ALKALI-SILICA REACTIVITY AND ACTIVATION OF GROUND PERLITE-CONTAINING CEMENTITIOUS MIXTURES

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ABSTRACT

ALKALI-SILICA REACTIVITY AND ACTIVATION OF GROUND PERLITE-CONTAINING CEMENTITIOUS MIXTURES

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Perlite is a volcanic mineral. The latest investigations on ground perlite showed that it is suitable for pozzolanic usage. Thus, it is of vital importance especially for countries rich in perlite such as Turkey. The aim of this study is to investigate the advantages and problems associated with using perlite in concrete and to identify accurate methods and amounts of use for producing durable cementitious mixtures.

Within the scope of this study, the alkali-silica reactivity of perlite containing cementitious mixtures were compared using four different methods. Expansion mechanism of the mixtures were tried to be understood by measuring the alkalinity of bath waters. In order to cope with early strength decreases caused by perlite addition, activation of the mixtures by chemical and thermal methods were attempted. It was found that chloride containing chemicals are very effective at later ages and sodium containing chemicals are more effective at early ages. Sodiumhydroxide addition to the perlite containing mixtures was found to be detrimental to both the initial and late-age strengths of mortars.

It was concluded that perlite addition generally results in a decrease in alkali-silica expansions. However, the expansion of concrete samples should be investigated comprehensively.

Thermal curing at high temperatures resulted in a rapid increase at 1-day strengths, however, for better ultimate strengths lower thermal treatments or no-thermal curing were found to be more effective. Compared to the traditional portland cement concretes, high-volume ground perlite concretes have environmental and economical advantages.

Keywords; Perlite, Pozzolan, Alkali-Silica Reaction, Chemical Activation, Thermal Activation

ÖZ

ÖĞÜTÜLMÜŞ PERLİT İÇEREN BAĞLAYICILARIN AKTiVASYONU VE ALKALi-SİLİKA REAKTİVİTESİ

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Perlit volkanik bir mineraldir. Son zamanlarda yapılan çalışmalarda özellikle öğütülmüş perlitin puzolanik malzeme olarak kullanılabileceği görülmüştür. Türkiye gibi perlit zengini ülkeler için hayati bir öneme sahiptir. Bu çalışmanın amacı, yüksek alkali içeren perlitin betonda kullanımı durumunda karşılaşılan olumlu ve olumsuz yanları araştırmak ve perlit kullanımı için doğru miktar ve yöntemleri tayin etmektir.

Bu çalışma kapsamında perlit içeren karışımların alkali-silika reaktivitesi dört farklı yöntemle karşılaştırılmıştır. Karışımların genleşme mekanizması, bekleme sularının alkalinitesi ölçülerek, anlaşılmaya çalışılmıştır. Perlit katılan durumlardaki düşük erken dayanım ile başa çıkmak için, karışımların kimyasal ve termal aktivasyonları denenmiştir. Aktivasyon denemelerinde klor içeren kimyasalların geç yaşlarda, sodyum içeren kimyasalların ise erken yaşlarda, perlitli karışımların dayanım kazanmalarına katkıda bulundukları görülmüştür. Sodyumhidroksitin ise, hem erken hem de geç yaşlarda perlitli karışımların dayanım kazanmasına olumsuz etkileri gözlenmiştir.

Çalışma sonucunda perlit katkısının alkali-silika genleşmelerini azalttığı görülmüştür. Ancak beton numunelerdeki uzamalar daha kapsamlı olarak araştırılmalıdır.

Yüksek sıcaklıklarda kürlenen numunelerin bir günlük dayanımlarında ani bir artış gözlenmişse de, daha yüksek nihai dayanımların, nispeten daha düşük termal koşullarda, hatta oda sıcaklığında elde edildiği görülmüştür.Yüksek miktarda öğütülmüş perlit içeren karışımların portland çimentolu geleneksel betona kıyasla çevresel ve ekonomik avantajlara sahiptir.

Anahtar Kelimeler: Perlit, Puzolan, Alkali-Silika Reaksiyonu, Kimyasal Aktivasyon, Termal Aktivasyon

To My Parents ….
To Kaan …

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LIST OF ABBREVIATIONS

OPC: Ordinary Portland Cement

PC: Portland Cement

T: Thermally Cured

C_2S: $2CaO.SiO_2$

C_3S: $3CaO.SiO_2$

C_3A: $3CaO.Al_2O_3$

CSH: Calcium-Silicate-Hydrate

CH: Portlandite

ASR: Alkali - Silica Reaction

SCM: Supplementary Cementitious Materials

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Technological developments around the world allow researchers to develop increasingly better and more economical construction materials. Also in the concrete industry, as a result of giant expansion of the commercial market, the use of ordinary portland cement is coming to an end. In addition to technical inadequacies and environmental threats, the cost of production has made it compulsory to look for alternative materials to cement. At such a point, investigations on the use of ground perlite for cement replacement are of vital importance especially for countries rich in perlite such as Turkey.

Studies on perlite-containing cements and concretes are very limited. The main use of perlite is in the agriculture sector instead of construction materials. The proven pozzolanic behaviour of perlite has not yet been exploited in the cement industry.

