cement fineness. The effects of greater fineness on strength are generally seen during the first seven days. [6]

2.1.4.2. Setting Time

The stiffening of the cement paste (cement + water) is called setting. The time starting from the mixing of cement and water until the cement paste sets is called the setting time. [12] Setting time of cement pastes is affected by several factors such as cement fineness, water-cement ratio, and chemical content. There are two important setting times defined [5]: initial setting (time length when the paste begins to stiffen considerably), and final setting (time length when the cement has hardened to the point at which it can sustain some load).

The cement paste is only shapeable during setting time. Thus, the initial setting time must be long enough, and the final setting time must be short enough. The standard setting time tests are:

- ASTM C 191: Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle [13]
- ASTM C 266: Standard Test Method for Time of Setting of Hydraulic-Cement Paste by Gillmore Needles [14]

2.1.4.3. Soundness

When referring to portland cement, "soundness" refers to the ability of a hardened cement paste to retain its volume after setting without undergoing delayed destructive expansion. This expansion is caused by slow hydration (or other reaction) of some compounds present in the hardened cement such as excessive amounts of free lime (CaO) or magnesia (MgO) [2]

According to the typical expansion test, a small bar of cement paste is placed into an autoclave. The autoclave is slowly brought around 2 MPa, and then kept at that pressure for 3 hours. The autoclave is then slowly brought back to room temperature and atmospheric pressure. The change in specimen length due to its time in the autoclave is measured and reported as a percentage. The standard autoclave expansion test is:

- ASTM C 151: Standard Test Method for Autoclave Expansion of portland Cement [11]

Another soundness test is Le Chatelier Test, which is also described in Turkish Standards (TS 24).

2.1.4.4. Strength

Strength tests for cement are carried on mortar specimens. According to the ASTM standards, cement mortar is prepared by mixing 1 part cement, 2.75 parts standard sand proportioned by weight with enough water to obtain a flow od 110 ± 5 in 25 drops of the flow [15]. (European Standards require a different combination of these materials)

The strength of cement mortar is typically defined in three ways: compressive, tensile and flexural. There are several factors affecting these strengths including: water-cement ratio, cement-fine aggregate ratio, type and grading of fine aggregate, method of mixing and moulding specimens, curing conditions, size and shape of specimen, moisture content during the time of test, loading conditions and age [4].

Since cement gains strength over time, the time at which a strength test is conducted must be specified. Typical times are 1 day, 3 days, 7 days, 28 days and 90 days. It should be considered that the strength tests on cement mortars are not directly related to concrete strength, however, are typically used as quality control measure. [5]

2.1.4.4.1. Compressive Strength

Compressive strength is the most common strength test. According to ASTM standards, the test is carried out on a 50 mm cement mortar test specimen that is subjected to a compressive load until failure. The maximum load must be reached in not less than 20 seconds and no more than 80 seconds. The standard cement mortar compressive strength test is:

- ASTM C 109: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [15]

2.1.4.4.2. Tensile Strength

The direct tension test does not provide any useful insight into the concrete-making properties of cements. However, it was still specified by ASTM C 190,”Method of Test for Tensile Strength of Hydraulic Cement Mortars,” until 1990 mainly due to being used as the most common test in the early years of cement since it was difficult to find machines that could compress a cement sample to failure. [5]

2.1.4.4.3. Flexural Strength

Flexural strength is a measure of tensile strength in bending. The test for flexural strength is carried out on a 40 x 40 x 160 mm cement mortar that is loaded at its center point until failure. The standard cement mortar flexural strength test is:

- ASTM C 348: Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars [16]

2.1.4.5. Specific Gravity

The specific gravity of portland cement is generally around 3.15. The specific gravities of portland-blast-furnace-slag and portland-pozzolan cements may be as low as 2.90. [5] The standard specific gravity test is:

- ASTM C 188: Standard Test Method for Density of Hydraulic Cement [17]

2.1.4.6. Heat of hydration

The hydration reaction of portland cement is exothermic. The heat generated during the hydration reaction is called heat of hydration. Heat of hydration is influenced by several factors. Among the most important, chemical composition and fineness of cement, water-cement ratio, curing temperature, and time can be listed. The rate of heat generation is significantly rapid in large mass concrete structures than it can be dissipated, which can create high temperatures in the inner parts of these large concrete masses that, in turn, may cause undesirable thermal stresses as the concrete cools to ambient temperature. On the other hand, high heat of hydration can help maintain favorable curing temperatures during cold weathers. [5] The standard heat of hydration test is:

- ASTM C 186: Standard Test Method for Heat of Hydration of Hydraulic Cement [18]

2.1.4.7. Loss on ignition

Loss on ignition determined by the weight loss of a sample after heating up a cement sample to a degree until a constant weight is obtained. A high loss on ignition generally indicates prehydration and carbonation, which may be caused by improper storage or transportation. [5] The standard loss on ignition test is contained in:

- ASTM C 114: Standard Test Methods for Chemical Analysis of Hydraulic Cement [19]

2.1.4.8. Insoluble Residue

The insoluble residue which is determined by treating the cement with hydrochloric acid is a measure of adulteration of cement. [1] The standard insoluble residue test is contained in:

- ASTM C 114: Standard Test Methods for Chemical Analysis of Hydraulic Cement [19]

2.2. Pozzolans

As previously defined in Section 1.1, pozzolans are siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value. However, when they are in a finely divided form, they chemically react with calcium Hydroxide in the presence of moisture. Thus, they possess cementitious properties.

All siliceous and aluminous materials are not pozzolanic, and the separation line between siliceous materials that are considered as pozzolans and those are not is not clear. However; crystalline minerals, like silica as quartz, alumina as corundum, and aluminosilicates as sillimanite (SA), and mullite (S_3A_2) are not lime combining materials at room temperature. Generally, siliceous and aluminous materials may show pozzolanic properties if they are finely grinded and in amorphous form. Thus, the chemical composition of a pozzolan does not clearly determine its ability to combine with calcium hydroxide and alkalies.

The actual improvement imparted by a particular pozzolanic material to a particular concrete mixture is strongly dependent on not only the chemical composition, but also physical and mineralogical properties of the pozzolan, which vary significantly both within and between the different types of material. Also for pozzolans to be used as a substitute for portland cement they would have to be cheap, easily accessible and available in large quantities.

2.2.1. Classification of Pozzolans

Pozzolans are mainly classified into two groups according to their origins as natural and artificial.

Natural pozzolans are naturally occurring volcanic origin materials such as some diatomaceous earths; opaline cherts and shales; tuffs and volcanic ashes or pumicites, any of which may or may not be processed by calcination; and various materials requiring calcinations to induce satisfactory properties, such as some clays and shales [6]. During calcination, which may occur naturally or may need to be carried out as part of a processing operation, the clay minerals decompose to form an amorphous or disordered aluminosilicate structure that reacts willingly with lime at ordinary temperatures. Natural pozzolans usually require grinding to cement fineness in order to be used in cements.

Raw or processed natural pozzolans have been used by mankind for construction purposes for thousands of years. Mortars and concretes using a mixture of lime and a natural pozzolan - typically a volcanic ash or tuff - were developed and used by the Greeks (700-600 BC), and later the Romans (150 BC), to build durable, water-containing structures such as aqueducts and water storage tanks. In fact, the name pozzolan comes from the town of Pozzouli in Italy where more than 2000 years ago the ancient Romans had produced a hydraulic binder by mixing lime with volcanic soil.

The latter type is the artificial pozzolans that are obtained as industrial by-products. Fly ashes (fine solid particles of ashes carried out from burning coal in power plants), silica fumes (finely divided by-products obtained in manufacturing of silicon metal or silicon alloys), and granulated blast furnace slags (by-products generated by the rapid cooling of non-ferrous substances in iron ores that are separated from the hot metal in a blast furnace) are the most common examples of artificial pozzolans. [12]

Turkey has large deposits of natural pozzolans which are widely used in the cement industry, and has a handful of industrial facilities that produce artificial pozzolans as by-products.

There is no unique detailed classification for pozzolanic materials. The classification chart according to the source of materials made by Massazza [24] is shown in Figure 2.1 to have a better understanding of pozzolans.

Pyroclastic sediments are formed by explosive breakage of magma during eruptions of varying degrees of violence. These processes involve the explosive release of gases from viscous magmas, producing an eruption column above the volcano. The rapid quenching of the explosive or aerial ejection of magma results in a glassy material containing entrapped air bubbles. The word pyroclastic is a combination of "pyro" meaning fire, and "clastic" meaning being made up of many pieces.

A pyroclastic deposit is the resulting layer or pile of material that has fallen to the ground by one or many pyroclastic eruptions. A pyroclastic rock is the hardened, solidified, or compressed version of an originally loose pyroclastic deposit. Rheinish trass of Germany as a coherent pyroclastic rock, and santorin earth of Greece as an incoherent pyroclastic rock are well known examples of pyroclastic pozzolans.

Clastic rocks are consolidated sedimentary rocks made up of broken fragments derived from pre-existing rocks. These fragments, which have been formed during chemical weathering of rocks, and have been transported mechanically to their places of deposition, may have originally been from igneous rocks, metamorphic rocks, or even other sedimentary rocks. Diatomaceous earth is a clastic pozzolan.

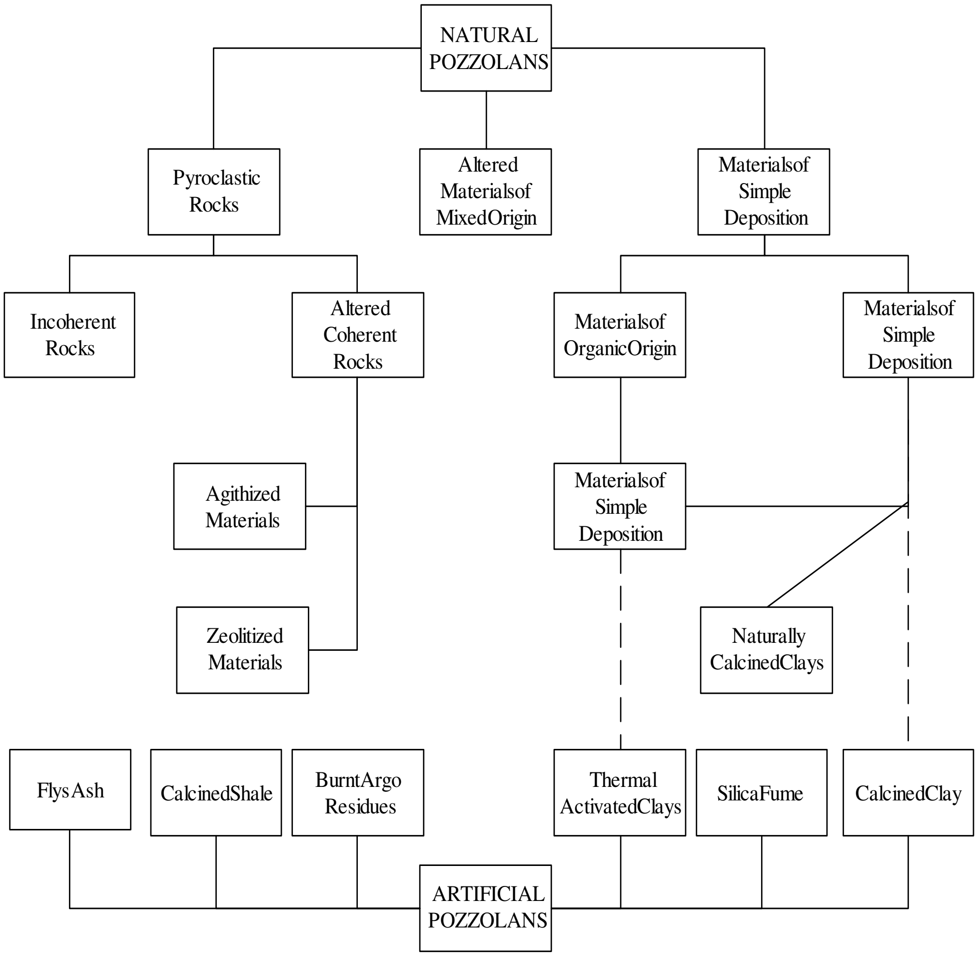

Figure 2.1. Classification of Pozzolanic Materials According to Massazza [24]

The pozzolans of mixed origin include the materials that were formed by various methods at the same time. Pyroclastic, clastic and organic origin materials may be found in layers in this type of pozzolanic rocks [25]. Some of the most common natural pozzolans and their chemical compositions are given in Table 2.3. [25]

Table 2.3. Chemical Compositions of Some Natural Pozzolans [25]

	Pozzolan	Country	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	LOI**
Incoherent Pyroclastic	Santorin Earth	Greece	65.10	12.50	5.50	3.00	1.10	-	-	-	-	3.50
	Bacolis	Italy	53.8	18.20	4.29	9.05	1.23	3.08	7.61	-	0.65	3.05
	Auvergne	France	46.60	17.60	11.80	9.84	5.58	3.14	1.76	-	0.02	0.24
	Kula	Turkey	48.52	17.49	7.80	7.84	1.41	5.20	3.10	2.02	0.29	1.75
	Salone	Italy	46.84	18.44	10.25	8.52	4.75	1.02	6.35	0.06	-	3.82
	Vizzini	Italy	50.48	16.77	11.59	4.86	5.24	0.87	0.17	0.08	0.15	9.68
	Volvic	France	54.30	16.80	-	-	-	4.47	2.60	-	-	-
Coherent Pyroclastic	Rhenish Trass	Germany	52.12	18.29*	5.81	4.94	1.20	1.48	5.06	-	-	11.10
	Trass	Indonesia	60.02	17.16	6.80	4.49	0.96	3.88	2.62	-	-	2.60
	Yellow Tuff	Italy	54.68	27.70	3.82	3.66	0.95	3.43	6.38	-	-	9.11
Clastic	Diatomaceous Earth	USA	60.04	16.30	5.80	0.92	2.29	-	-	-	-	11.93
	Diatomaceous Earth	Turkey (Ankara)	88.32	3.47	0.48	0.42	0.26	0.17	0.28	0.18	-	5.84
	Diatomaceous Earth	Turkey	84.24	4.75	0.91	0.94	0.26	0.15	0.25	-	0.09	8.47
Materials of Mixed Origin	Sacrofano	Italy	89.22	3.05	0.77	2.28	-	-	-	-	-	4.67
Materials of Organic Origin	Washington State	USA	85.97	2.30	1.84	-	0.61	0.21	0.21	-	-	n/s
Naturally Burned Clays	Porcellanite	Trinidad	56.79	25.79	7.61	0.06	0.28	0.10	0.42	-	0.57	7.60

(*) $Al_2O_3 + TiO_2$ (**) Loss on Ignition

2.2.2. Pozzolanic Activity

Pozzolanic activity refers to the capacity and velocity of the reaction between aluminosilicates in pozzolan and CH to form cementitious products. [21,26] The activity of pozzolans is not understood well due to the heterogeneous structure of pozzolans and complex nature of the hydration [26]; however, major factors that affect its activity can be listed as follows [21]:

i. The activity of a pozzolan is greater as its content of "SiO2 + Al2O3 + Fe2O3" or the amount of reactive material is higher.
ii. In order to be chemically reactive, the pozzolanic material must have an amorphous structure.
iii. The pozzolanic particles should be sufficiently fine to react with CH.

For a pozzolan, its activity is mainly depended on the surface area for short terms, and on chemical and mineralogical composition for longer terms. [26] There are several test methods recommended for the determination of pozzolanic activity which may be grouped as chemical, physical (such as quantitative XRD), and mechanical tests, however, none of these tests is considered completely satisfactory. [26]

The pozzolanic activity of a natural pozzolan or fly ash is determined by finding its strength activity index, which is the ratio of the mortar cube compressive strength of test specimens prepared by 20% pozzolan – 80% PC mixture to control specimens prepared by 100% PC according to ASTM C 311 [27]. The tests on the mortar cubes may be conducted at either 7-day or 28-day or both. Strength activity index is calculated as follows [12]:

Strength activity index (SAI) = (A/B) x 100

where:

A = Average compressive strength of test mixture cubes, and
B = Average compressive strength of control mixture cubes.

According to ASTM C 618, SAI should be at least 75. The main deficiency of this mechanical test is the low early strength gain rates of the test specimens, but still this method is the most meaningful one from the end users point of view. The standard tests on pozzolans are listed below:

- ASTM C 618: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete [1]
- ASTM C 311: Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in portland-Cement Concrete [27]
- ASTM C 593: Standard Specification for Fly Ash and Other Pozzolans for Use With Lime [28]

2.2.3. Pozzolanic Reaction

The chemical reactions of finely divided pozzolans with CH under moist conditions are called the pozzolanic reaction. The reaction of PC and pozzolan progresses like an acid-base reaction of lime and alkalies with oxides (SiO_2, Al_2O_3, and Fe_2O_3) of the pozzolan [31]. The main chemical reaction that takes place between the silica of pozzolan and CH can be shown as below:

$$\text{Calcium Hydroxide} + \text{Silica} + \text{Water} \rightarrow \text{C-S-H} + \ldots.$$

This reaction will result in both a decrease in the amount of free CH (Figure 2.2), and an increase in the amount of C-S-H and other products of low porosity [31].