1.2 OBJECTIVE and SCOPE

The aim of this study is to investigate the advantages and problems associated with using perlite in mortars and concrete and to identify accurate methods and amounts of use for producing durable cementitious mixtures.

Within the scope of this study, alkali-silica reactivities of perlite containing-mixtures were compared by using four different methods. Expansion mechanism of the mixtures was explored by measuring the alkalinity of bath waters in which specimens were kept. In order to cope with early age strength reduction induced by perlite addition, chemical and thermal methods of activation of the mixtures were attempted. Mortars with increasing amounts of perlite were activated using varying amounts of chemicals. Based on the findings of the initial tests, only some of the chemical activators were used, at a single amount, in the remainder of the activation trials.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 CONCRETE

Concrete is the most widely used construction material and is obtained by mixing water, cement, aggregate and some additives (if needed) together.

As per a paper commissioned by UNEP journal, 1.05x 10^{10} tons of concrete building material was obtained by the year 1997 whereas the global steel production was 5,8x 10^{8} tons and 10 % of it goes to reinforced concrete [7].

Although concrete is neither as strong nor as tough as steel, there is a greater demand for it in the construction field than for any other material.

Since concrete is usually the most economical and readily available material which can be formed into different shapes and which has excellent durability under water when compared with other construction materials, its market demand and production increases day by day.

The estimated annual amount of concrete production 12,5 million m^3 in 1963 had increased to 848,7 million m^3 by the year 2007 [1, 2]. This dramatical increase in concrete consumption has especially been caused by developing countries such as Turkey. In 1988, the recorded ready-mixed concrete production was 1,5 million m^3 by 25 companies and only 30 plants, where as in 2007, it had increased to 74,4 million

m^3 produced by 477 companies and 845 plants [3]. Also the earthquake in the Marmara Region of Turkey in 1999 which resulted in tremendous loss of life and property, had a big share in the accelerated increase of ready-mixed concrete consumption.

2.1.1 Main Components of Concrete

One of the reasons why concrete is the most preferred construction material in the field is its easily available main constituents such as water, aggregate and cement. Although lots of specifications have been introduced to outline the proper use of these materials in concrete, it is still not difficult to obtain qualified materials.

The main quality standards and specifications followed during construction and production are quite often those specified by the American Society for Testing and Materials (ASTM), British Standards Institution (BSI), International Organization for Standardization (ISO), European Committee for Standardization (CEN), American Concrete Institute (ACI). Turkey also has national standards for concrete and its components published by the Turkish Standards Institution (TSE).

2.1.1.1 Mixing Water

Mixing water for concrete is the material that starts the chemical reactions in cement through the hydration process. Since the complex nature of these reactions are not completely understood yet, any strange compound introduced into concrete, is found initially suspicious by practitioners. There also some compounds which may exist in the mixing water whose deleterious effect to the hydration process has been proven. Sugar, organic materials of water and algae can be counted in the group, which retards the setting of concrete. There are also some other materials that decrease strength or cause reinforcing bars to corrode.

ASTM C 1602, BS-3148 and TS-EN 1008 standards give the definition and qualities of suitable mixing water.

2.1.1.2 Aggregates

Aggregates, as a mixture of both coarse and fine aggregate, are the materials occupying the greatest volume in concrete. Physical and chemical properties of an aggregate such as; water content, water absorption capacity, specific gravity, bulk density, resistance to frost damage, shape, surface texture, abrasion resistance , alkali reactivity, compressive strength, heat conductivity, porosity, coefficient of thermal expansion, Poisson's ratio and modulus of elasticity directly affect the properties of concrete [4]. Besides the combination ratios of different aggregate size fractions, the gradation and fineness modulus of aggregates can influence the strength and durability of concrete. Both ASTM and Turkish Standards gave the limitations on and the requirements for the above-mentioned properties of aggregates.

2.1.1.3 Cement

Since the third ingredient, cement, is the most expensive and the most important component of concrete, it will be dealt with in greater detail.
Hydraulic or water-resisting cements consist essentially of portland cement and its several modifications. ASTM C 150 defines portland cement as a hydraulic cement produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, and a small amount of one or more forms of calcium sulfate as an interground addition. Clinkers are 5 to 35-mm diameter nodules of a sintered

material that is produced when a raw mixture of predetermined composition is heated to high temperatures.

In order to supply the main constituents of portland cement, naturally occurring calcium carbonate materials such as limestone, chalk, marl, sea shells and siliceous additives such as clays and shales are preferred.

Raw materials collected from quarries are mixed in specific proportions and sent to a rotary kiln. Having a maximum temperature of approximately 1450 ^{o}C at their lower ends, inclined rotary kilns burn the raw materials to decompose them into oxides, and with increasing temperature, recomposition of these oxides into the main components of the cement in the form of clinker occurs. After the cooling of clinker, a calculable amount of a limited set regulator (gypsum) is added to the product and they are ground together. A schematic diagram of the cement production process is presented in Figure 1.