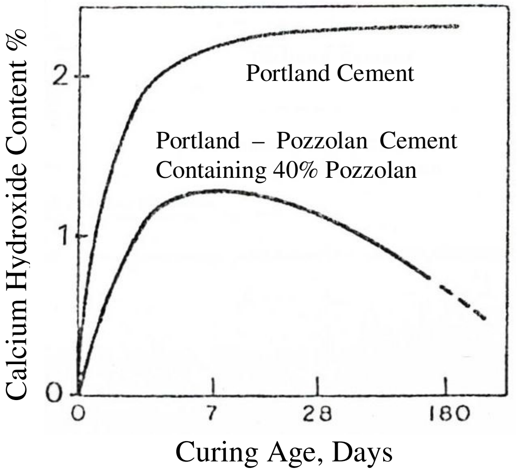

Figure 2.2. Changes in Calcium Hydroxide Content of Hydrating portland - Pozzolan Cement [31]

This is where the role of complementary cementing materials becomes significant through the formation of microporous secondary mineralogical hydrates around these particles, tending to fill the large capillary pores. This mechanism, during which large pores slowly get transformed into microporous products containing numerous fine pores, is known as “pore-size refinement”.

2.2.4. Portland-Pozzolan Cements

Portland-pozzolans cements are described as a hydraulic cement consisting of an intimate and uniform blend of portland or portland blast-furnace slag cement and fine pozzolan produced either by intergrinding portland cement clinker and pozzolan, by blending portland cement or portland blast-furnace slag cement and finely divided pozzolan, or a combination between intergrinding and blending, in which the pozzolan constituent is between 15-40% in ASTM C 595 [22].

2.2.5. Effects of Pozzolans on Cement Based Systems

Pozzolans are added to mortar mixes mainly to advance workability, resistance to water penetration and resistance to chemical attacks. Using natural pozzolans in cement based systems affects some other major properties such as water requirement, time of setting, heat of hydration, bleeding, strength, permeability, alkali-silica reactivity, and even unit cost. [12]

The use of finely divided pozzolans generally increase water requirement which can be surmounted by addition of water reducing admixtures. However, some pozzolanic materials may have little or no effect on water requirement, and others may decrease the water requirement of concrete. [31] The shape of the added fine mineral particle plays an important role in the water requirement. Minerals with unfavourable shapes with too high surface area generally have high water demands. [31]

The workability of the cement mixture is improved by the addition of pozzolanic materials due to the increase in both the paste volume-since generally pozzolans are lighter than portland cement- and the amount of fine materials which augments the mobility of the aggregate in concrete resulting in a plasticising effect. [4, 12, 31]

The replacement of cement with natural Pozzolans slightly increases the setting time of the resultant concrete. The delay depends on the type and amount of the Pozzolan added. [4, 12]

The deficient fine particles, particularly which can pass through 75µm sieve, in the available concrete aggregates can be supplied by the use of finely divided pozzolans; so that bleeding and segregation will be reduced, and the strength of the concrete will be increased. The rise in the ratio of surface area of solids to volume of water by the addition of pozzolans also lowers bleeding. [12, 31]

The heat evolved during hydration of pozzolanic concretes is generally lower because of the partial replacement of portland cement with pozzolan. In fact the pozzolanic reaction evolves some heat. However, the reaction rate is much slower than rate of hydration of portland cement. The slow reaction rate also lengthens the setting time for pozzolanic concrete. [4, 12]

Concretes containing pozzolanic materials normally have lower strengths at early ages and at least same or higher strengths for later ages. The strength development related with pozzolan is mainly the result of chemical interaction between the natural Pozzolan and portland cement during hydration. Besides, the pozzolanic concrete requires longer curing periods than ordinary portland cement concretes. [12, 31]

2.2.6. Uses of Pozzolans

A pozzolan is used in three ways to produce a binding effect [21]:

i. Directly by mixing pozzolan with calcium hydroxide,
ii. By intergrinding PC clinker with some gypsum and pozzolan (as an additive) to produce portland-pozzolan cements,
iii. By separately grinding the pozzolan and then mixing the ground material (as an admixture) into the concrete mixture during or before the batching operation of concrete.

Directly mixing pozzolan with calcium hydroxide is not a common application at the present time, though this procedure was extensively used in ancient times. Nowadays, this method is used only in the production of lime-pozzolan mixtures for pavement subbases or for some small applications [21]. On the other hand, using pozzolan as an addition or as an admixture are very common [26].

Using pozzolan as an addition during intergrinding, to produce portland-pozzolan cements, guarantees more homogeneous cement. However, it is more difficult to control the particle size distribution, since the grindabilities of the pozzolan and PC clinker are different from each other. Generally, the pozzolan is softer than PC clinker, which results in a finer gradation in the produced cement [25]. A better controlled particle size distribution can be obtained by using the pozzolan as an admixture. The main problem of this method is producing a homogeneous mixture, which can be eliminated by installing proper equipments in the factories. In Turkey, although using pozzolan as an admixture brings generally about better performance of cements, using pozzolan as an addition is preferred mainly due to the higher investment cost of the installing required equipments [26].

While using pozzolan in cements, the specifications for blended portland cements should also be considered. Accordance to standards can be determined using either prescriptive or performance specifications. A prescriptive specification gives chemical or physical requirements that are not directly related to performance, whereas a performance specification sets limits for physical test results only. [29]

The main advantage of prescriptive specifications is them providing well-defined means for the manufacturer to demonstrate compliance with chemical composition, but this advantage is a limiting factor on the options of cement manufacturers by restricting the use of constituent materials, and thus acts like a barrier to innovation. On the other hand, compliance with performance specifications allows the use of different constituent materials. However, it is more sensitive to the test methods used to predict performance. [29]

ASTM C 595 Standard Specification for Blended Hydraulic Cements [22], which has prescriptive, and performance elements, limits the maximum pozzolan constituent by 40 mass % of the portland-pozzolan cement, and prescribes ingredients and proportions. On the other hand, ASTM C 1157 Standard Performance Specification for Hydraulic Cement [30] is a performance-only standard, which limits neither the content nor the type of the blended components in the cement. The standard physical requirements, the types of hydraulic cements, and the strength range limits according to ASTM C 1157 are given in Tables 2.4, 2.5 and 2.6 respectively.

Table 2.4. Types of Hydraulic Cements According to ASTM C 1157

Cement Type	Description
Type GU	Hydraulic cement for general construction
Type HE	High early strength
Type MS	Moderate sulfate resistance
Type HS	High sulfate resistance
Type MH	Moderate heat of hydration
Type LH	Low heat of hydration

Table 2.5. Strength Range Limits

Strength Range	5	10	17	25	35	45
Compressive Strength, min, Mpa	5	10	17	25	35	45
Compressive Strength, max, Mpa	15	20	30	40	60	…

Table 2.4: Standard Physical Requirements of ASTM C 1157[30]

Cement Type	GU	HE	MS	HS	MH	LH
Fineness	A	A	A	A	A	A
Autoclave Length Change, max, %	0.80	0.80	0.80	0.80	0.80	0.80
Time of Setting, Vicat Test[B]						
Initial, not less than, min	45	45	45	45	45	45
Initial, not more than, min	420	420	420	420	420	420
Air Content of Mortar Volume, %	C					
Strength Range[D]						
1 day	---	10	---	---	---	---
3 days	10	17	10	5	5	---
7 days	17	---	17	10	10	5
28 days	---	---	---		---	17
Heat of Hydration						
7 days, max, kJ/kg (kcal/kg)	---	---	---	---	290 (70)	250 (60)
28 days, max, kJ/kg (kcal/kg)	---	---	---	---	---	290 (70)
Mortar Bar Expansion						
14 days, % max	0.020	0.020	0.020	0.020	0.020	0.020
Sulfate Expansion (Sulfate Resistance)[E]						
6 months, max, %	---	---	0.10	0.05	---	---
1 year, max, %	---	---	---	0.10	---	---
Option R- Low Reactivity with Alkali-Reactive Aggregates[F]						
Expansion						
14 days, max, %	0.020	0.020	0.020	0.020	0.020	0.020
56 days, max, %	0.060	0.060	0.060	0.060	0.060	0.060
Optional Physical Requirements						
Early Stiffening, Final Penetration, min, %	50	50	50	50	50	50
Compressive Strength,[G] min, MPa (psi), 28 days	28.0 (4060)	---	28.0 (4060)	---	22.0 (3190)	---

[A] Both amount retained when wet sieved on the 45-µm (No. 325) sieve and specific surface area by air permeability apparatus in m^2/kg shall be reported on all certificates of test results requested from the manufacturer

[B] Time of setting refers to initial setting time in Test Method C 191

[C] Air content shall be reported on all certificates of test results requested from the manufacturer. A given value in mortar does not necessarily assure that the desired air content will be obtained in concrete.

[D] Lowest Strength Range whose minimum shall apply at the specified age unless a higher Strength Range is specified by the purchaser. See Table 2.6 for the applicable strength limits.

[E] In the testing of HS cement, testing at one year shall not be required when the cement meets the 6 month limit. An HS cement failing the 6 month limit shall not be rejected unless it also fails the one year limit.

[F] Compliance with this requirement shall not be requested unless the cement will be used with alkali-reactive aggregate.

[G] When 28-day strengths are specified, sufficient time must be allowed for completion of the test. When required on a certificate of test results, special arrangements shall be made for storage of the cement pending completion of the test.

2.3. Grinding

The cement industry consumes about 2% of the global primary energy production which is almost 5% of the total industrial energy consumption (International Energy Agency). The industry has been accused of wasteful energy use due to low efficiency processes that it employs, such as burning, cooling and especially grinding [26].

Table 2.7 shows the distribution of the total electrical energy consumption during cement production; as seen 62% of the total electrical energy is consumed for grinding raw materials and clinker.

Table 2.7. The Total Electrical Energy Consumption during the Production of Cement [32]

Process	Electrical Energy Consumption (%)
Management	5
Grinding raw materials	*24*
Mixing raw materials	6
Producing and cooling clinker	22
Grinding clinker	*38*
Packaging, loading, transportation	5
Total	100

Several variables can affect the efficiency and productivity of grinding circuit such as operating conditions of separators, air flow through the mill, ball sizes and ratio in the mill compartments, material filling, and speed of rotation.

In Turkey, 35 million tones of cement is produced annually from more than 100 grinding circuits, and the production rate is increasing. The grinding circuits available are very complex; and the processing units include vertical roller mills, high pressure grinding rolls, tube mills, horomills and air separators [33].

In most of the factories, ball mills are used for the fine grinding of portland cement clinker. The ball mill consists of a cylindrical drum, sometimes tapered at one end, and has a charge of steel balls (up to 40% by volume) ranging in size. Ball mills reduce material to particle size by the abrasive effect of steel balls or cylpebses during the rotation of the grinder. The product size obtained can be as small as 5μm and the size reduction is dependant upon the charge and the grinding time. The lining material of the grinder is also of great importance, since there is a significant amount of wear taking place due to the action of the steel balls.

Some mills are compartmentalized with each subsequent section having a smaller ball size. The materials can pass through to the proceeding section, but the balls cannot, which ensures that the smaller particles are attacked by the smaller grinding media.

The driving force of change is the efficiency of fuel used to produce electrical energy, which has a large influence on clinker production costs. The circuits available are very long lived, with economic lives of at least 30 to 40 years, which means changes in the number and type of the circuits occur slowly. In addition to the mentioned factors, grindability of the materials used is also affecting the energy consumption of the grinding line. Therefore the knowledge of grindability characteristics of cement raw materials is very important as far as the energy requirement of the grinder and selection of the grinding media are concerned [26].

Studies have shown that products of intergrinding and separately grinding do not have the same particle size distribution for the same energy level, and during intergrinding some interactions occur between the particles of different ingredients of cement. [58]

CHAPTER 3

PERLITE

3.1. Definition and Characteristics

Perlite (Figure 3.1) is a glassy volcanic rock of acidic nature. The name perlite is originated from “pearl stone”, since some types of the rock breaks up into small rounded masses that often have pearly luster. [35, 36]

Figure 3.1. Perlite [34]

When perlite is heated to a suitable point in its softening range expands up to twenty times of its original volume creating a cellular material of extremely low bulk-density that caters to various application demands. [35, 36, 37]

3.1.1. Formation of Perlite

The slowly cooling pockets of acidic magma that were trapped beneath the earth's surface will form granite. If molten acidic magma -which has none or few amount of gas in it - erupt and congeal above the surface, it will form rhyolite. The eruption may also form a froth creating pumice which has large pores in its structure caused by the movement of gas bubbles. Pumice has no water in its structure because of its highly porous nature. [38, 39]

The presence of water and moderate amount of gas in the melt changes the scenario. The melt which flows through an environment which has active water -coming from lakes, swamps, streams, or continuous rains- will quench rapidly forming obsidian- natural glass-. At this stage, some amount of absorbed water can be held in the glass. [40, 41]

In the subsequent years, the obsidian will alter into a glassy, gray-brown rock through hydration caused by absorption of water during and after cooling at varying rates, dependent upon environment, glass chemistry, and temperature. Water absorption starts along cooling fractures in the obsidian and proceeds as concentric circles expanding away from the fractures toward the solid cores of unfractured rock resulting in the weaking and breakage of the bonds of the glass structure. The amount of water in the hydrated obsidian can vary but is typically less than 4%. This newly formed rock is known as “perlite”. [40, 41]

The water within the raw perlite, which does not leave the rock under normal circumstances, occurs in two main forms. 94 to 98% of this water was inserted in the fine capillaries of perlite by physical means, and did not enter into the chemical compositions of glass or minerals. This portion of the water which can be defined simply wetness on the surface of the rock is named as free water. It does little to effect the expansion process except to make handling more difficult and to consume energy otherwise needed for expansion. It can be removed by heating, or by suction. [34, 40, 45,] The rest 2 to 6% of water, that did enter into the chemical composition of the volcanic glass as molecules, and consequently united with the volcanic glass, is called combined water. The glass cannot be crystallized due the presence of active water in its structure. [37, 40]

The combined water has also two main effects; it lowers the softening point of the mineral, and it acts as the blowing agent which causes the molten rock to expand. [35]

Perlite is metastable, and sooner or later with age it will, like any glass, devitrify into microcrystalline quartz and feldspar. Because of this instability, most occurrences are generally young and of Tertiary or Quaternary Age (less than 50 million years old). [42]

3.2. Mining of Perlite

Perlite mining generally takes place in remote areas, and its environmental impact is not severe. [48] Mining perlite is generally easy due to the youthfulness of the rock and closeness of it to the surface. Perlite is usually mineable by open pit methods- at or near the surface- over broad areas of 80-100 m thick .The quality of ore does not show considerable variation in short distances which also increases the mines production rates. The fractured texture and brittleness of perlite makes it possible to use mobile ripping equipments such as bulldozer to harvest the rock; so that the drilling and blasting expenses are minimized resulting a quite low overall cost of mining. [36, 40, 42, 43]

The Figure 3.2 shows a processing open pit strip perlite mine where no blasting is required. The bulldozers are used to push up piles of crude rock, load it into dump trucks, and then drop down it into a jaw type crusher. [36, 46]

Figure 3.2. Perlite Mine [46]

The perlite is later on conveyed to a secondary cone crusher for further crushing. After being reduced to correct size, the crushed perlite is dried to eliminate the surface moisture. Finally, it is screened and stored according to grade, prior to shipment to customers of mainly expansion plants. [36, 46]

Sizing is important, since it determines which end uses, in expanded form, can be met. The normal range of raw product sizing is 8 mesh (2.36 mm) to 30 mesh (0.60 mm) and some blending may be done to meet specific product gradation. The most commercially requested size ranges are 0.3-1 mm and 0.8-3mm. Figure 3.3 shows a typical comminution flow. [42]

Crude ore can be used in sand blasting, foundry and steel industries, special casting sand and mixtures. However, it is mainly used as a slag coagulant. [47] In fact, the demand for perlite other than for expansion is very low.