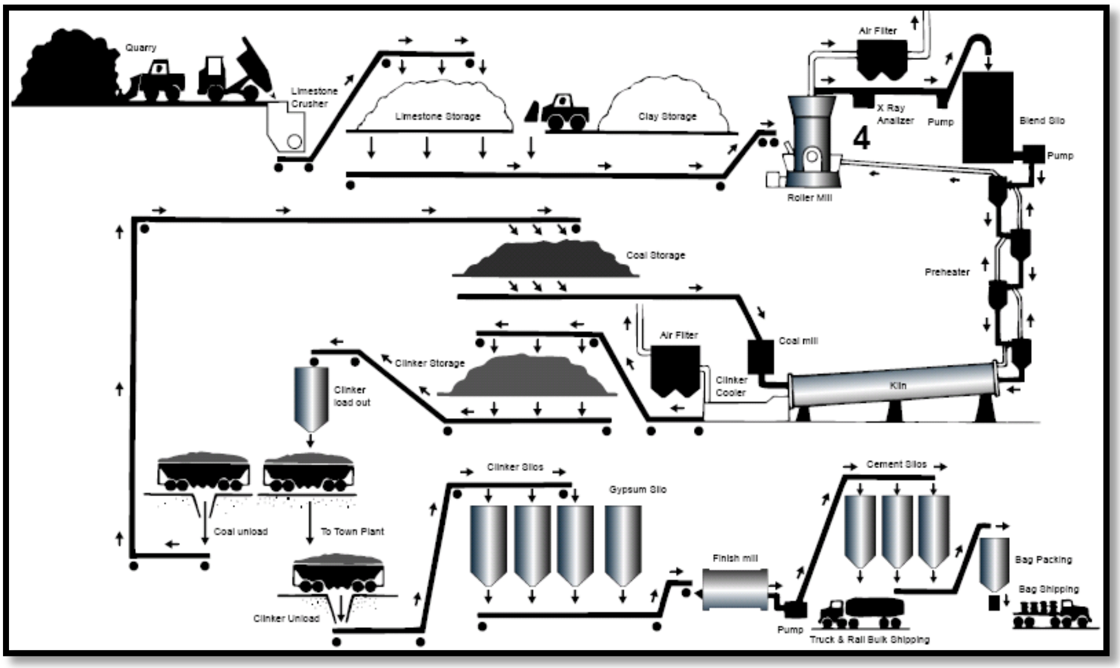


Figure 1. The Cement Production Process [1]

Clayey raw materials mainly consist of silicates, alumina and a small amount of iron. During burning, they decompose into SiO_2 and Al_2O_3 oxides at about 600^oC, and a small amount of Fe_2O_3 oxide is also formed.

Calcareous raw materials contain mostly calcium carbonate structure and partially magnesite ($MgCO_3$), silicate, ferric oxide, alumina etc. In the rotary kiln, calcium carbonate decomposes into CaO and $CO_{2,}$ whereas, $MgCO_3$ decomposes into MgO and CO_2 at about 900^oC. During continuous burning, these oxides react with each other to form the main components of cement. These chemical reactions can be briefly summarized as follows.

Heated together, CaO and SiO_2 can combine to form four distinct compounds;

1. Metasilicate ($CaO.SiO_2$)
2. Rankinite ($3CaO.2SiO_2$)

3. Orthosilicate ($2CaO.SiO_2$)
4. Compound $3CaO.SiO_2$

The first two compounds are not constituents of portland cement. Orthosilicate is present in cements in four forms;

- α $2CaO.SiO_2$, stable at above 1447 ^oC
- α’ $2CaO.SiO_2$, stable at above 800-1447 ^oC
- β $2CaO.SiO_2$, stable at above 670 ^oC
- γ $2CaO.SiO_2$, stable at above 780-830 ^oC

However, only the β form of C_2S has cementitious value. Tricalcium silicate, is the principle cementing constituent in portland cement. It is unstable above 1900 ^oC and below 1250 ^oC, explaining the need for high kiln temperatures during production.

Burned together CaO and Al_2O_3 can produce five different compounds.

1) $3CaO.Al_2O_3$
2) $12CaO.7Al_2O_3$ ($5CaO.3Al_2O_3$)
3) $CaO.Al_2O_3$
4) $CaO.2Al_2O_3$ ($3CaO.5Al_2O_3$)
5) $CaO.6Al_2O$

$3CaO.Al_2O_3$ is present in portland cement.

$12CaO.7Al_2O_3$ ($5CaO.3Al_2O_3$) is occasionally present in portland cement.

$CaO.Al_2O_3$ is one of the main constituents of high alumina cement.
$3CaO.5Al_2O_3$ is one of the cementing compounds in high alumina cement. However, its cementing value is entirely accounted for by the CA which it contains. Burned together CaO and Fe_2O_3 can form two compounds; $CaO.Fe_2O_3$ (monocalcium ferrite) and $2CaO.Fe_2O_3$

(dicalcium ferrite). Neither mono nor dicalcium ferrite exists in portland cement.

When Al_2O and SiO_2 are burned together, they form sillimonite , andalusite and cyanite. However, compounds of alumina and silica alone do not occur in portland cement. Burned together CaO, Al_2O_3 and Fe_2O_3 form brown-millerite (C_4AF) which is counted among the main components of portland cement [5].