The tightly sized range of product required by the most expanders causes the mining and processing of the ore to generate significant quantities –high up to 30%- of unmarketable fines that cannot be sold and typically disposed of as waste, which accordingly increases the net cost of the product. [42] However the overburden, reject ore and mineral fines produced during ore mining and processing are used to reclaim the mined-out areas, and therefore little waste remains. Airborne dust is captured by baghouses, and there is nearly no runoff that contributes to water pollution. [48]

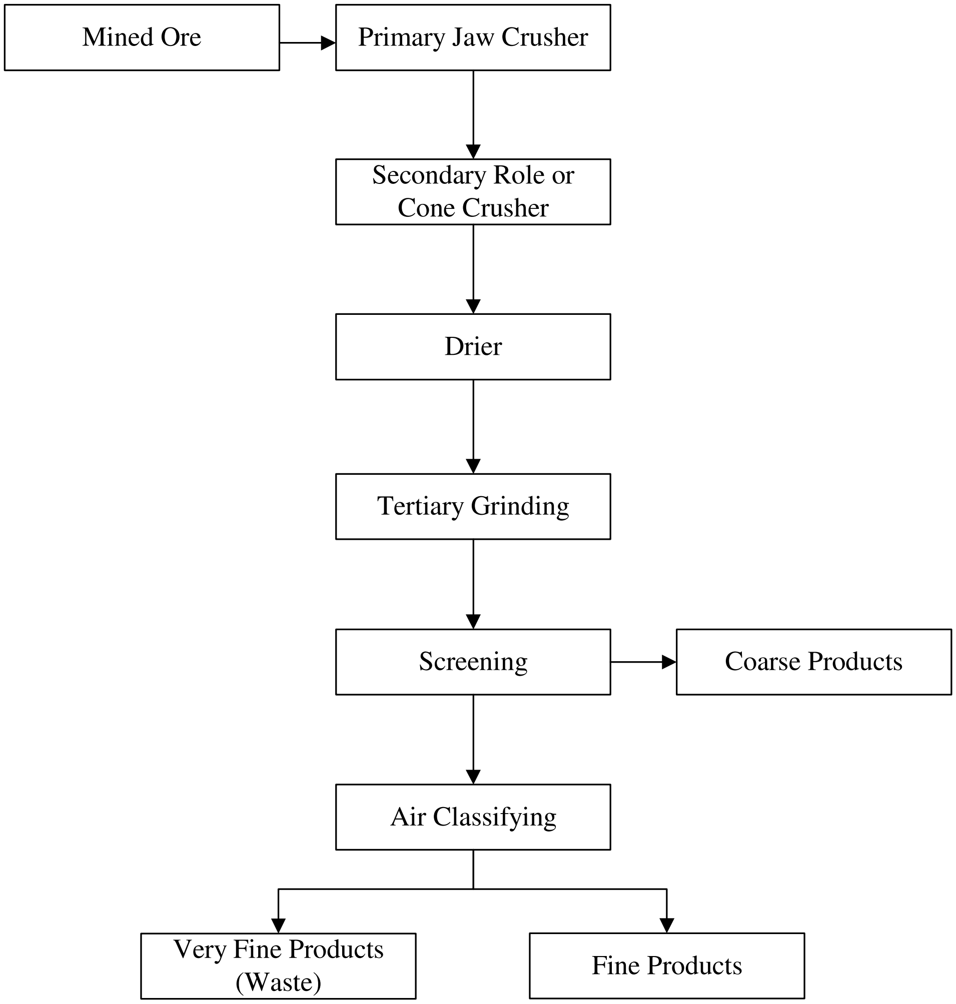

Figure 3.3. Typical Communition Flow of Perlite [42]

The density of the end product is also very important, since specific applications require specific densities of expanded perlite. [36, 42, 43]

In order to minimize high shipping costs of the bulky, low density expanded perlite; expansion process is generally conducted at an expansion facility remote from the mine, but central to target markets. [36, 42]

3.2.1. Typical Chemical and Physical Properties of Perlite

Perlite is generally in light gray color; but sometimes it may be black, light green or brown. Whatever the color of crude perlite is, the expanded perlite is always white. [34, 36, 43]

Perlite has characteristic concentric or arcuate onionskin fractures. The porous nature makes it to gain adsorbtivity and absorptivity properties. The physical properties of perlite are summarized in Table 3.1. [34, 35, 36, 37, 42, 43, 44]

Table 3.1. Physical Properties of Perlite [44]

Property		
Color	:	White, gray, black
Free Moisture, Maximum	:	0.5%
pH (of water slurry)	:	6.5 - 8.0
Specific Gravity	:	2.2 - 2.4
Bulk Density (loose weight)	:	32-400 kg/m^3
Softening Point	:	871-1093°C
Fusion Point	:	1260-1343°C
Specific Heat	:	0.2 cal/g°C
Thermal Conductivity (at 24°C)	:	0.04-0.06 W/m·K

Table 3.2 shows the chemical analysis of crude perlite. [43, 44]

Table 3.2. Typical Chemical Analysis of Crude Ore [43, 44]

Compound		Content, %	Compound		Content, %
Silicon Dioxide	SiO_2	73.8	Chlorine	Cl	<0.0005
Aluminium Oxide	Al_2O_3	13.9	Chromium	Cr	<0.007
Sodium Oxide	Na_2O	4.7	Copper	Cu	<0.0015
Potassium Oxide	K_2O	4.3	Gallium	Ga	<0.05
Calcium Oxide	CaO	0.9	Lead	Pb	<0.001
Ferric Oxide	Fe_2O_3	0.9	Manganese	Mn	<0.3
Magnesium Oxide	MgO	0.3	Molybdenum	Mo	<0.002
Water (moisture)	H_2O	<1.0	Nickel	Ni	<0.02
Arsenic	As	<0.001	Sulphur	S	<0.2
Barium	Ba	<0.1	Titanium	Ti	<0.1
Boron	B	<0.01	Zirconium	Zr	<0.003

3.3. Expanded Perlite

Perlite's relatively high combined water content of two to six percent distinguishes it from other hydrous volcanic glasses such as obsidian, hydrated volcanic ash, and pumicite. This chemically bonded water held within the perlite glass structure expands on heating to create a cellular material of extremely low bulk density. [34, 35, 37, 36, 42, 43, 44]

The expansion process of perlite requires very careful delivery of heat and then removal of the particle from the heat zone. The particle must be heated quickly enough above its softening point (871°C) usually in a rotary horizontal or stationary vertical furnace, so that it becomes soft enough to expand before the combined water in its structure vaporizes. The formed steam acts to expand the softened material, increasing the porosity of the structure and decreasing the original density, so that consequently the rock expands creating countless tiny bubbles. The resultant product is named as expanded perlite. [34, 40, 42, 44]

The very light expanded grains produced during expansion are withdrawn from the furnace by means of suction fans, then cooled with entrained air, sometimes heat treated to improve strength and absorption resistance, and finally collected in cyclones and air classified into the desired size ranges, from 4 mesh (4.75 mm) to 200 mesh (0.075 mm). Ultra fine particles are collected by baghouses and electrostatic precipitators to guarantee clean-air discharge from the processing facility. [42]

The final bulk density of the product will be determined by the water content of the ore together with the heating cycle. Representative values of bulk density are 2200 - 2400 kg/m^3 for crude perlite, 900 - 1100 kg/m^3 for crushed perlite, and 60 - 120 kg/m^3 for expanded perlite. Three stages of perlite production for the same weight of perlite in Figure 3.2 [44] illustrate the great increase in volume after furnacing. [35, 40, 42, 44]

Crude Perlite Crushed Crude Perlite Expanded Perlite

Figure 3.4. Expanded Perlite [44]

The expanded perlite has a wide range of uses, generally due to its properties of extremely low bulk density, high brightness, high absorption, low thermal and acoustical conductivity, and non-flammability. The absence of any apparent health hazard is also increasing its usage rate. The chemical analysis of expanded perlite is given in Table 3.3. [42, 43]

Table 3.3. Typical Chemical Analysis of Expanded Perlite [43]

Compound	Content, %	Compound	Content, %
SiO_2	71.0 - 75.0	FeO	0.0 - 0.1
Al_2O_3	12.5 - 18.0	Cr	0.0 - 0.1
Na_2O	2.9 - 4.0	Ba	0.0 - 0.05
K_2O	0.5 - 5.0	PbO	0.0 - 0.03
CaO	0.5 - 2.0	NiO	Negligible
Fe_2O_3	0.1 - 1.5	Cu	Negligible
MgO	0.02 - 0.5	B	Negligible
TiO_2	0.03 - 0.2	Be	Negligible
H_2O	2.0 - 5.0	Free Silica	0.0 - 0.2
MnO_2	0.0 - 0.1	Total Chlorides	0.0 - 0.2
SO_3	0.0 - 0.2	Total Sulphates	None

3.4. Uses of Perlite

The method to expand perlite was discovered in 1928. However, expanded perlite was not extensively used until 1945. Perlite began to gain market share as the other lightweight materials by the help of the building boom after the World War II.

The unit price of local crushed and sieve ore is around 8$ per ton in Turkey.

Some basic usage areas of crushed and sized perlite can be listed as follows [36]:

- in manufacturing of sewage pipes owing to its resistance to some acids and alkalies,
- in the production of interior and exterior plasters that are used in:
  - constructions that are exposed to water,
  - water insulation of roofs and terraces,
  - construction of swimming pools,
- in railway sleeper beds,
- in abrasive industry,
- in water treatment centers as filter sand,
- in highways as asphalt filler,
- in foundries as silica source, metal cleaner, or slag coagulant.

The uses of expanded perlite can be generally categorized as construction, horticultural, and industrial applications. Constructional applications are explained in Section 3.4.1.

3.4.1. Construction Applications

Owing to its thermal or acoustic insulation, lightweight, or fire resistance, expanded perlite is generally used in construction applications. Main uses of perlite in the construction sector will include [42]:

- Acoustic tiles and wallboard
- Lightweight concrete aggregate
- Caulking compounds
- Loose fill insulation

- Pipe insulation coatings
- Plaster aggregate & texturing
- Paint texturing
- Refractory products
- Insulating roofing compounds
- Fireproofing coatings
- Lightweight joint cement filler
- Chimney linings

Insulation boards that are all fibre, perlite, and perlite-gypsum formed boards used mainly in roofing, walls, door cores and ceilings constitute the largest market for perlite. Several varieties of gypsum plaster insulation board produced by using perlite as an aggregate are also marketed which has the advantage of reduced thermal conductivity and greater ease of installation. Cast gypsum fibreboard –a new product developed in Europe- contains perlite and could be used as an ideal alternative of the standard gypsum wallboard. [42]

The steady decline in the use of interior plaster that is replaced by prefabricated boards directly affects the consumption of perlite used as an aggregate for portland cement and gypsum plaster especially in USA. However, it is still being commonly used in Europe. Using perlite as an aggregate in portland cement and gypsum plasters for exterior applications and for the fire protection of beams and columns is also very efficient. [35, 37, 42]

The lightweight concrete aggregate and loose-fill insulation are also competitive markets that are subjected to substitution and price pressure, mainly from air-entraining agents in the case of concrete that do not involve as much strength loss as does perlite. [36, 42, 43]

In the rivalry construction sector exfoliated vermiculite, expanded clay or shale, pumice, mineral wool and fiberglass, all compete generally for the same market, and each has specific advantages and/or shortcomings in different product areas. However, expanded perlite prevails where it has a price advantage and some particularly desirable properties to offer. [36, 42, 43]

Perlite is also used in carefully formulated mixes that are used to finish-coat gypsum such as lightweight joint cement and spray-on ceiling and wall textures. Lightweight joint cement is foam that is mainly composed of very fine perlite microspheres processed with silicone. The silicone repels water permitting even the particles smaller than 0.147 mm to retain their cellular voids, which consequently reduce the weight of the applied coating. [42]

In the spray-on textures, expanded perlite is used as a bulking additive aggregate that provides a coarse textured surface which is very common for residential ceilings. Styrofoam may be substituted for perlite in these coatings. However, the adverse health affects of styrofoam is still being researched. [42]

Expanded perlite is also used in the manufacture of cast concrete blocks. The lightweight products obtained are offered at a premium price, but with only modest response; since the reduction of placement costs and related expenses does not offset the price premiums. [42]

Perlite is rot, vermin and termite resistant; so that it is ideal for insulating low temperature and cryogenic vessels. Due to its being fairly resistant to acids and alkalies, perlite is used in pipe insulation coatings. [34, 35, 37, 44]

Studies also showed that when expanded perlite is mixed with portland cement, it undergoes pozzolanic reactions. [52, 53] Besides, there are some studies showing that perlite powder has a significant pozzolanic effect. [54]

3.5. Reserves, Production and Consumption

The perlite reserves are generally located on volcanic regions of early Tertiary or middle Quaternary Age. [36, 43]

3.5.1. Worldwide Reserves, Production and Consumption

Total worldwide perlite reserve is around 6,715 million tons. The ready to mine portion is only 25% of the total reserve. Detailed information on perlite reserves is summarized in Table 3.4. [43]

Table 3.4. Worldwide Reserves of Perlite (million tons) [43]

Country	Perlite Ready to Mine	Potential Reserve of Perlite	Total Reserves
Turkey	998	3578	4576
Russia	454	907	1361
Greece	45	272	317
USA	45	181	226
Japan	9	45	54
Philippines	9	36	45
Mexico	5	18	23
Other	23	91	114
Total	1587	5128	6715

Perlite is mined and expanded all over the world, and the production rate of perlite is not directly related with the reserves. The United States is estimated to be the largest producer of crude and expanded perlite. Even at the present situation, 62 companies are operating. [43, 49]

The main producers of perlite other than U.S., in descending order, can be listed as Greece, Japan, Hungary and Turkey. The thirteen countries listed in Table 3.5 produced around 1.65 million tons of perlite. However, this total does not include several producer countries, such as Algeria, Bulgaria, China – probably the largest or second largest producer in the world -, Iceland, and Mozambique owing to lack of reliable figures since the output is not reported, and available information is inadequate. [49]

Table 3.5. Perlite World Production by Country (metric tons) [49]

Country	1997	1998	1999	2000	2001	2002
Armenia	6	35	35	35	35	35
Australia*	5	5	5	5	5	5
Greece &	501	500	435	360	360	360
Hungary*	120	130	148	150	151	150
Iran	10	13	15	15	15	15
Italy	60	60	60	60	60	60
Japan	290	251	260	250	250	250
Mexico*	52	55	62	69	80	80
Philippines	20	6	10	6	6	6
Slovakia	25	24	19	17	15	15
South Africa	0.4	0.4	0.4	0.4	0.4	0.4
Turkey*	103	124	148	149	150	150
United States	706	685	711	672	588	521
Total	1,900	1,890	1,910	1,790	1,720	1,650

(*) Crude Ore
(&) Screened Perlite

Generally, perlite is not stored, since its production is directly correlated with the perlite consumption. [36] Perlite is generally consumed in expanded form due to its outstanding insulation properties and very low bulk density. The trendline for perlite consumption is strictly parallel to the development and recession periods in the construction sector which is the main consumer of crude and expanded perlite. Global consumption of perlite is rising slowly, but steadily at an average annual rate of growth around 2% per year. [36, 49]

Currently, around 43% of the total world consumption of perlite is accounted for Americas, predominantly the USA, Mexico, and Canada; the United States is estimated to be the largest consumer. Around 70% of the total perlite consumption in USA is done by the construction sector -70% in constructional applications, 10% in horticultural applications, 9% as filtering material, 7% as filling material and 3% in other applications-; and it is important to note that around 70% of perlite consumption in construction sector is due to the insulation board and ceiling tile production. Western Europe is the next largest consumer with 18% of world consumption. [36, 49]

3.5.2. Reserves, Production and Consumption of Turkey

In Turkey, the main perlite reserves are found on early Tertiary or middle Quaternary age volcanic regions and of good quality.The reserves are generally close to surface; so that operating the mines is generally easy. The total perlite reserve in Turkey is around 4.5 billion tons, which is nearly 2/3 of the worldwide perlite reserve. The distribution of the reserves of perlite is given on Table 3.6 [36] and Figure 3.6.

Although Turkey has rich reserves and potential the domestic consumption is limited. Perlite as one of the best isolation materials has never gained the theoretical acceleration in domestic consumption of Turkey. [36]

Table 3.6. Perlite Reserves in Turkey [36]

Region	(Possible) Reserve (tons)
Ankara- Çamlıdere	8.000
Ankara-Çubuk	32.000
Ankara- Kızılcaham	34.200
Balıkesir-Evrindi	25.000
Balıkesir- Savastepe-Sındırga	47.000
Bitlis-Adilcevaz-Tatvan-(Van-Ercis)	1.400.000
Çankırı-Orta	30.000
Çanakkale-Biga	3.400
Eskisehir-Seyitgazi	20.000
Erzincan-Merkez	27.000
Erzurum-Pasinler	100.000
Izmir-Bergama	16.500
Izmir-Dikili	8.000
Izmir-Foça	16.500
Izmir-Menderes (Cuma Ovası)	60.000
Kars -Sarıkamıs	1.500.000
Manisa-Demirci-Soma	18.600
Manisa-Saruhanlı	18.000
Nevsehir-Acıgöl	862.000
Nevsehir-Derinkuyu (Nigde-Gölcük)	350.000
Total	4.576.200

(*) Other than the regions mentioned above, it is known that there is a significant amount of perlite reserve in Kars-Göle region.

Figure 3.5. Perlite Reserves in Turkey

In Turkey, perlite is consumed mainly in three general categories: 60% in construction, 17% in horticultural and 20% in industrial applications. The yearly consumption of expanded perlite is around 100,000 m^3. Taking into account that from 1 ton of crude perlite around 12 m^3 of expanded perlite is obtained; it may be concluded that total screened perlite consumption is around 8000-8500 tons per year. [36] The yearly perlite production is around 150,000 tons in Turkey; details are given in Table 3.7. [36]

Table 3.7 Perlite Production in Turkey [36]

Year	Production (tons)
1997	103,416
1998	124,312
1999	147,818
2000	149,429
2001	150,000

The ratio of perlite reserves to perlite production is quite poor in Turkey than other producer countries. The low prices especially after 1995 caused economic problems for local producers in Turkey [36].

The main problems in perlite industry of Turkey especially about the domestic consumption can be listed as below [36, 43]:

- Perlite, its by-products and their usage are not known enough, so they are not used as much as they could have been.
- Generally perlite producers, remind that although perlite is a good insulation material, the usage of it is not so practical and requires technical knowledge which increases the labor cost.
- The perlite mixtures, to give the desired result, should be prepared carefully, so they should be prepared by technical personnel.
- If precast members are manufactured, to encounter the problems listed above, they cost high prices.
- The expanded perlite occupies large space due to its low density, which increases the transportation costs. As a result, expansion facilities are only located around 3-4 major cities. For other cities the transportation problem is still going on as a major problem.
- During the expansion of perlite fuel oil is required, which results in increase of the total cost of the production due to the increase in fuel oil prices.

Besides the domestic problems, revising the exporting strategies of perlite is also required.

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1. Experimental Program

The experimental program of this study is composed of four major sections:

a) Determination of general chemical, physical and mechanical characteristics of the materials according to the related ASTM standards.
b) Determination of the effect of intergrinding clinker and gypsum with perlite from different sources with different percentages on the grindability properties during the production of blended cements.
c) Determination of the effects of the source, fineness, percentage, and grinding method of perlite addition on various properties of “portland cement – perlite pastes” such as water requirement, normal consistency, setting time, and autoclave expansion.
d) Determination of the effects of the source, fineness, percentage, and grinding method of perlite addition on various properties of “portland cement – perlite mortars” such as flow, and compressive strength.

During the research, perlites from two different sources – Izmir (PI) and Erzincan (PE) – were used as replacement of portland cement clinker with two different percentages: 20% and 30% by weight. Then for each mix proportion, materials were ground with gypsum to obtain the grinding curves of the resultant cements. Two different Blaine fineness values were chosen for the cements to be produced: 320 m^2/kg and 370 m^2/kg. A total of 22 cements were used for paste and mortar specimens as shown in Table 4.1.

Table 4.1. Cement Labels Used in the Study

Label	Description
PC/320	Ordinary portland cement with Blaine fineness of 320 m^2/kg.
I PI 20/320	Blended cement produced by intergrinding clinker, gypsum and PI in a ratio of 76.8/3.2/20 by weight respectively to Blaine fineness of 320 m^2/kg.
I PE 20/320	Blended cement produced by intergrinding clinker, gypsum and PE in a ratio of 76.8/3.2/20 by weight respectively to Blaine fineness of 320 m^2/kg.
S PI 20/320-320	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PI having Blaine fineness of 320 m^2/kg in a ratio of 80/20 by weight respectively.
S PE 20/320-320	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PE having Blaine fineness of 320 m^2/kg in a ratio of 80/20 by weight respectively.
I PI 30/320	Blended cement produced by intergrinding clinker, gypsum and PI in a ratio of 67.28/2.8/30 by weight respectively to Blaine fineness of 320 m^2/kg.
I PE 30/320	Blended cement produced by intergrinding clinker, gypsum and PE in a ratio of 67.28/2.8/30by weight respectively to Blaine fineness of 320 m^2/kg.

S PI 30/320-320	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PI having Blaine fineness of 320 m^2/kg in a ratio of 70/30 by weight respectively.
S PE 30/320-320	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PE having Blaine fineness of 320 m^2/kg in a ratio of 70/30 by weight respectively.
S PI 20/320-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m2/kg with PI having Blaine fineness of 370 m2/kg in a ratio of 80/20 by weight respectively.
S PE 20/320-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m2/kg with PE having Blaine fineness of 370 m2/kg in a ratio of 80/20 by weight respectively.
S PI 30/320-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PI having Blaine fineness of 370 m^2/kg in a ratio of 70/30 by weight respectively.
S PE 30/320-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 320 m^2/kg with PE having Blaine fineness of 370 m^2/kg in a ratio of 70/30 by weight respectively.
PC/370	Ordinary portland cement with Blaine fineness of 370 m^2/kg.

S PI 20/370-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 370 m^2/kg with PI having Blaine fineness of 370 m^2/kg in a ratio of 80/20 by weight respectively.
S PE 20/370-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 370 m^2/kg with PE having Blaine fineness of 370 m^2/kg in a ratio of 80/20 by weight respectively.
I PI 20/370	Blended cement produced by intergrinding clinker, gypsum and PI in a ratio of 76.8/3.2/20 by weight respectively to Blaine fineness of 370 m^2/kg.
I PE 20/370	Blended cement produced by intergrinding clinker, gypsum and PE in a ratio of 76.8/3.2/20by weight respectively to Blaine fineness of 370 m^2/kg.
S PI 30/370-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 370 m^2/kg with PI having Blaine fineness of 370 m^2/kg in a ratio of 70/30 by weight respectively.
S PE 30/370-370	Blended cement produced by mixing separately ground PC having Blaine fineness of 370 m^2/kg with PE having Blaine fineness of 370 m^2/kg in a ratio of 70/30 by weight respectively.
I PI 30/370	Blended cement produced by intergrinding clinker, gypsum and PI in a ratio of 67.28/2.8/30 by weight respectively to Blaine fineness of 370 m^2/kg.
I PE 30/370	Blended cement produced by intergrinding clinker, gypsum and PE in a ratio of 67.28/2.8/30 by weight respectively to Blaine fineness of 370 m^2/kg.

Table 4.2 described the abbreviations used in naming the cement types.

Table 4.2. The Description of the Abbreviations Used in Cement Names

Type of Grinding:

S = Separate grinding

I = Intergrinding

Source of Perlite:

PI = Izmir Perlite

PE = Erzincan Perlite

First number following the source indicated:

Percent of perlite by weight of cement

Number following the slash sign:

Blaine fineness of cement in m^2/kg

The Last number following the dash sign:

Blaine fineness of addition used in producing separately ground cement in m^2/kg

The ordinary portland cement produced, Izmir Perlite, and Erzincan Perlite are denoted by the symbols PC, PI and PE respectively, followed by their fineness such as PC/370: ordinary portland cement with Blaine fineness value of 370 m^2/kg.

In all produced blended cements, Blaine values in ± 5 m^2/kg sensitivity of 320 and 370 m^2/kg were accepted as nominal.

The compositions of the produced cements are given in Table 4.3.

Table 4.3. Compositions of the Cements Used in the Study

Label	Clinker (%)	Perlite (%)	Gypsum (%)	Type of Grinding	Perlite
PC/320	96	0	4	-	-
I PI 20/320	76.8	20	3.2	I	PI
I PE 20/320	76.8	20	3.2	I	PE
S PI 20/320-320	76.8	20	3.2	S	PI
S PE 20/320-320	76.8	20	3.2	S	PE
I PI 30/320	67.2	30	2.8	I	PI
I PE 30/320	67.2	30	2.8	I	PE
S PI 30/320-320	67.2	30	2.8	S	PI
S PE 30/320-320	67.2	30	2.8	S	PE
S PI 20/320-370	76.8	20	3.2	S	PI
S PE 20/320-370	76.8	20	3.2	S	PE
S PI 30/320-370	67.2	30	2.8	S	PI
S PE 30/320-370	67.2	30	2.8	S	PE
PC/370	96	0	4	-	-
S PI 20/370-370	76.8	20	3.2	S	PI
S PE 20/370-370	76.8	20	3.2	S	PE
I PI 20/370	76.8	20	3.2	I	PI
I PE 20/370	76.8	20	3.2	I	PE
S PI 30/370-370	67.2	30	2.8	S	PI
S PE 30/370-370	67.2	30	2.8	S	PE
I PI 30/370	67.2	30	2.8	I	PI
I PE 30/370	67.2	30	2.8	I	PE

4.2. Materials Used

One type of ordinary portland cement clinker and two types of perlite were used for paste and mortar specimens in this study. The types of tests performed on these materials and the relevant test standards are given in Table 4.4.

Table 4.4. Tests Performed on Portland Cement and Perlite

Tests Performed on	Relevant Standard
a) Portland Cement	
Chemical Analysis	ASTM C 114 [19]
Fineness by Blaine Air Permeability	ASTM C 204 [9]
Density of Hydraulic Cement	ASTM C 188 [17]
Fineness of Hydraulic Cement by the 45-μm Sieve	ASTM C 430 [10]
XRD Trace	
b) Perlite	
Chemical Analysis	ASTM C 114 [19]
Fineness by Blaine Air Permeability	ASTM C 204 [9]
Density	ASTM C 188 [17]
Fineness of Hydraulic Cement by the 45-μm Sieve	ASTM C 430 [10]
XRD Trace	

4.2.1. Portland Cement Clinker and Gypsum

For the production of cements, the clinker of SET Cement Plant in Ankara was chosen. The clinker was crushed before grinding operation to reduce the very large particles. Then, the crushed clinker was sieved through ASTM 3/8” sieve (9.5 mm).

The gypsum, the main retarder in PC, was also taken from SET Cement Plant in Ankara. Before being used in the PC production, gypsum was also crushed and sieved from ASTM 3/8” sieve to a maximum particle size of 9.5 mm; and dried at 40°C in the laboratory. For all cements produced gypsum/clinker ratio was 4/96 by weight. The result for the chemical composition of the PC produced determined by XRF are shown in Table 4.5.

Table 4.5. Oxide Compositions of the Raw Materials Used in the Research

Oxides	PC, %	PI, %	PE, %
SiO_2	21.00	76.57	75.30
Al_2O_3	4.98	9.99	9.35
Fe_20_3	3.57	0.96	1.36
CaO	63.58	0.51	0.60
MgO	1.86	0.03	0.05
Na_2O	0.14	0.00	0.00
K_2O	0.74	5.58	4.82
SO_3	2.52	0.04	0.06

The main compounds of the used PC are calculated by using Bogue’s Equations [4] and shown in Table 4.6.

Table 4.6. Compound Composition of the Used Portland Cement

Compound	Content (%)
C_3S	65.41
C_2S	10.71
C_3A	7.16
C_4AF	10.86

The initial particle size distribution of the clinker is shown in Table 4.7.

Table 4.7. Initial Particle Size Distribution of the Raw Materials

Sieves		Percent Cumulative Material Passed from Each Sieve		
No.	Opening (mm)	Clinker	PI	PE
¾"	19.1	100.0	100.0	100.0
½"	12.7	100.0	100.0	100.0
⅜"	9.5	100.0	100.0	100.0
#4	4.76	91.9	100.0	100.0
#8	2.38	67.2	88.0	91.7
#16	1.19	43.6	58.8	62.5
#30	0.59	30.3	37.4	41.3
#50	0.297	20.7	20.3	22.4
#100	0.149	13.6	9.0	10.0
Pan	-	0.0	0.0	0.0

4.2.2. Perlites

In this research, perlites from two different sources – Izmir and Erzincan - were chosen to represent the wide range of perlite reserves in Turkey. While selecting the sources, the potential for being used in the cement industry was also taken into consideration. Both of the perlites were crushed, and sieved through ASTM No. 4 sieve (4.75 mm) before grinding operation not only to reduce very large particles.

The chemical compositions of PI and PE used in the study determined by XRF are given in Table 4.5. For better understanding of the structure of the perlites, their X-ray diffractograms were investigated. For the X-ray diffraction (XRD) measurements, materials were ground very finely in order to obtain homogeneity of grain size. The XRD traces of the perlites are given in Appendix A.3.

The initial particle size distributions of the perlites used in the study are given in Table 4.7.

4.3. Production of the Cements

The last step in the production cycle of the PC is the process of pulverizing the clinker with a small amount of gypsum, if present together with some additives. The major part of the total energy consumption during cement production in cement plants is due to the grinding process. For that reason, interest has focused on saving grinding energy for many years.

Generally, adding a pozzolan during this process reduces the energy consumption of the mills to produce the cement from pure PC clinker of the same fineness; since pozzolans are usually softer and easier to grind than PC clinker.

4.3.1. Grinding the Materials

In order to measure relative grindability of cements, a laboratory type ball mill that was 450 mm in length and 420 mm in diameter was used for all grinding processes. The revolution rate for grinder was around 30 revolutions per minute. The grinding elements used were both balls and cylpebs; both monodisperse and polydisperse grinding element fillings were investigated.

The grinding trials with monodisperse grind balls in which only small balls were used resulted in quite high Blaine fineness values together with some unground particles. It is observed that using polydisperse grinding element fillings was much more effective than using monodisperse ones. After several discussions with Turkish Cement Manufacturers Association using a combination of grinding balls whose sizes were ranging from 30 mm to 70 mm with a combination of fine cylpebs addition was chosen as the best option.

The size distribution of the grinding elements used is given in Table 4.8 The grinding element weight and distribution filled into the ball mill was identical in all grinding operations.

Table 4.8. The Size Distribution of Grinding Elements

	Dimensions (mm)	Weight (kg)	Weight (%)
Spherical Balls (diameter)	70	14.10	14.39
	65	3.00	3.06
	60	10.00	10.20
	55	9.74	9.94
	50	12.00	12.24
	40	13.40	13.67
	30	21.76	22.20
Cylpebs (diameter x length)	10 x 10 20 x 20 30 x 30	14.00	14.29
Total	-	98.00	100.00

The raw material mass was kept constant at 7 kg within all different proportions of clinker, perlite, and gypsum. The gypsum - clinker ratio was kept constant as 4/96 by weight for each of the produced cements.

Another factor that can influence the test results was the initial particle size distribution of the raw materials. Clinkers having maximum particle sizes of 19.1 mm (ASTM No. 3/4" sieve) and 9.5 mm (ASTM No. 3/8" sieve) respectively ground with 4% of gypsum. The results show that the effect of the initial size was not as great as expected.

The temperature of the laboratory was measured to be in the range of 17-22 °C in all of the tests. In brief, the factors that were tried to be kept constant throughout the tests since they might affect the resultant grinding curves are listed as follows:

- Size distribution and weight of steel charges
- Weight of the raw materials put into the grinder
- Revolution rate of the grinder
- The gypsum percent relative to the clinker weight
- Maximum particle size of each raw material used
- Temperature of the laboratory

4.3.2. Obtaining the Grinding Data

Several different cements were obtained by intergrinding or separate grinding the raw materials in different proportions. The raw material proportions used in grinding are given in Table 4.9.

During the grinding procedure, after every 30 minutes the machine was stopped, and a sample about 100 g was taken. Besides the samples taken at every 30 minutes, some samples were obtained in between these regular interval times in order to determine the exact fineness aimed. While taking a sample, it was tried to obtain the most representative one. The samples taken were used to determine some properties of the cement such as specific gravity, Blaine fineness, and amount of material retained on 45-µm sieve according to ASTM C 188 [17], ASTM C 204 [9], and ASTM C 430 [10] respectively.

Table 4.9. Raw Material Proportions Used in Grinding

Label	Clinker (%)	Perlite (%)	Gypsum (%)	Perlite
PC	96	0	4	-
PI	0	100	0	PI
PE	0	100	0	PE
I PI 20	76.8	20	3.2	PI
I PI 30	67.2	30	2.8	PI
I PE 20	76.8	20	3.2	PE
I PE 30	67.2	30	2.8	PE

After the conformance of the perlites to ASTM C 618 [1] requirements was checked, blended cements of several types are produced by:

- Intergrinding, or separate grinding and mixing the materials (I and S),
- Using two types of perlites (PI and PE),
- Changing the replacement amount of perlite with PC (20% and 30%),
- Using different Blaine fineness values (for interground cements 320, 370 m^2/kg, and for separately ground cements 320+320, 320+370, 370+370 m^2/kg for cement and addition respectively).

The laser particle size distributions of perlites and cements with Blaine fineness of 320 m^2/kg and 370 m^2/kg were also determined for better understanding of the grinding performance by using Malvern Mastersizer laser particle size analyzer. A laser particle sizer is also the most efficient way to analyze the large numbers of samples, since it is extremely accurate, and it enables the determination of a large range of particle sizes.

4.4. Tests on Cement Pastes and Cement Mortars

Tests performed on these cement pastes and mortars and the relevant test standards are summarized in Table 4.10.