2.2 CEMENT/CONCRETE PRODUCTION AND ENVIRONMENT

Despite the fact that cement is the indispensible construction material of the world, the negative environmental impact of the cement manufacturing process are non-ignorable. The cement industry has a big share in two of the world’s important problems; global warming and energy shortage.

Cement manufacture requires very high temperatures (about 1500^oC) to initiate the reactions and phase changes necessary to form the complex mineral compounds that give cement its unique properties. Excluding the quarrying process, concrete manufacturing energy consumption, as of the year 2002, was measured as 4982000 Btu/ton in the USA only [6]. Also the cement industry is held responsible for about 5% of the global anthropogenic CO_2 emission. About 50% of the CO_2 emitted is, released by limestone decomposition in the kiln, and the other half is mainly due to fuel burning [7]. Besides CO_2, cement manufacture creates and emits other deleterious materials such as; airborne dust, SO_2, NO_x, CO etc. A series of measures are being taken and/or suggested to be taken on these environmental concerns. Some opportunities to cope with these problems are listed below [6] ;

- Shifting to more energy efficient processes (from wet to dry process-this of course may create other problems),

- Installing improved heat recovery systems from clinker coolers,
- Utilizing waste fuels,
- Replacing high carbon fuels by low-carbon fuels,
- Sequestering CO_2 from the gas streams
- Changing cement product formulations (increased use of alternative cements).

However, since these problems are the result of cement production, obviously the panacea would be complete (or partial for an intermediate method of mitigation) replacement of cement. In this context, researchers have concentrated on the study of cement replacement materials.

2.3 CEMENT REPLACEMENT MATERIALS

The use of cementing materials precedes to the invention of portland cement. The simplest form of a binder material is found in ancient Egyptian buildings as dried bricks covered with a moist layer of Nile mud. The Egyptians people were also preparing mortars from burnt gypsum. As for the Greeks and Romans, their mortars were prepared with a relatively more modern method by slaking lime and mixing it with sand. Moreover, these mixtures had worldwide usage. However, both the Greeks and Romans were aware that certain volcanic deposits, in finely ground form and mixed with lime and sand, yielded a durable mortar. The next major binding material discovery was volcanic tuff, found near Pozzuoli and later being named after this city as pozzolan. The roman mixture of lime and natural and artificial pozzolan was set as the most suitable construction material for a long time. Much later, as a result of several trials, portland cement was invented by Joseph Aspdin in 1824 [4,5,8].

Since its invention, portland cement has been the main construction material in the world. However, for environmental and economical reasons, the above mentioned materials which have been used as cementitious materials in past, are being reevaluated for use in blended cements, as an alternative to portland cement. Also, the chemical properties of portland cement are trying to be altered by changing the burning process of materials, for energy saving purposes. New materials are tried for complete or partial replacement of portland cement. Both natural material sources and industrial wastes are investigated in terms of their pozzolanic and other binding properties.

The term ‘pozzolan’ is defined in ASTM C125 as; siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely ground form and in the presence of moisture, chemically react with calcium hydroxide to form compounds possessing hydraulic cementitious properties [9].

Although there are several different classification factors, most researchers agree on dividing pozzolans into two main groups as natural and artificial.

Artificial pozzolans are, within the definition of a pozzolan, materials that have little or no cementitious value but will develop binding properties in finely divided form and in the presence of moisture. Those materials are not the primary products of the industry producing them. They are either a waste or a by-product of the main industry [1]. Low calcium fly ash, silica fume, calcined shales, burnt agro residues and glazed ceramic waste may be given as a few examples of this wide group. However, despite the pozzolanic behavior of ground-blast furnace slag and high calcium fly ash, they are not counted among artificial pozzolans owing to their self-cementing properties.

Natural pozzolan is defined as “either a raw or calcined natural mineral that has pozzolanic properties”[10]. Mehta (1987) classifies natural pozzolans into 4-four groups on the basis of the principal lime-reactive constituent ;

1. Unaltered volcanic glass
2. Volcanic tuff
3. Calcined clay or shale
4. Raw or calcined opaline silica

However, since volcanic tuffs usually include unaltered siliceous glass, this classification is not applicable to first and second group. Mielenz et al.[10] classifies natural pozzolans into 5 groups based on the identity of the pozzolanic constituents;

1. Volcanic glass
2. Opal
3. Clays
4. Zeolites
5. Hydrated oxides of aluminum.

The most widely accepted classification, made by Massazza [11], based on the geological origins of natural pozzolans, is shown below

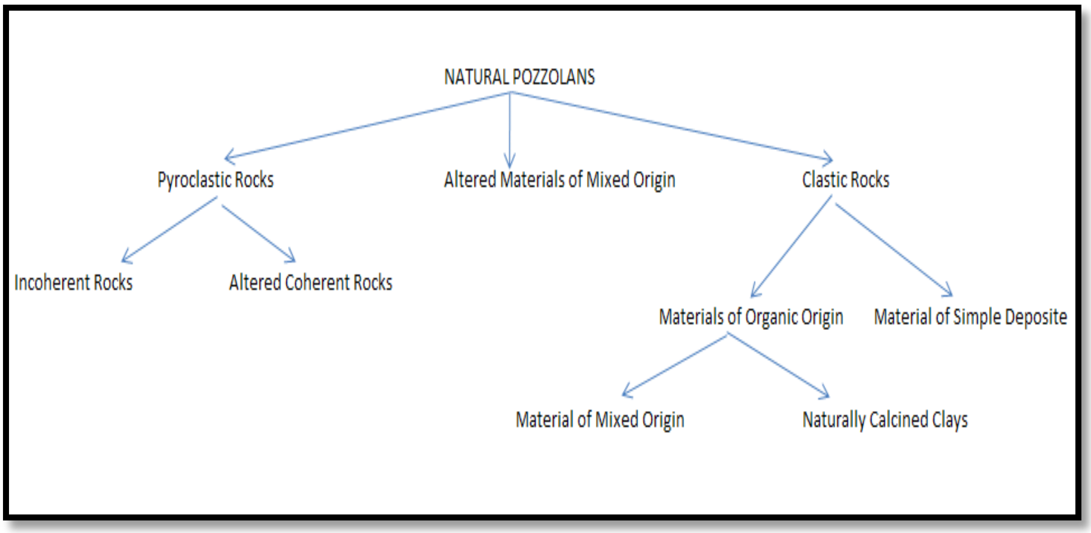


Figure 2. Classification of Natural Pozzolans [10]

2.4 PERLITE

Perlite is a glassy volcanic rock which belongs to the riolite family of surface rocks with a water content of 2-5%. In the case of a rapid heating up to ~900 ^{o}C, it can expand up to 4-40 times of its original volume. In industry, the name perlite is used for both the raw material (rock) and the expanded material. It may have different appearances; compact, fine, porous, brittle, sandy etc., and a color spectrum from white to black. Due to its heterogeneous structure, it is hard to identify by visual inspection.

Figure 3. Different Forms of Perlite [12]

Perlite ores were formed during the acidic volcanism activity of the tertiary and later tertiary geologic periods. Volcanic formations are related with the existence of faults, and existence of faults depends on new dislocations.

From a paleogeographic and paleomorphologic point of view, perlite formations are commonly expected in aqueous mediums like coastlines and shallow lakes.

Perlite is one of the main constituents of volcanos that moves with high pressure gases during magmatic events. In volcanic activities, melted magma moves upward via the collected gases in the center of magma. These volcanic materials possess different properties. The non-homogenous structure of perlite may be explained with this variety [13]. Perlite ores are found in-situ together with acidic magmatic rocks and the chemical properties of SiO_2-rich perlite proves its magmatic origin. The glassy texture of perlite is related to the quick cooling of the magma [14].

Perlite studies in Turkey go back to 1950s. In Turkey, a large variety of perlite exists. The types of perlite found in Turkey are listed below [15];

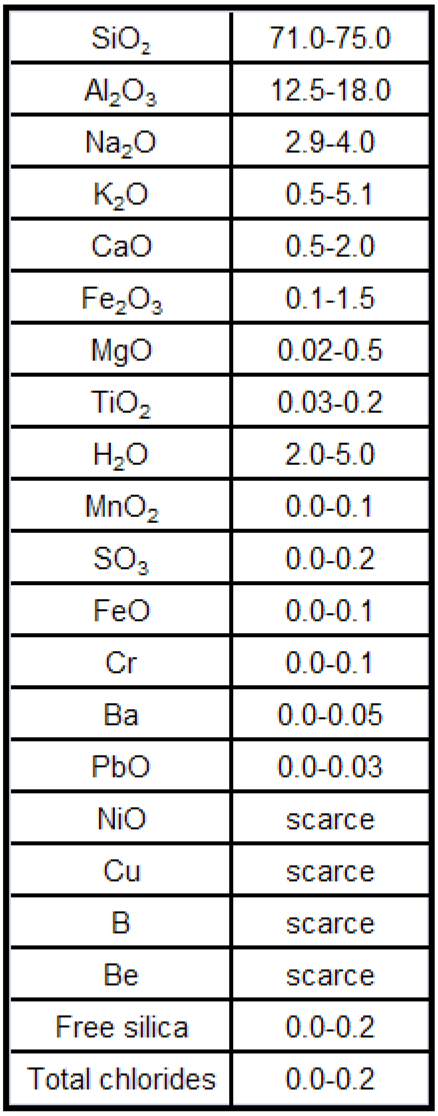
1. Granular Perlite
2. Pumicite Perlite
3. Concentric Structured Perlite
4. Devitrified Perlite
5. Phenicrystalline Perlite
6. Sandy Perlite

Typical physical and chemical properties of perlite are given in Table 1 below. The maximum and minimum values of the properties are indicated [16].