Table 4.10. Tests Performed on Cement Pastes and Mortars

Tests Performed on	Relevant Standard
a) *Cement Paste*	
Normal Consistency	ASTM C 187 [55]
Setting Time	ASTM C 191 [13]
Autoclave Expansion	ASTM C 151 [11]
b) *Cement Mortar*	
Flow	ASTM C 109 [15]
Water Requirement	ASTM C 311 [27]
Strength Activity	ASTM C 311 [27]
Compressive Strength of Mortar	ASTM C 109 [15]

Normal consistency and setting time tests were performed according to ASTM C 187 [55] and ASTM C 191 [13] respectively. Normal consistency tests were conducted mainly to observe the changes in the water requirement of pastes due to perlite substitution.

Autoclave expansion tests were conducted according to ASTM C 151 [11], mainly as an indication of potential delayed expansion largely caused by CaO, and MgO, or both.

A total of 22 mortars were produced with several different proportions of materials. The compressive strengths of mortar cubes were determined at 2, 3, 7, 28, 56 and 91 days in compliance with ASTM C 109 [15].

4.4.1. Curing Condition

Test specimens used in compressive strength tests were cured in a moist room in water at 21±2 ºC until the day of test, and tested immediately after removal from water while still wet.

CHAPTER 5

TEST RESULTS AND DISCUSSIONS

5.1. XRD Traces of Perlites

The X-ray traces of the perlites are given in Appendix A.3. From the X-ray traces, it can be seen that Erzincan Perlite is slightly more amorphous than Izmir Perlite. Due to their amorphous nature, the mineralogical compositions of perlites can not be determined exactly by X-ray diffraction analyses.

When their chemical compositions obtained by XRF are examined it is seen that perlites have around 75% SiO_2 and 10% Al_2O_3. When compared to other natural pozzolans, mentioned in Table 2.3, the values seem to be sufficient to be a candidate for being a pozzolanic material. The other oxides for perlites are generally lower than the other natural pozzolans except the K_2O content.

5.2. Conformance of the Perlites to ASTM C 618 [1]

Before proceeding to further tests, the conformance of the perlites to ASTM C 618 [1] was checked. The results of the tests performed are given with the ASTM requirements in Table 5.1. For the tests, the Blaine fineness values of the perlites and PC were 370 and 320 m^2/kg respectively.

Table 5.1. Conformance of the Perlites to ASTM C 618 [1]

	PI	PE	ASTM C 618 [1]
Chemical Requirements			
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	87.52	86.01	Min. 70.0
SO_3, %	0.04	0.06	Max. 4.0
Loss on ignition, %	4.22	4.13	Max. 10.0
Physical Requirements			
Fineness			
Amount retained when wet-sieved on 45-µm sieve, %	31	31	Max. 34
Strength activity index			
7 day (% of control)	80.3	85.1	Min. 75
28 day (% of control)	81.9	85.9	Min. 75
Water requirement (% of control)	103	100	Max. 115
Soundness			
Autoclave expansion or contraction, %	0.05	0.07	Max. 0.8

From Table 5.1 it is seen that both PI and PE conform to the chemical and physical requirements of ASTM C 618 [1].

5.3. Results of The Tests

5.3.1. Tests on Perlite

The specific gravity of Erzincan Perlite is slightly greater than the specific gravity of Izmir Perlite. The specific gravities for both of the perlites did not change significantly with grinding as shown in Figure 5.1.

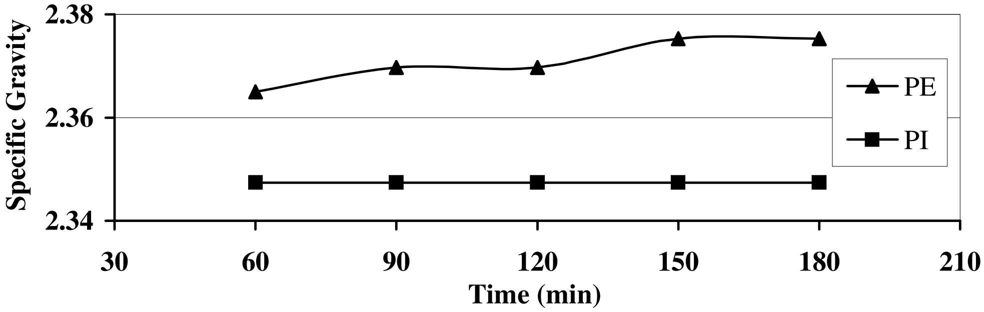

Figure 5.1. Variation of Specific Gravities of Perlites with Grinding Time

The variations in the Blaine specific surface areas of the perlites with the grinding time are given in Figure 5.2. From the figure, it can be seen that Erzincan perlite has higher Blaine values than Izmir perlite for a given grinding time. The difference of Blaine values between the two grinding curves is around 50 m^2/kg throughout 180 minute grinding time. However, this value is slightly decreasing with the increasing grinding time. PC resulted in lowest fineness values for the same grinding time.

From Figure 5.2, it is also seen that especially for PC by increasing grinding time the slopes of the curves decreases indicating that it becomes harder to make PC finer. In other words, the efficiency of grinding media is lowered. However, similar behaviors were not observed for perlites until a grinding time of 180 minutes. Therefore, it can be concluded that perlites were more grindable than PC, and the grindability of PE is higher than that of PI.

The Blaine value is not completely decisive on the grindability of perlites as explained in Chapter 2. The amount retained when wet-sieved on 45-µm sieve, is also another important parameter for investigating the grindability properties. Figure 5.3 shows the variations in percent materials retained when wet-sieved on 45-µm sieve with increasing grinding time.

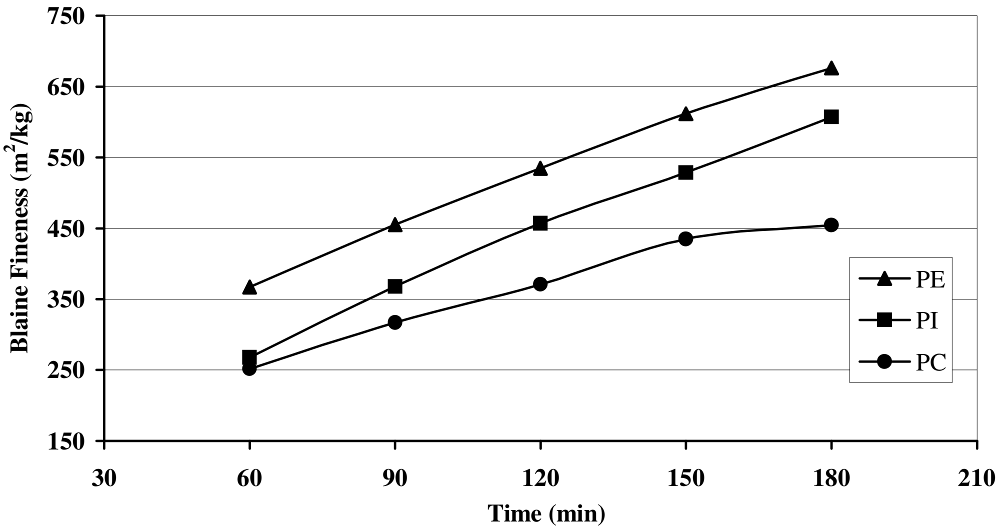

Figure 5.2. Variation of Blaine Fineness of Perlites and PC with Grinding Time

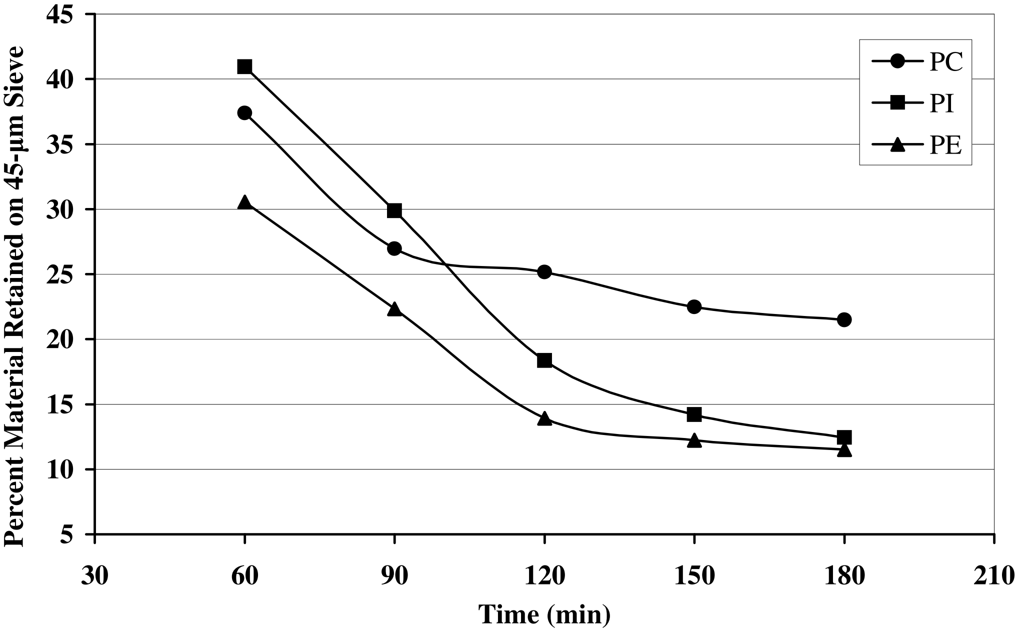

Figure 5.3. Effect of Grinding on the Percent Material Retained on 45-µm Sieve When Wet Sieved

From Figure 5.3 it is seen that Erzincan perlite satisfies the fineness requirement of ASTM C 618 even after being ground for 60 minutes. However, Izmir Perlite satisfies the requirement after being ground for 80 minutes. It can also be seen that for perlites the percents retained on 45-µm sieve when wet sieved do not decrease uniformly with the increasing grinding time. The decreases in the percents retained are in a descending manner. This may be an indication of reduction in the effectiveness of grinding media as the particle sizes get finer. It can again be observed that PC is the hardest, and PE is the easiest to grind.

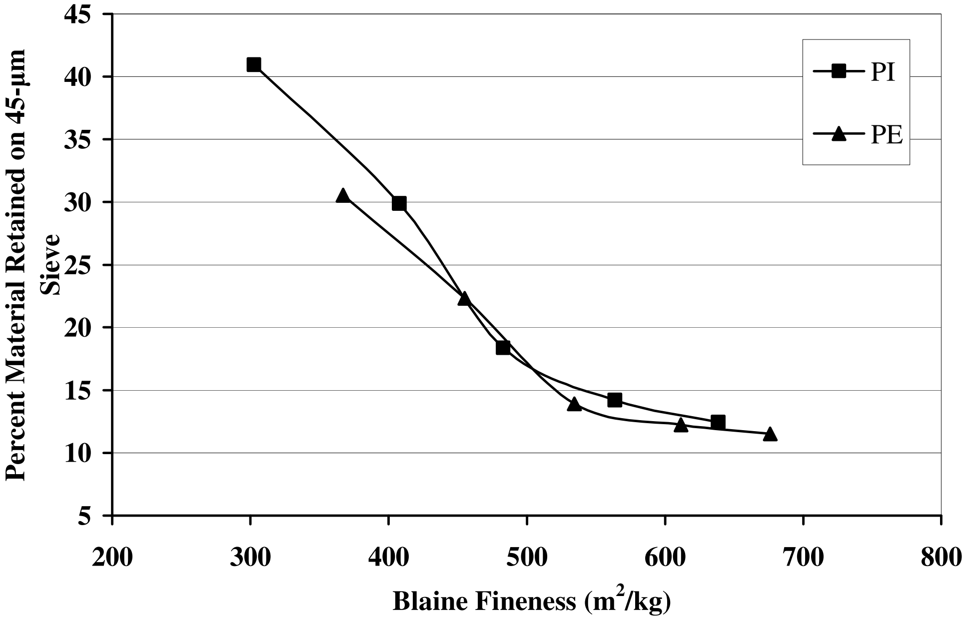

Figure 5.4. Percent Material Retained on 45-µm Sieve when Wet Sieved versus Blaine Fineness Value

From Figure 5.4, it is seen that the variation of the percent material retained on 45-µm sieve when wet sieved with the Blaine fineness is very similar after 450 m^2/kg for PI and PE. This also shows their similar behavior with respect to grinding. As a result, from all of the fineness parameters mentioned, it can be concluded that PE is more grindable than PI; they both are more grindable than PC. For better understanding of the grinding performance, particle size distributions of PC, PI, and PE on two different Blaine values are determined by laser diffraction. The results are given in detail in Appendix A.1 and summarized in Table 5.2. Table 5.3 provides a brief summary on the grinding details on PC and perlites.

Table 5.2. Particle Size Distributions of PC and Perlites Corresponding to Different Finenesses

Material	Size (µm)					
	>93	>59	>44	>30	>15	>5
PC/320	4.0	15.8	26.7	39.8	58.8	84.4
PI/320	13.9	30.1	40.6	52.0	68.5	87.9
PE/320	12.5	28.7	39.4	51.2	68.1	87.0
PC/370	3.2	12.2	20.6	32.1	51.8	80.5
PI/370	9.8	23.9	34.4	46.1	63.9	86.0
PE/370	5.8	16.1	25.2	36.8	56.3	82.7

Table 5.3. Summary for Grinding Details of PC and Perlites with Blaine Fineness Values of 320 and 370 m^2/kg

Material	PC/320	PI/320	PE/320	PC/370	PI/370	PE/370
Grinding Time (min)	95	70	45	120	80	60
Specific Gravity	3.12	2.35	2.36	3.13	2.35	2.36
Per. Ret. on 45-µm sieve	26.7	35.9	34.7	25.2	30.8	30.5
Median Particle Size (µm)	22.46	35.18	32.00	16.65	28.11	19.33

From Tables 5.2 and 5.3, it can be seen that the particle size distribution of PI gets slightly finer with increasing Blaine fineness. The median particle size for PI is decreased only around 20% (from 35.18 to 28.11 µm) with the increase of Blaine fineness from 320 to 370 m^2/kg. On the other hand, for the same change in the Blaine fineness, the particle size distribution of PE gets finer considerably. The median particle size for PE is decreased around 40% (from 32.00 to 19.33 µm). From this it may be concluded again that when ground in this grinding media, PE is finer than PI for the same Blaine. This can not be observed from Blaine fineness or 45-µm wet sieve analysis. Besides, when the particle size distribution of PC is examined, it is seen that it is finer than perlites for a given fineness.

5.3.1.1. Water Requirement and Strength Activity Index

The water requirement and strength activity indices of the ground perlites were determined according to ASTM C 311 [27]. The portland cement used in this test is PC/32, prepared in the laboratory. The results are given in Table 5.4.

Table 5.4. Water Requirement and Strength Activity Indices of PI, PE

Perlite	Blaine Fineness (m^2/kg)	Water Requirement (% of control)	Strength Activity Index	
			σ_7 (%)	σ_{28} (%)
PI	370	103	80.3	85.1
PE	370	100	83.0	85.9

When the water requirements of perlites are compared, it is seen that PE requires slightly more water than PI, which is expected due to its finer particle size distribution. The water requirement of blended cements will be discussed in section 5.3.2.2.

Strength activity indices at 7 and 28 days indicate that strength activity of PE is slightly higher than that of PI. The main reason for this can be finer particle size distribution of PE. 7 day strength activity indices are 80.3 and 83.0 % for PI and PE, respectively, due to little or no pozzolanic reactions occurred during the first 7 days of the hydration. 28 day, strength activity indices of perlites are increased to 85.1 and 85.9 respectively, which show the ongoing pozzolanic reactions.

5.3.2. Tests on Blended Cements

5.3.2.1. Specific Gravity, Fineness and Particle Size Distribution

For the blended cements with PI and PE, the variation of specific gravity, Blaine fineness, and percent material retained on 45-µm sieve with the grinding time is given in detail in Appendix A.2.

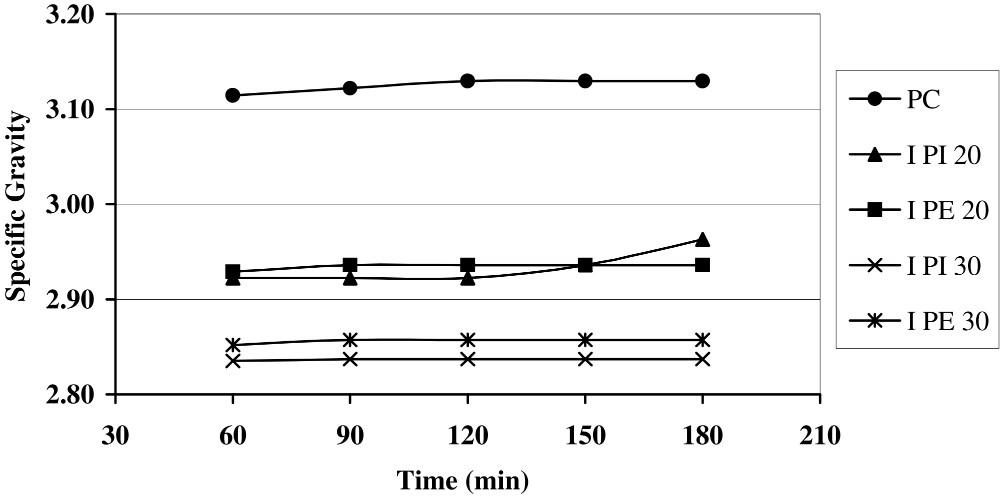

Figure 5.5. Variation of Specific Gravities of Blended Cements with Grinding Time

The specific gravities of blended cements are 7-10 % lower than ordinary portland cement, which are generally in line with the values in section 5.3.1. The specific gravities of blended cements do not change significantly with the increasing time as seen in Figure 5.5.