Table1. Physical Properties of Perlite [16]

Color:	White, gray , black
Hardness:	5-6 (Mohs)
Specific Gravity:	2200-2400
Loose Density:	320-400 kg/m^3
Softening Point:	871-1093^{o}C
Specific Heat:	0.2 cal/g^{o}C
Thermal Conductivity:	0.04 W/Mk
Refractive Index :	1.5
pH:	6.5-8.0
Free Moisture:	Max. 0.5 %

Table 2. Typical Chemical Properties Of Perlite [16]

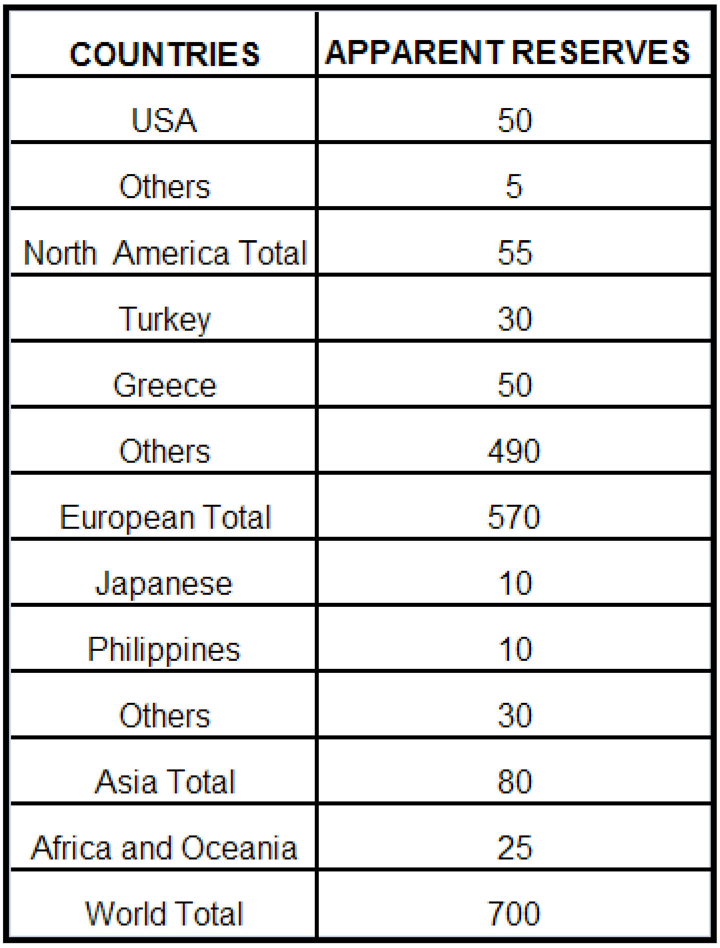


SiO_2	71.0-75.0
Al_2O_3	12.5-18.0
Na_2O	2.9-4.0
K_2O	0.5-5.1
CaO	0.5-2.0
Fe_2O_3	0.1-1.5
MgO	0.02-0.5
TiO_2	0.03-0.2
H_2O	2.0-5.0
MnO_2	0.0-0.1
SO_3	0.0-0.2
FeO	0.0-0.1
Cr	0.0-0.1
Ba	0.0-0.05
PbO	0.0-0.03
NiO	scarce
Cu	scarce
B	scarce
Be	scarce
Free silica	0.0-0.2
Total chlorides	0.0-0.2

2.4.1 Perlite in Turkey

Although conflicting literature exists, it is a widely accepted fact that Turkey is the country with the largest perlite reserves in the world. One source provides the information in Table 3, regarding perlite reserves of countries [16]:

Table 3.World Perlite Reserves (million tons) [16]



COUNTRIES	APPARENT RESERVES
USA	50
Others	5
North America Total	55
Turkey	30
Greece	50
Others	490
European Total	570
Japanese	10
Philippines	10
Others	30
Asia Total	80
Africa and Oceania	25
World Total	700

In Table 3, the total apparent perlite reserve of Turkey is calculated as 4.3% of worlds reserves. Conflicting information about perlite reserves in Turkey, provided by the state planning organization of Turkey is given in Table 4 [16].In this table, besides the regional dispersion of the perlite reserves, the total perlite reserve of Turkey as 4.58 billion tones. That is a number which corresponds to 2/3 of the world's perlite reserves. The conflict between reserve base and apparent reserves (reserve) originated from the definition of the terms. The definition of reserves and reserve base are given in USGS minerals as follows;

Reserve base is defined as part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the inplace demonstrated (measured plus indicated) resource from which reserves are estimated. Reserves are defined as part of the reserve base which could be economically extracted or produced at the time of determination [17].

Table 4. Regional Dispersion of Perlite Reserve Base of Turkey [16]

Region	Potential reserves (Thousand tons)
Ankara-Çamlıdere	8.000
Ankara-Çubuk	32.000
Ankara-Kızılcahamam	34.200
Balıkesir-Evrindi	25.000
Balıkesir-Savaştepe-Sındırga	47.000
Bitlis-Adilcevaz-Tatvan (Van-Erciş)	1.400.000
Çankırı-Orta	30.000
Çanakkale-Biga	3.400
Eskişehir-Seyitgazi	20.000
Erzincan-Merkez	27.000
Erzurum-Pasinler	100.000
İzmir-Bergama	16.500
İzmir-Dikili	8.000
İzmir-Foça	16.500
İzmir-Menderes (Cuma Ovası)	60.000
Kars-Sarıkamış	1.500.000
Manisa-Demirci-Soma	18.600
Manisa-Saruhanlı	18.000
Nevşehir -Acıgol	862.000
Nevşehir-Derinkuyu(Niğde-Gölcük)	350.000
Total	4.576.200

Despite the huge reserves available in Turkey, annual-production is only about 15% of the total world production. The worldwide production with detailed information for different countries is given in Table 5 [18]. According to Table 5, Turkey's annual perlite production varies from 7.54% to 15.3% of the worldwide total.

Table 5. Worldwide Production of Perlite (in metric tons) [18]

Country	**2003**	**2004**	**2005**[e]	**2006**[e]	**2007**[e]
Armenia [e]	35.000	35.000	35.000	35.000	35.000
Australia[e,1]	5.000	5.000	6.000	6.500	7.000
Greece, screened	525.000	525.000	525.000	525.000	525.000
Georgia	NA	45.000	45.000	45.000	45.000
Hungary[e,1]	59.530	65.100	65.000	71.000	71.000
Iran	26.495	31.259	31.000	30.000	30.000
Italy [e]	60.000	60.000	60.000	60.000	60.000
Japan [e]	240.000	240.000	240.000	240.000	240.000
Mexico[1]	194.463	188.027	91.724	41.219	41.000
Philippines	6.000	5.510	4.410	4.500	4.500
Slovakia	15.000	23.840	13.000	20.000	20.000
South Africa[e]	400	400	400	400	400
Turkey[1]	136.633	133.829	140.000	250.000	270.000
United States[2]	493.000	508.000	508.000	454.000	409.000
Zimbabwe	5.000	4.000	4.000	3.000	3.000
Total	1.810.00	1.870.00	1.770.00	1.790.000	1.760.000

[e]: Estimated [1]: Crude ore
[2]: Processed ore sold and used by producers

Perlite is used in various sectors, in many ways other than as a construction material. It is used in the agricultural, medical, chemical and nutritional, ceramics and glass and metal industries among other, as a filter material, a filler, an insulation material, an admixture etc.

However, almost all the ways in which perlite is used take advantage of its physical properties like low density, porous structure, fire resistance etc. Even in the construction field, the most preferred usage of perlite is as an insulator or lightweight concrete aggregate. Ground perlite is not used as a pozzolan yet.

The Turkish mining industry was predominantly made up of medium to large-scale public enterprises and some small-sized private enterprises that appeared in their surroundings. However, the mining industry experienced a radical structural change by privatizations which took place in the last decade. These privatizations, including that of Eti Holding A.Ş, caused the sector to be reformed by only small-medium sized private sector enterprises and the obliteration of public enterprises in the mining industry. Unfortunately, today even in reports by the State Statistical Institution of Turkey, D.İ.E (T.İ.K) , it is not possible to come across to any perlite producers in the list of ‘important enterprises in the mining sector’ [19].

2.4.1.1 Attempts To Use Perlite as A Pozzolanic Cement Replacement Material

The most comprehensive study on the pozzolanic use of perlite is a doctoral thesis by Erdem [20]. A masters thesis by Meral [21], conducted at the same institution, preceded this study.

Meral [21] worked to show the pozzolanic property of perlite and according to the definition in ASTM C 618, it was proven that Turkish perlites possess sufficient pozzolanic characteristic to be used in the cement and concrete industry. Moreover, all blended cements produced using Turkish perlites satisfied the setting time, autoclave expansion and compressive strength requirements of ASTM C 1157.

Pozzolanic properties of perlite were investigated by three different methods in Erdem [20]; chemical analysis for ASTM C 618 requirements, x-ray diffraction method and insoluble residue tests. All three methods proved that perlite possesses certain pozzolanic properties [20, 22].

In addition to Meral's thesis, investigations on the durability of perlite-incorporating blended cements were conducted by Erdem [20]. Chloride penetration, alkali-silica reactivity and sulfate resistance properties of blended cements were investigated. His results briefly showed that; perlite incorporation decreased chloride penetration and sulfate attack due to pore refinement. In the case of the alkali-silica reaction, it was observed that, expansion due to alkali-silica reaction decreases with the use of perlite at high levels. However, the detrimental effect of low-level perlite replacement on ASR depends on the high alkali content of this mineral admixture. It was suggested that at a low replacement level the alkalis contributed by perlite is greater than those contributed by the portland cement.

Apart from these complex studies, some additional literature exist on this subject. Bektaş et al. [23] investigated the efficiency of perlite powder in suppressing the alkali-silica reaction. It was observed that, proportionally with replacement levels, perlite powder decreases expansion due to ASR. Besides the pozzolanic effect of perlite on ASR decreasing process, the highly porous structure of expanded perlite was considered to work as an air entrainment agent that holds expanded alkali-silica gels in its structural pores.

The pozzolanic effect of perlite powder in concrete was determined analytically by Yu et al. [24]. As a result of a series of calculations, it was concluded that perlite powder possesses a significant pozzolanic property and is a good active admixture for concrete.