For the purpose of observing the effect of intergrinding on the specific gravities of blended cements, firstly specific gravities of the cements obtained by intergrinding at different periods were found. Then, the same type of cements (having the same material composition as that of interground cements) were produced by combining the "clinker + gypsum" and perlite that were ground separately for the same grinding periods as applied to the interground cements.

Table 5.5. Combined and Actual Specific Gravities of Cements Obtained by Intergrinding

Material	Grinding Time (min)				
	60	90	120	150	180
I PI 20	2.92	2.92	2.92	2.94	2.96
C PI 20	2.96	2.97	2.97	2.97	2.97
I PI 30	2.83	2.84	2.84	2.84	2.84
C PI 30	2.88	2.89	2.89	2.89	2.89
I PE 20	2.93	2.94	2.94	2.94	2.94
C PE 20	2.96	2.97	2.98	2.98	2.98
I PE 30	2.85	2.86	2.86	2.86	2.86
C PE 30	2.89	2.90	2.90	2.90	2.90

* The letter "I" in front of the cement type shows intergrinding.

** The letter "C" in frount of the cement type shows that the cement was obtained by combining the materials that were ground separately.

The specific gravities of cements obtained by intergrinding are lower than the ones obtained by combining separately ground materials. This shows that there is an interaction between perlite and clinker during the grinding process.

The Blaine fineness values of cements obtained by intergrinding or by combining separately ground materials are given in Table 5.6. Table 5.7 shows the percent retained on 45-µm sieve when wet sieved values for the same cements.

As seen from Table 5.6, Blaine fineness values for the cements obtained by intergrinding are lower than values for cements obtained by combining separately ground materials. Contrarily, from Table 5.7 it is observed that the percent retained on 45-µm sieve values for cements obtained by intergrinding are lower than the values for cements obtained by combining separately ground materials which may be due to perlite in the interground cement being relatively finer than the perlite ground separately.

Table 5.6. Blaine Values (m^2/kg) of Cements Obtained by Intergrinding or by Combining Separately Ground Materials

Material	Grinding Time (min)				
	60	90	120	150	180
I PI 20	249	318	377	431	475
C PI 20	262	335	394	461	491
I PI 30	239	310	370	422	463
C PI 30	267	344	405	474	510
I PE 20	263	335	389	442	498
C PE 20	275	345	404	470	499
I PE 30	277	343	406	453	501
C PE 30	286	359	420	488	521

Table 5.7. Percent Material Retained on 45-μm Sieve of Cements Obtained by Intergrinding or by Combining Separately Ground Materials

Material	Grinding Time (min)				
	60	90	120	150	180
I PI 20	37.7	29.5	23.8	19.9	18.2
C PI 20	38.1	27.5	23.8	20.8	19.7
I PI 30	37.8	30.5	21.4	19.5	15.4
C PI 30	38.5	27.8	23.1	20.0	18.8
I PE 20	36.7	27.1	22.9	20.6	19.2
C PE 20	36.0	26.0	22.9	20.4	19.5
I PE 30	36.7	25.9	18.2	16.1	15.6
C PE 30	35.3	25.6	21.8	19.4	18.5

For better understanding of the variations of the Blaine fineness and the percent material retained on 45-μm sieve with the grinding time two graphs are given in Figures 5.6 and 5.7 respectively.

From Figures 5.6 and 5.7, it can be observed that interground cements with PE results in much higher Blaine fineness values, and much lower percent material retained on 45-μm sieve values relative to PC. The increase in the amount of PE in the cement, results in additional increase in Blaine, and decrease in percent material retained values.

From the figures, it can be seen that interground cements with PI also results in higher Blaine Fineness values, and lower percent material retained on 45-μm sieve values relative to PC, but the changes are not as noticeable as the ones with PE. The increase in the amount of PI in the interground cement lowers the Blaine values, although it decreases the percent material retained on 45-μm sieve values.

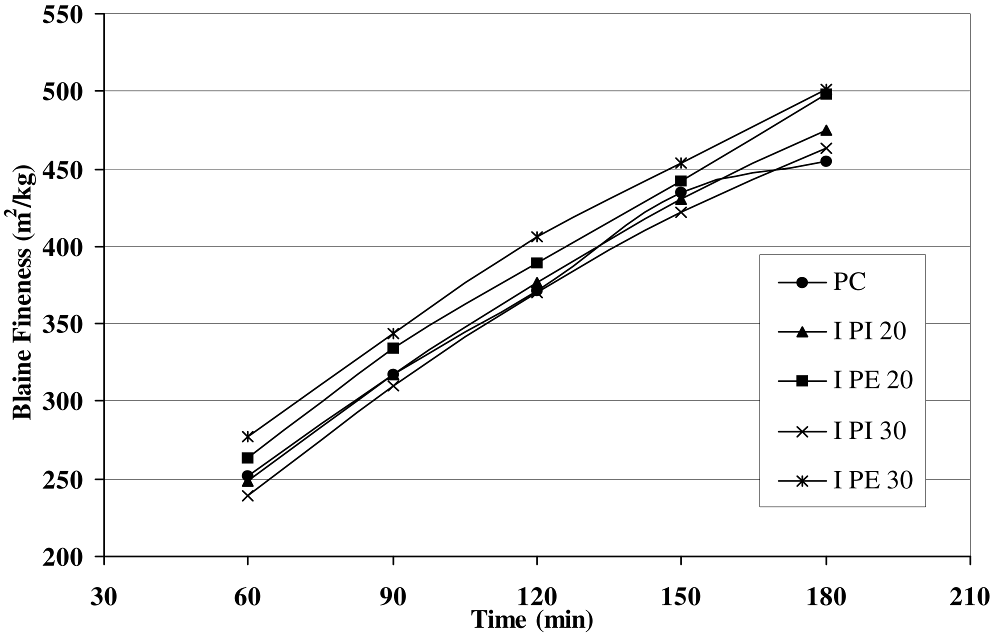

Figure 5.6. Variation of Blaine Fineness Values With Respect to Grinding Time for Interground Cements and PC

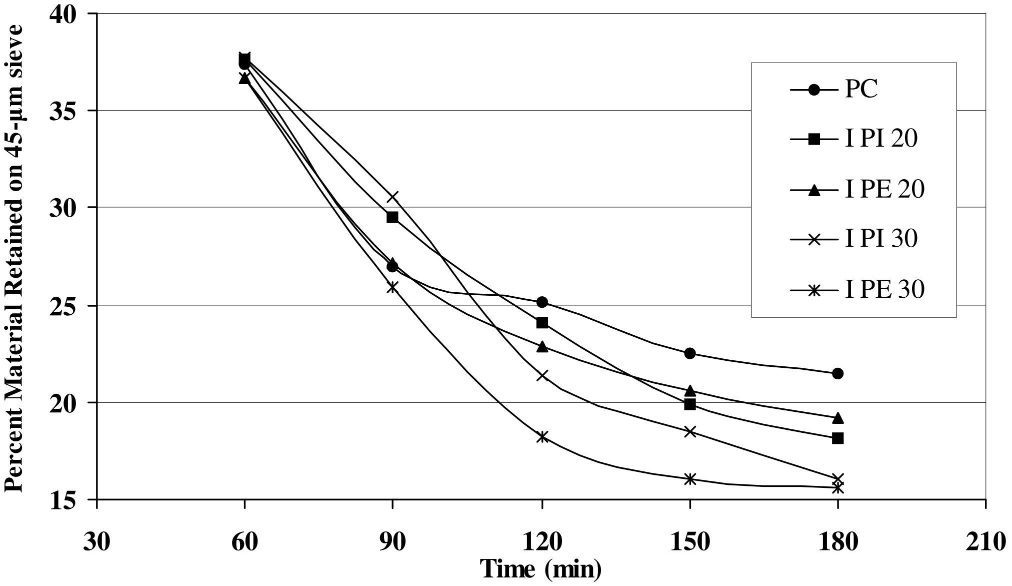

Figure 5.7. Variation of Percent Material Retained on 45-µm Sieve Values With Respect to Grinding Time for Interground Cements and PC

The grinding data obtained for cements with Blaine fineness of 320 and 370 m^2/kg which will be used in the further stages of the study is summarized in Tables 5.8 and 5.9.

Table 5.8. Summary of the Grinding Details of Perlites and PC with Blaine Fineness Values of 320 m^2/kg

Material	PC/320	PI/320	I PI 20/320	I PI 30/320	PE/320	I PE 20/320	I PE 30/320
Grinding Time (min)	95	70	90	97	45	87	82
Specific Gravity	3.12	2.35	2.92	2.84	2.36	2.94	2.86
Per. Ret. on 45-µm sieve	26.7	35.9	29.5	28.4	34.7	28.1	28.8
Median Particle Size (µm)	22.46	35.18	20.84	22.46	32.00	20.84	20.84

Table 5.9. Summary of the Grinding Details of Perlites with Blaine Fineness Values of 370 m^2/kg

Material	PC/370	PI/370	I PI 20/370	I PI 30/370	PE/370	I PE 20/370	I PE 30/370
Grinding Time (min)	120	80	115	120	60	108	101
Specific Gravity	3.13	2.35	2.92	2.84	2.36	2.94	2.86
Per. Ret. on 45-µm sieve	25.2	30.8	23.8	21.4	30.5	24.6	25.9
Median Particle Size (µm)	16.65	28.11	17.94	16.65	19.33	16.65	19.33

For better understanding of the grinding performance, laser particle size distributions of blended cements with Blaine fineness 320 and 370 m^2/kg are determined. The results of the laser particle size distributions of interground and separately ground cements together with particle size distributions of PC, PI and

PE are given in Table 5.10. The values for separately ground cements are calculated by the weighted mean of the values for the PC and perlite in consideration. The detailed particle size distributions are given in Appendix A.1.

Table 5.10. Particle Size Distributions of the Cements Used in the Study

Material	Size (μm)					
	>93	>59	>44	>30	>15	>5
PC/320	4.0	15.8	26.7	39.8	58.8	84.4
PI/320	13.9	30.1	40.6	52.0	68.5	87.9
PE/320	12.5	28.7	39.4	51.2	68.1	87.0
S PI 20/320-320	6.0	18.7	29.5	42.3	60.7	85.1
S PE 20/320-320	5.7	18.4	29.2	42.1	60.7	84.9
I PI 20/320	6.5	18.0	27.2	39.2	58.7	83.3
I PE 20/320	4.3	15.0	25.0	37.8	57.3	83.2
S PI 30/320-320	7.0	20.1	30.9	43.5	61.7	85.5
S PE 30/320-320	6.5	19.7	30.5	43.3	61.6	85.2
I PI 30/320	5.7	17.5	27.4	39.8	58.8	83.4
I PE 30/320	5.1	16.4	26.2	38.3	57.5	83.3
S PI 20/320-370	5.2	17.4	28.2	41.1	59.8	84.7
S PE 20/320-370	4.4	15.9	26.4	39.2	58.3	84.1
S PI 30/320-370	5.7	19.8	31.7	45.7	66.2	93.3
S PE 30/320-370	4.5	17.5	28.9	42.9	63.9	92.3
PC/370	3.2	12.2	20.6	32.1	51.8	80.5
PI/370	9.8	23.9	34.4	46.1	63.9	86.0
PE/370	5.8	16.1	25.2	36.8	56.3	82.7
S PI 20/370-370	4.5	14.5	23.3	34.9	54.2	81.6
S PE 20/370-370	3.7	12.9	21.5	33.1	52.7	80.9

I PI 20/370	2.7	11.8	21.0	33.5	53.4	81.1
I PE 20/370	2.6	10.9	20.2	32.7	52.4	80.3
S PI 30/370-370	5.2	15.7	24.7	36.3	55.4	82.1
S PE 30/370-370	4.0	13.3	22.0	33.5	53.2	81.1
I PI 30/370	3.2	12.6	21.4	33.3	52.7	81.0
I PE 30/370	2.2	11.9	21.7	35.0	55.9	81.8

The variations of the particle size distributions are also presented comparatively in Tables 5.11 and 5.12 for better analysis of the data. In Table 5.11, the values for cements obtained by intergrinding are expressed as the percentages of the values for the PC at the same fineness.

Table 5.11. Comparison of the Particle Size Distributions of Blended Cements Obtained by Intergrinding Relative to PC Having the Same Fineness

Material	Size (μm)					
	>93	>59	>44	>30	>15	>5
PC/320	100	100	100	100	100	100
I PI 20/320	163	114	102	98	100	99
I PE 20/320	107	95	94	95	97	98
I PI 30/320	142	111	103	100	100	99
I PE 30/320	128	104	98	96	98	99
PC/370	100	100	100	100	100	100
I PI 20/370	86	97	102	104	103	101
I PE 20/370	81	90	98	102	101	100
I PI 30/370	102	104	104	104	102	101
I PE 30/370	69	98	105	109	108	102

From Table 5.11, it has been observed that interground cements with PI are coarser than interground cements with PE, and they are coarser than PC for lower Blaine values. However, as the Blaine increases, accordingly as the grinding time increases, intergrinding with perlite results in a considerably finer particle size distribution.

In Table 5.12, the values for cements obtained by separate grinding are expressed as the percentages of the values for interground cements having the same fineness and composition.

Table 5.12. Variation in Particle Size Distributions of Separately Ground Cements Relative to Interground Cements Having Same Fineness and Composition

Material	Size (μm)					
	>93	>59	>44	>30	>15	>5
I/320	100	100	100	100	100	100
S PI 20/320-320	92	104	108	108	103	102
S PE 20/320-320	134	123	117	111	106	102
S PI 30/320-320	122	115	113	109	105	103
S PE 30/320-320	128	120	117	113	107	102
I/370	100	100	100	100	100	100
S PI 20/370-370	165	123	111	104	101	101
S PE 20/370-370	144	119	107	101	101	101
S PI 30/370-370	159	125	115	109	105	101
S PE 30/370-370	180	112	101	96	95	99

From Table 5.12, it has been observed that the particle size distributions of separately ground cements are generally coarser than interground cements especially for higher Blaine values. In other words, interground provides finer cements and the increasing grinding time enlarges the gap between the particle size distributions of cements produced by intergrinding and separate grinding, mainly due the high amount of interactions during grinding.

It is shown in previous studies that the harder component (clinker in the case of clinker-natural pozzolan; or slag, in the case of slag-clinker mixes) acts as a grinding media to the softer one. [58, 23] Therefore the finer particle size distribution of interground cements can be explained as follows: the separately ground perlites have a coarser particle size distribution when compared to clinker for a given Blaine fineness as seen in Table 5.2. It is also seen from Table 5.10 that when separately ground PC and perlite are mixed, the resultant cement is coarser than PC. Therefore, during intergrinding the increased fineness of perlite can not be explained only by the steel charges, but also by the clinker. The interactions between clinker and perlite yielded in a finer particle size distribution.

From Table 5.10, it has been observed that the blended cements with higher perlite content are slightly coarser than that of lower perlite content not only for separately ground cements, but also for interground cements. The reduction in the fineness of interground cements with higher perlite content can be explained with the increase in the perlite content and the reduction in the interactions between clinker and perlite.

5.3.2.2. Normal Consistency, Setting Time and Autoclave Expansion

Normal consistency, setting time and autoclave expansion tests were performed on the cement pastes made with blended cements with different proportioning of materials. The test results are given in Table 5.13 and Figure

5.8. Normal consistencies of the cements are expressed as the ratio of the amount of water required for normal consistency to the dry weight of cement.

Table 5.13. Normal Consistency and Autoclave Expansion Results

Cement	Normal Consistency (%)	Autoclave Expansion (%)	Cement	Normal Consistency (%)	Autoclave Expansion (%)
PC/320	23.4	0.07	PC/370	23.5	0.06
S PI 20/320-320	24.2	0.05	S PI 20/370-370	24.8	0.04
S PI 30/320-320	24.2	0.02	S PI 30/370-370	25.4	0.02
I PI 20/320	24.0	0.05	I PI 20/370	24.8	0.04
I PI 30/320	24.3	0.02	I PI 30/370	25.2	0.02
S PE 20/320-320	24.3	0.07	S PE 20/370-370	24.8	0.06
S PE 30/320-320	24.7	0.06	S PE 30/370-370	25.4	0.04
I PE 20/320	24.2	0.06	I PE 20/370	24.8	0.06
I PE 30/320	24.8	0.05	I PE 30/370	25.4	0.04
S PI 20/320-370	24.0	0.05	S PE 20/320-370	24.4	0.06
S PI 30/320-370	24.5	0.02	S PE 30/320-370	25.0	0.05

From Table 5.13, it is seen that blended cements with perlite require slightly higher water for normal consistency relative to PC. For blended cements with same composition, the type of grinding, soure of perlite, or increase in the introduced perlite's fineness (in this case from 320 m^2/kg Blaine to 370 m^2/kg) does not affect the required water considerably. On the other hand, the increase in the amount of perlite in the blended cements from 20% to 30% yields in slightly higher water requirement which may be due to absorption of some water by perlite.

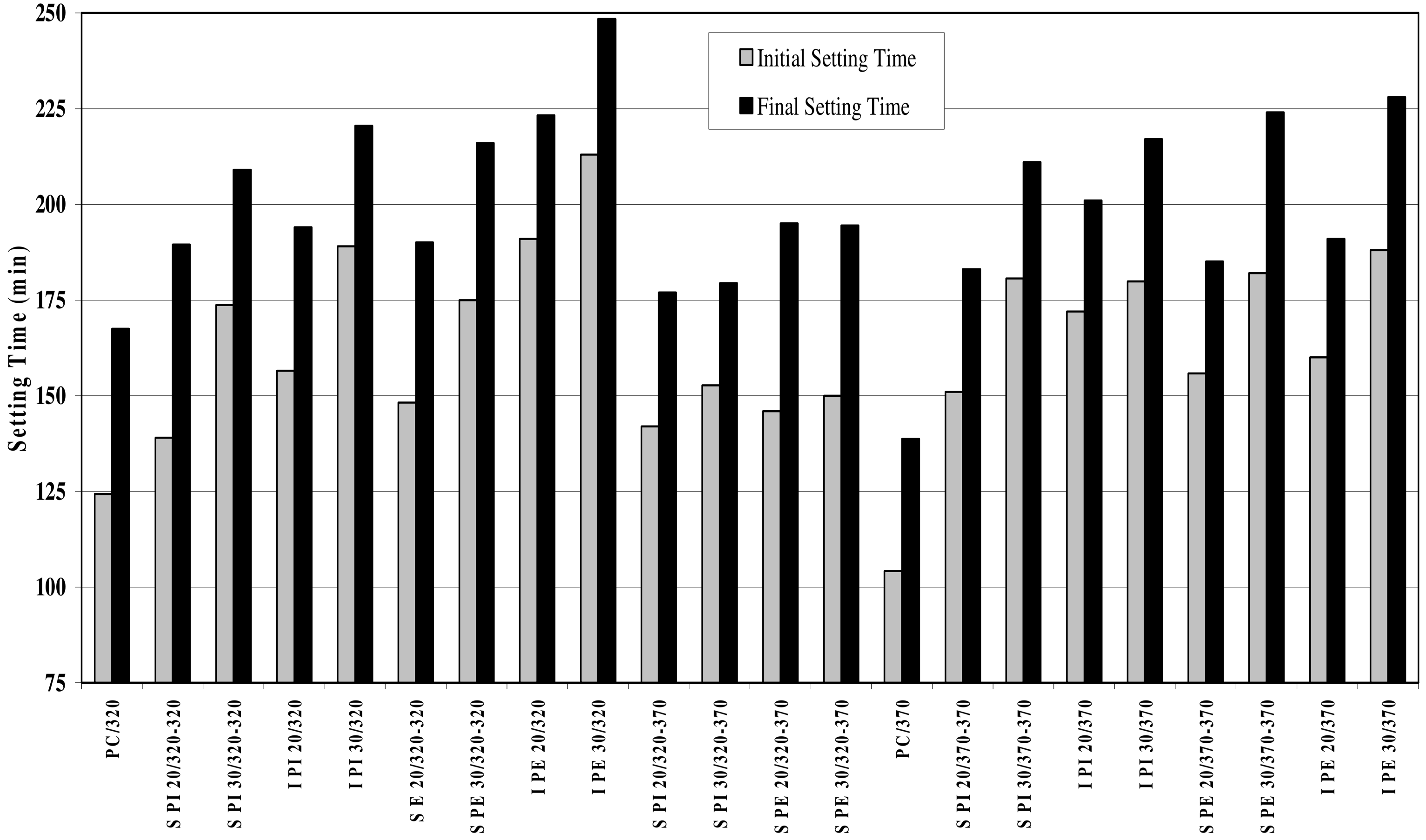

Figure 5.8. Setting Times of Cements

From Table 5.13, it is seen that the autoclave expansion test results are far below the ASTM C 1157 limitations (0.80%). However, it can also be concluded that autoclave expansions are reduced with perlite introduction mainly related with the decrease in the cement content. The increase in the perlite content decreases the autoclave expansion values as expected. Type of grinding, or increase in the introduced perlite's fineness does not change the autoclave expansion notably for blended cements. Besides, it is observed that cements with PE results in negligibly higher autoclave expansion values than that of PI for same fineness values, and composition possibly due to higher MgO content.

The ASTM C 1157 limits the initial and final setting times as 45 min. and 420 min. respectively. From Figure 5.8, it is seen that all of the produced cements satisfy the requirement. It is also observed that perlite introduction increases the initial and final setting times considerably relative to PC. For blended cements, the initial and final setting times of separately ground cements are generally shorter than that of interground cements. It is also noticed that as the perlite content in the blended cement increases the initial and final setting times lengthen notably, again due to the reduction in the cement content. Besides, the introduction in the perlite's fineness generally shortens the initial and final setting times.

5.3.2.3. Compressive Strength of Mortars

Mortars for compressive strength tests were prepared in accordance with ASTM C 109 [15]. Compressive strengths of mortars made with blended cements and portland cements were determined for 2, 3, 7, 56, and 91 days of age and given in Table 5.14 together with the flow values and water/binder ratios of fresh mortars. Flows for mortars with PC/320 and PC/370 are 97 and 100 respectively. For the mortars with blended cements, a flow value of 110±5 is chosen as stated in ASTM C 109 [15].

Table 5.14. Water – Binder Ratio, Flow and Compressive Strength of Mortars

Cement	Water/ Binder	Flow (%)	Compressive Strength (MPa)					
			σ_2	σ_3	σ_7	σ_{28}	σ_{56}	σ_{91}
PC/320	0.48	97	22.5	24.4	35.5	49.6	51.5	53.6
I PI 20/320	0.50	111	17.5	20.8	29.1	39.6	46.8	51.3
I PE 20/320	0.50	106	17.7	21.5	29.5	42.8	46.0	51.7
S PI 20/320-320	0.50	108	17.5	21.7	26.1	41.8	47.2	50.2
S PE 20/320-320	0.50	110	17.9	21.8	26.6	38.1	47.6	50.4
I PI 30/320	0.51	114	15.1	15.9	26.9	40.3	44.3	46.3
I PE 30/320	0.51	115	14.1	18.7	27.9	35.5	44.3	46.5
S PI 30/320-320	0.51	109	13.7	16.6	27.6	34.7	40.1	42.6
S PE 30/320-320	0.51	111	12.6	17.5	27.0	35.3	42.4	45.3
S PI 20/320-370	0.51	112	16.9	21.8	29.3	42.7	48.4	52.0
S PE 20/320-370	0.51	112	19.4	21.2	28.3	40.4	49.2	51.7
S PI 30/320-370	0.51	108	15.7	17.1	27.7	39.8	44.2	47.4
S PE 30/320-370	0.51	108	14.2	17.9	27.2	37.6	42.8	46.6
PC/370	0.48	100	25.4	28.5	38.5	50.8	52.8	54.2
S PI 20/370-370	0.50	106	17.8	22.3	30.0	43.3	48.1	53.4
S PE 20/370-370	0.50	110	20.7	22.7	31.7	43.7	50.4	53.1
I PI 20/370	0.50	110	22.0	22.8	30.4	44.9	47.8	53.4
I PE 20/370	0.50	109	18.9	24.4	32.1	47.7	50.3	56.1
S PI 30/370-370	0.52	112	16.7	19.1	28.6	40.0	46.0	48.2
S PE 30/370-370	0.52	107	18.6	19.5	28.3	39.8	44.6	49.8
I PI 30/370	0.52	109	16.9	19.9	30.6	41.0	45.3	48.6
I PE 30/370	0.52	108	19.1	18.9	30.6	41.9	47.0	50.7

From Table 5.14, it is seen that water requirement for cements with same composition are equal, which also means water requirement is not affected notably by the grinding type, or source of perlite. Besides, it is seen that as the perlite amount increases so does the water requirement which may be related with some water absorbed by perlite particles.

The blended cements produced can be categorized as Type GU cement according to ASTM C 1157 [29] that limits the strength ranges as 10 to 20 MPa, and 17 to 30 MPa for 3, and 7 days respectively. As seen from table 5.14, the produced cements generally satisfy the strength requirements of ASTM C 1157 [29]. Some compressive strengths exceed the maximum limitations of 20 and 30 MPa.

For better understanding of compressive strength of mortars made with blended cements and portland cements, the strength values are expressed as percentages of the values for the PC as the same fineness (for S/320-370 as PC/320) in Table 5.15.

From Table 5.15, it is seen that perlite introduction reduce the initial strength of cement mortars for the first 2-3 days considerably relative to PC. But after 7 days, strength values of blended cements start to rise more firmly by catching up to 75% of the strength values of PC which is expected since the cement content is reduced and the contribution of the pozzolan to strength development occurs sometime after 7 days hydration [31]. With increasing time, the difference between the compressive strengths of blended cements and PC continues to decrease.

From Table 5.15, it is seen that the separately ground cements results in lower strength values relative to interground cements. The lower strength of separately ground cements may be explained not only by their coarser particle size distribution, but also by them being less homogeneous than cements obtained by intergrinding.

Table 5.15. Compressive Strength of Blended Cements Relative to PC

Cement	Compressive Strength (% of strength of mortar with PC)					
	σ_2	σ_3	σ_7	σ_{28}	σ_{56}	σ_{90}
PC/320	100	100	100	100	100	100
I PI 20/320	78	85	82	80	91	96
I PE 20/320	78	88	83	86	89	97
S PI 20/320-320	78	89	74	84	92	94
S PE 20/320-320	79	89	75	77	92	94
I PI 30/320	67	65	76	81	86	86
I PE 30/320	62	77	79	72	86	87
S PI 30/320-320	61	68	78	70	78	80
S PE 30/320-320	56	72	76	71	82	85
S PI 20/320-370	75	89	83	86	94	97
S PE 20/320-370	86	87	80	81	96	96
S PI 30/320-370	70	70	78	80	86	88
S PE 30/320-370	63	73	77	76	83	87
PC/370	100	100	100	100	100	100
S PI 20/370-370	70	78	78	85	91	98
S PE 20/370-370	81	79	82	86	96	98
I PI 20/370	87	80	79	88	91	99
I PE 20/370	74	86	84	94	95	104
S PI 30/370-370	66	67	74	79	87	89
S PE 30/370-370	73	68	74	78	85	92
I PI 30/370	66	70	80	81	86	90
I PE 30/370	75	66	80	83	89	93

From Table 5.15, it is also observed that the increase in the introduced perlite's fineness increase the resultant strengths considerably as expected.

From the table, it can be concluded that blended cements with PE generally have higher strength values than blended cements with PI for long and short term. The reason for this can be strength activity index of PE. For short term higher strength values, the finer particle size distribution of cements with PE can also be said.

From the table, it can be observed that as the perlite content increases the strength decreases especially for the short term for the blended cements with the same perlite, and same Blaine fineness. This may be explained by their low PC content and slightly higher water - binder ratio. The difference between those strengths gets considerably smaller with age.

CHAPTER 6

CONCLUSIONS

Pozzolanic materials are widely used in the cement and concrete industry. They are either interground with portland cement clinker (and some small amount of gypsum) to produce blended cements, or used as finely divided admixtures in making portland-pozzolan type concrete.

Although various types of pozzolans are used in the cement and concrete industry, perlite has never been commercially used so far.

Considering that perlite might possess suitable properties for use in the cement and concrete industry, its properties were thought to be worth investigating.

Knowing that approximately two-thirds of the world reserves are in Turkey, perlite was obtained from two different sources (Izmir and Erzincan) and tests were conducted on these samples. In addition to the studies for determining the pozzolanic properties of those perlites, several blended cements were produced by separate grinding or intergrinding, using perlite replacement amounts of 20% or 30% at a Blaine fineness of 320 or 370 m^2/kg.

The following conclusions were derived as a result of the tests conducted on Turkish perlites and the cements produced with them:

1. Turkish perlites possess sufficient pozzolanic characteristics to be used in cement and concrete industry. They satisfy the requirements given in ASTM C 618.

2. All blended cements with perlite satisfy the setting time, autoclave expansion and compressive strength requirements given in ASTM C 1157.
3. Interground blended cements give slightly higher compressive strength values as compared to those produced by combining separately ground materials. On the other hand, when the fineness of the perlite in blended cements obtained by separately grinding is increased the strength values increase considerably.
4. Perlites are softer to grind than the portland cement clinkers. Therefore, it requires less energy to produce blended cements by intergrinding the clinker and the perlite together, or by combining the separately ground perlite and clinker as compared to that required to grind only the clinker for portland cement production.
5. Blended cements produced by 20% perlite addition give higher strength values than those produced by 30% perlite having the same fineness values. However, the strength difference between these two types of cements gets less in the long run.

CHAPTER 7

RECOMMENDATIONS

In this study, pozzolanic properties of perlite, and some basic properties of blended cements with perlite are investigated. The studies should be continued with using different fineness values and compositions.

Further studies should also be made to determine the durability characteristics of the produced cements such as sulfate resistance and reactivity with alkali-reactive aggregates.

Properties of fresh and hardened concrete prepared with blended cements with perlite should also be determined.

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APPENDICES

A.1. Particle Size Distributions

a) Particle Size Distributions for PI, PE, PC and Interground Cements with Blaine Fineness Value of 320 m^2/kg

Size (*μm*)	Materials PI/320	PE/320	PC/320	I PI 20/320	I PI 30/320	I PE 20/320	I PE 30/320
0.533	0.08	0.11	0.15	0.10	0.09	0.10	0.08
0.574	0.18	0.23	0.32	0.21	0.18	0.21	0.17
0.618	0.32	0.40	0.56	0.37	0.33	0.37	0.30
0.666	0.50	0.63	0.87	0.58	0.53	0.58	0.47
0.718	0.72	0.88	1.22	0.82	0.75	0.82	0.68
0.774	0.96	1.13	1.58	1.08	1.00	1.09	0.90
0.834	1.2	1.38	1.92	1.35	1.26	1.36	1.15
0.899	1.46	1.62	2.26	1.63	1.54	1.64	1.41
0.969	1.73	1.86	2.58	1.92	1.83	1.94	1.70
1.04	2.01	2.10	2.91	2.22	2.14	2.25	2.00
1.13	2.29	2.33	3.22	2.53	2.47	2.58	2.33
1.21	2.59	2.56	3.53	2.85	2.82	2.92	2.68
1.31	2.89	2.79	3.83	3.19	3.18	3.27	3.05
1.41	3.19	3.02	4.14	3.55	3.57	3.65	3.44
1.52	3.50	3.27	4.45	3.93	3.97	4.04	3.86
1.64	3.83	3.53	4.78	4.34	4.41	4.46	4.32
1.76	4.16	3.82	5.13	4.77	4.87	4.91	4.80
1.90	4.50	4.13	5.50	5.25	5.37	5.39	5.32
2.05	4.87	4.48	5.92	5.77	5.90	5.92	5.88
2.21	5.25	4.88	6.38	6.33	6.47	6.48	6.49
2.38	5.66	5.32	6.89	6.95	7.09	7.10	7.14

2.56	6.10	5.82	7.45	7.63	7.77	7.77	7.83
2.76	6.58	6.39	8.08	8.37	8.49	8.50	8.58
2.98	7.10	7.01	8.77	9.18	9.28	9.29	9.39
3.21	7.66	7.69	9.52	10.15	10.13	10.14	10.25
3.46	8.27	8.44	10.35	11.00	11.04	11.07	11.17
3.73	8.93	9.25	11.25	12.01	12.02	12.07	12.15
4.02	9.64	10.12	12.21	13.09	13.07	13.14	13.20
4.33	10.42	11.04	13.25	14.24	14.20	14.29	14.31
4.66	11.25	12.01	14.37	15.46	15.39	15.52	15.50
5.03	12.14	13.03	15.56	16.73	16.65	16.83	16.75
5.42	13.09	14.1	16.84	18.07	17.98	18.21	18.08
5.84	14.10	15.19	18.19	19.46	19.38	19.67	19.48
6.29	15.16	16.32	19.63	20.90	20.83	21.20	20.95
6.78	16.28	17.48	21.14	22.39	22.34	22.79	22.48
7.31	17.44	18.65	22.73	23.92	23.90	24.43	24.08
7.88	18.66	19.85	24.39	25.49	25.50	26.13	25.74
8.49	19.93	21.07	26.11	27.09	27.13	27.87	27.45
9.15	21.24	22.3	27.89	28.73	28.80	29.64	29.21
9.86	22.59	23.56	29.72	30.40	30.49	31.45	31.02
10.62	23.98	24.85	31.58	32.10	32.22	33.27	32.87
11.45	25.41	26.17	33.47	33.84	33.96	35.12	34.75
12.34	26.88	27.52	35.38	35.63	35.73	36.99	36.66
13.30	28.39	28.93	37.31	37.46	37.53	38.88	38.60
14.33	29.94	30.39	39.25	39.33	39.36	40.79	40.56
15.45	31.52	31.91	41.19	41.26	41.22	42.72	42.55
16.65	33.15	33.50	43.15	43.24	43.13	44.69	44.56
17.94	34.83	35.16	45.12	45.27	45.07	46.69	46.59
19.33	36.54	36.88	47.12	47.36	47.07	48.74	48.64
20.84	38.31	38.69	49.14	49.50	49.11	50.83	50.73
22.46	40.12	40.56	51.22	51.69	51.21	52.98	52.85
24.20	41.99	42.51	53.35	53.92	53.37	55.18	55.00
26.08	43.92	44.53	55.54	56.20	55.59	57.45	57.19
28.11	45.91	46.62	57.82	58.50	57.86	59.78	59.43
30.29	47.97	48.77	60.17	60.84	60.19	62.18	61.71
32.00	49.53	50.39	61.96	62.56	61.94	63.97	63.41

35.18	52.31	53.28	65.16	65.57	65.02	67.15	66.42
37.92	54.59	55.63	67.81	67.96	67.52	69.75	68.85
40.86	56.95	58.06	70.55	70.37	70.05	72.40	71.33
44.04	59.39	60.56	73.33	72.77	72.60	75.04	73.83
48.00	62.30	63.53	76.54	75.50	75.51	78.04	76.70
51.15	64.50	65.78	78.89	77.49	77.64	80.20	78.80
55.12	67.17	68.50	81.59	79.79	80.10	82.67	81.23
59.41	69.93	71.27	84.19	82.04	82.50	85.03	83.58
64.00	72.73	74.07	86.63	84.20	84.80	87.23	85.82
69.00	75.56	76.90	88.93	86.30	87.01	89.29	87.96
74.36	78.34	79.68	91.01	88.30	89.08	91.17	89.95
80.14	81.06	82.41	92.89	90.17	91.00	92.87	91.77
86.36	83.67	85.05	94.55	91.91	92.75	94.39	93.43
93.07	86.15	87.54	96.00	93.50	94.32	95.74	94.90
100.3	88.46	89.87	97.22	94.92	95.69	96.91	96.18
108.1	90.57	91.99	98.22	96.18	96.87	97.89	97.28
116.5	92.47	93.88	99.00	97.25	97.86	98.70	98.19
125.6	94.15	95.52	99.58	98.15	98.67	99.41	98.92
135.3	95.62	96.90	99.93	98.88	99.28	99.90	99.46
145.8	96.88	98.02	100.00	99.46	99.71	100.00	99.81
157.2	97.93	98.90	100.00	99.87	99.95	100.00	99.97
169.4	98.77	99.54	100.00	99.99	100.00	100.00	100.00
182.5	99.39	99.92	100.00	100.00	100.00	100.00	100.00
196.7	99.77	100.00	100.00	100.00	100.00	100.00	100.00
213.0	99.94	100.00	100.00	100.00	100.00	100.00	100.00
228.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00
246.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00
265.4	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Median	*35.18*	*32.00*	*22.46*	*22.46*	*22.46*	*20.84*	*20.84*

b) Particle Size Distributions for PI, PE, PC and Interground Blended Cements with Blaine Fineness Value of 370 m^2/kg

Size	Materials						
(μm)	PI/370	PE/370	PC/370	I PI 20/370	I PI 30 /370	I PE 20/370	I PE 30/370
0.533	0.09	0.10	0.09	0.13	0.13	0.12	0.13
0.574	0.19	0.20	0.18	0.27	0.26	0.25	0.27
0.618	0.35	0.37	0.33	0.48	0.47	0.46	0.49
0.666	0.55	0.59	0.52	0.76	0.75	0.73	0.78
0.718	0.78	0.84	0.75	1.08	1.07	1.04	1.11
0.774	1.02	1.11	1.01	1.43	1.42	1.38	1.47
0.834	1.27	1.41	1.29	1.79	1.78	1.74	1.84
0.899	1.54	1.72	1.59	2.17	2.16	2.12	2.22
0.969	1.81	2.05	1.92	2.56	2.55	2.51	2.62
1.04	2.10	2.4	2.28	2.96	2.96	2.93	3.04
1.13	2.39	2.76	2.66	3.38	3.38	3.36	3.46
1.21	2.70	3.15	3.07	3.81	3.80	3.81	3.89
1.31	3.02	3.55	3.50	4.24	4.24	4.27	4.33
1.41	3.35	3.98	3.97	4.69	4.70	4.75	4.79
1.52	3.71	4.42	4.47	5.16	5.16	5.25	5.25
1.64	4.08	4.90	5.00	5.64	5.64	5.77	5.73
1.76	4.47	5.39	5.57	6.14	6.15	6.31	6.23
1.90	4.89	5.92	6.18	6.67	6.68	6.89	6.75
2.05	5.34	6.49	6.83	7.23	7.24	7.50	7.30
2.21	5.83	7.09	7.53	7.83	7.85	8.16	7.89
2.38	6.35	7.74	8.29	8.48	8.50	8.86	8.52
2.56	6.91	8.43	9.10	9.19	9.20	9.62	9.19
2.76	7.51	9.18	9.97	9.95	9.97	10.44	9.92
2.98	8.15	9.97	10.91	10.79	10.81	11.32	10.71
3.21	8.84	10.83	11.91	11.69	11.72	12.28	11.57
3.46	9.58	11.74	12.99	12.68	12.71	13.31	12.49
3.73	10.36	12.72	14.14	13.75	13.78	14.50	13.48
4.02	11.20	13.77	15.36	14.9	14.95	15.60	14.55
4.33	12.09	14.88	16.67	16.15	16.2	16.87	15.69

4.66	13.04	16.06	18.06	17.48	17.55	18.23	16.9
5.03	14.04	17.32	19.53	18.89	18.99	19.66	18.18
5.42	15.10	18.65	21.08	20.39	20.51	21.18	19.54
5.84	16.23	20.05	22.71	21.96	22.12	22.76	20.96
6.29	17.41	21.53	24.41	23.61	23.80	24.42	22.45
6.78	18.66	23.08	26.17	25.32	25.56	26.15	23.99
7.31	19.97	24.70	28.00	27.09	27.38	27.93	25.60
7.88	21.34	26.39	29.88	28.91	29.25	29.77	27.25
8.49	22.78	28.13	31.81	30.78	31.17	31.65	28.95
9.15	24.27	29.94	33.78	32.67	33.13	33.57	30.7
9.86	25.82	31.8	35.78	34.6	35.11	35.52	32.49
10.62	27.42	33.7	37.8	36.55	37.12	37.49	34.32
11.45	29.07	35.65	39.85	38.52	39.14	39.48	36.19
12.34	30.76	37.63	41.92	40.5	41.18	41.49	38.1
13.30	32.49	39.63	44.00	42.5	43.22	43.51	40.05
14.33	34.26	41.67	46.09	44.52	45.27	45.54	42.05
15.45	36.06	43.72	48.19	46.56	47.32	47.58	44.10
16.65	37.89	45.8	50.31	48.62	49.39	49.64	46.19
17.94	39.75	47.89	52.44	50.71	51.47	51.72	48.34
19.33	41.65	50.01	54.58	52.84	53.57	53.82	50.54
20.84	43.57	52.14	56.75	55.00	55.69	55.95	52.8
22.46	45.54	54.3	58.93	57.3	57.83	58.12	55.12
24.20	47.54	56.48	61.13	59.46	60.01	60.34	57.50
26.08	49.59	58.69	63.36	61.76	62.22	62.6	59.95
28.11	51.70	60.93	65.6	64.11	64.46	64.91	62.44
30.29	53.86	63.19	67.88	66.52	66.74	67.29	65.01
32.00	55.48	64.86	69.57	68.32	68.44	69.07	66.93
35.18	58.37	67.79	72.51	71.50	71.42	72.22	70.32
37.92	60.73	70.12	74.83	74.03	73.81	74.75	73.01
40.86	63.14	72.48	77.13	76.56	76.2	77.3	75.69
44.04	65.62	74.84	79.41	79.05	78.57	79.84	78.34
48.00	68.56	77.55	81.96	81.85	81.24	82.69	81.33
51.15	70.79	79.5	83.79	83.84	83.16	84.71	83.45
55.12	73.46	81.76	85.87	86.08	85.34	86.98	85.86
59.41	76.12	83.93	87.84	88.18	87.41	89.08	88.13

64.00	78.72	85.99	89.7	90.13	89.35	90.99	90.23
69.00	81.28	87.95	91.44	91.92	91.17	92.71	92.16
74.36	83.73	89.75	93.02	93.52	92.83	94.2	93.89
80.14	86.06	91.4	94.45	94.95	94.31	95.48	95.41
86.36	88.22	92.89	95.72	96.20	95.62	96.55	96.72
93.07	90.21	94.22	96.83	97.27	96.76	97.44	97.80
100.3	92.01	95.4	97.78	98.17	97.74	98.15	98.67
108.1	93.62	96.44	98.55	98.88	98.53	98.73	99.37
116.5	95.06	97.32	99.16	99.42	99.16	99.18	99.83
125.6	96.32	98.07	99.64	99.78	99.64	99.53	99.97
135.3	97.39	98.68	99.94	99.97	99.94	99.77	100.00
145.8	98.28	99.16	100.00	100.00	100.00	99.89	100.00
157.2	98.99	99.5	100.00	100.00	100.00	99.97	100.00
169.4	99.55	99.71	100.00	100.00	100.00	100.00	100.00
182.5	99.92	99.83	100.00	100.00	100.00	100.00	100.00
196.7	100.00	99.91	100.00	100.00	100.00	100.00	100.00
213.0	100.00	99.97	100.00	100.00	100.00	100.00	100.00
228.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00
246.5	100.00	100.00	100.00	100.00	100.00	100.00	100.00
265.4	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Median	*28.11*	*19.33*	*16.65*	*17.94*	*17.94*	*17.94*	*19.33*

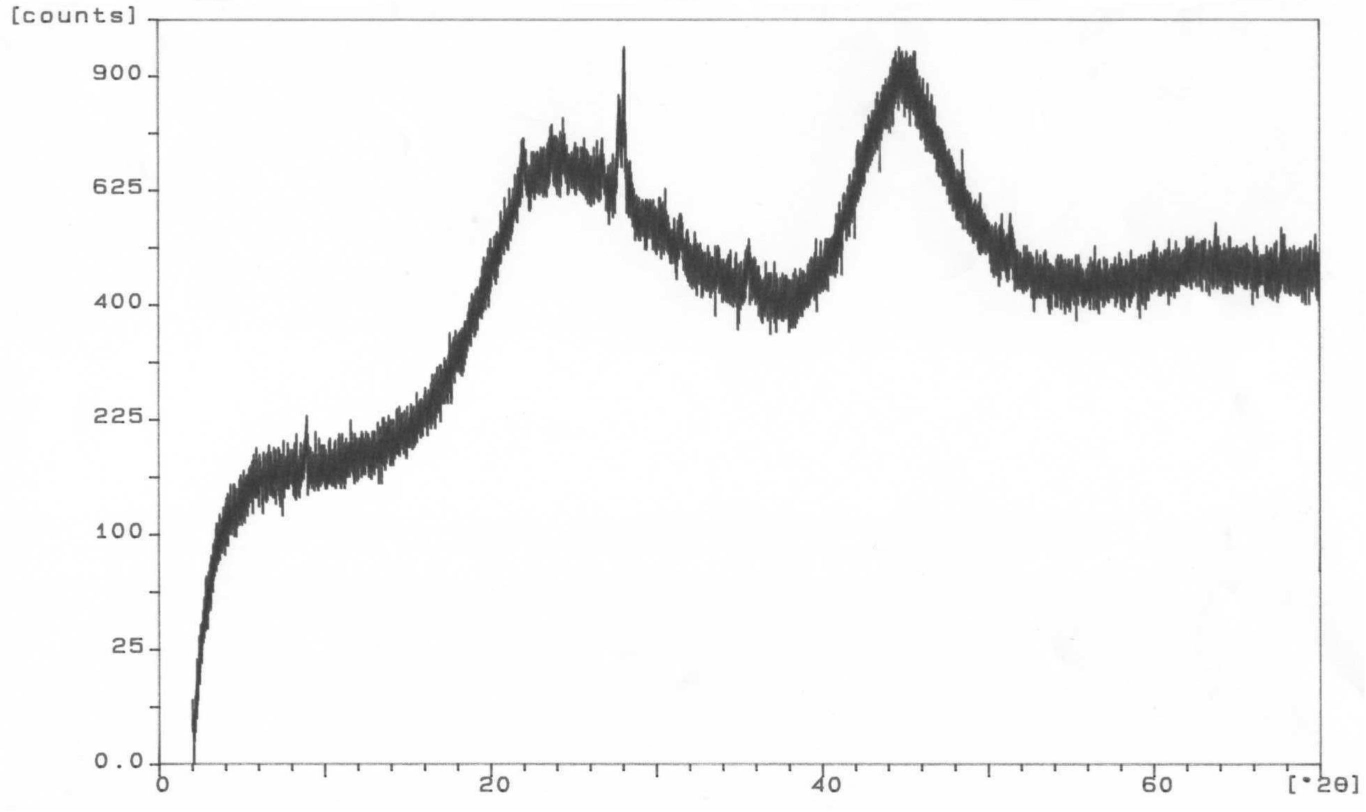
A.2. Variation of Specific Gravity, Blaine Fineness and Percent Retained on 45-μm Sieve When Wet Sieved Values of PC, PI, PE and Interground Blended Cements with Grinding Time

Material	Time (min)	Specific Gravity	45μm (%)*	Blaine Fineness (m^2/kg)	Median Particle Size (μm)
PC	60	3.11	37.4	252	-
PC	90	3.12	27.0	317	-
PC	95	3.12	26.7	321	22.46
PC	120	3.13	25.2	371	16.65
PC	150	3.13	22.5	435	-
PC	180	3.13	21.5	455	-
PI	60	2.35	41.0	303	-
PI	70	2.35	35.9	320	35.18
PI	80	2.35	30.8	372	28.11
PI	90	2.35	29.9	408	-
PI	120	2.35	18.4	483	-
PI	150	2.35	14.2	564	-
PI	180	2.35	12.5	639	-
PE	45	2.36	34.7	323	32.00
PE	60	2.36	30.5	367	19.33
PE	90	2.37	22.3	455	-
PE	120	2.37	13.9	535	-
PE	150	2.38	12.2	612	-
PE	180	2.38	11.5	676	-

I PI 20	60	2.92	37.7	249	-
I PI 20	90	2.92	29.5	318	20.84
I PI 20	115	2.92	23.8	366	17.94
I PI 20	120	2.92	23.8	377	-
I PI 20	150	2.94	19.9	431	-
I PI 20	180	2.96	18.2	475	-
I PE 20	60	2.93	36.7	263	-
I PE 20	87	2.94	28.1	322	20.84
I PE 20	90	2.94	27.1	335	-
I PE 20	108	2.94	24.6	370	16.65
I PE 20	120	2.94	22.9	389	-
I PE 20	150	2.94	20.6	442	-
I PE 20	180	2.94	19.2	498	-
I PI 30	60	2.83	37.8	239	-
I PI 30	90	2.84	30.5	310	-
I PI 30	97	2.84	28.4	320	22.46
I PI 30	120	2.84	21.4	370	16.65
I PI 30	150	2.84	18.5	422	-
I PI 30	180	2.84	16.1	463	-
I PE 30	60	2.85	36.7	277	-
I PE 30	82	2.86	28.8	318	20.84
I PE 30	90	2.86	25.9	343	-
I PE 30	101	2.86	25.9	369	19.33
I PE 30	120	2.86	18.2	406	-
I PE 30	150	2.86	16.1	453	-
I PE 30	180	2.86	15.6	501	-

A.3. X-Ray Diffractograms of Perlites

a) Perlite of Izmir



b) Perlite of Erzincan