Considering the pozzolanic properties of perlite, limestone filler was substituted by perlite in a study by Katsioti et al. [25]. As a result of both perlite and fly ash replacements, hydraulic compounds - portlandite, CSH and ettringite were formed. Mechanical strength and modulus of elasticity of the samples were similarly satisfactory.

Some perlite-containing mixture trials were studied by Erdem [26]. It was suggested that, if expanded perlite is used with blended portland cement, a small amount of lime must be added to the mixtures for the activation of perlite.

The mining and processing of perlite results in the production of perlite fines, which currently have no economic value and are stockpiled as waste at the mining site. Ray et al. [27] studied the pozzolanic use of these perlite fines' in blended cements. They compared perlite-containing cement with silica fume-and fly ash-incorporating cementitious materials. It was found that, the 28-day strength of samples with perlite fines were higher than the strength samples with identical levels of fly ash-replacement and these values were comparable to those of the control sample.

A similar study was conducted by Vessalas et al. [28], again using the material called pitchstone which is a form of volcanic glass but having a water content of more than 5 % and derived as a waste product of perlite production.10 %, 20 % and 40 % replacement levels were inspected. Pitchstone fine (perlite waste) additions of 10 % and 20 % were found to conform to ASTM standards based on the strength activity index measurements. However, 40% replacement did not give satisfactory results from a strength activity point of view. Besides pitchstone, fine additions were found to reduce segregation and bleeding, thus aiding workability of portland cement blends.

2.5 THE ALKALI-SILICA REACTION

The alkali-silica reaction is a chemical reaction within concrete between specific siliceous constituents of aggregates and the alkali hydroxides in the pore solution. The reaction product is alkali silica gel, formation of which is accompanied by absorption of a large amount of moisture, if available, and subsequent swelling at variable amounts. This swelling within hardened concrete presents a risk of cracking and overall expansion [8].

The gel is of an “unlimited swelling” type. It absorbs water and has a tendency to increase in volume. As the gel is confined by the surrounding hydrated cement paste, internal pressures may eventually lead to expansion cracking and disruption of the hydrated cement paste [8].

It is now partly possible to recognize potentially reactive aggregates and minerals by petrographic examinations. However, it is difficult to define a casual link between the microscopic evidences and the damage affecting the structure. In some cases, the amount of the expansion in concrete caused by alkali silica reaction increases with the increasing reactive constituent in the aggregate. In many other cases there is a limiting amount (or pessimum) of reactive constituent for obtaining the greatest expansion [5]. The pessimum behaviour of some reactive aggregates can be explained by the balance between available active silica and concentration of alkalis. It was also noted that pessimum behaviour is most pronounced for the rapid reacting types of silica such as opal. The pessimum value of an aggregate is higher at lower water-cement ratios and at higher cement contents. Like pessimum behaviour, reactive aggregates must be of an ideal size for the highest expansion due to the reaction.

The alkali silica reaction is a very slow reaction and its consequences may not be evident for many years. The reason for this is very complex and processes involved are still debated. The sizes of the reactive particles in aggregates affect the reaction speed. Fine particles of 20-30 μm diameter can lead to expansion within one or two months whereas the larger particles may need many years to give harmful reactions [8].

The actual reactivity of aggregate is affected by its particle size and porosity. When the alkalis originate from the portland cement only, their concentration at the reactive surface of aggregate will be governed by the magnitude of surface. Within limits, the expansion of concrete made with a reactive aggregate is greater, the higher the alkali content of cement and, for given alkali content in cement the greater the cement fineness [30].

One of the other factors affecting the progress of alkali aggregate reaction is the permeability of hydrated cement paste since it controls the movement of water and various ions, as well as silica gel. It is a known fact that pozzolans reduce the risk of alkali-silica reaction, primarily due to their ability to react with the alkalis in the pore solution more rapidly than the sand-sized or coarse aggregate-sized reactive minerals can. This ability depends on the fineness and the dispersion of the pozzolans, otherwise they can contribute to the expansion due to alkali silica reaction [8].

2.5.1 Evaluation of Test Methods For Alkali-Silica Reactivity in Concrete

Numerous tests have been devised to ascertain whether a particular aggregate or concrete mix will show alkali-silica reactivity. These tests focus on checks concerning either the aggregate alone or the concrete mix or a simplified variant of it.

A number of tests have been introduced concerning the direct evaluation of aggregates which, if applied with care, identify alkali-reactive materials in aggregate particles satisfactorily. Petrographic examination using a polarising microscope with thin sections cut from the aggregates is becoming increasingly important as a first step in identifying components which may potentially be reactive. This method does not confirm that such materials will be reactive and deleterious in a concrete so other tests need to be applied if suspect materials are observed in the aggregate particles [31].

Following the explanation by Stanton [29] of ASR, the test method he described was standardized as ASTM C 227 and adopted all around the world. In this method, fine-sized crushed aggregate mixed with cement into mortars are kept at 38 ^{o}C in a humid environment for 14 days. However, after some failures were observed where alkali reactive rock had been used in Ontario in 1950 and the test method could not recognize these reactive aggregates, a new search was started for an effective ASR test method [32, 33].

The Canadian concrete prism test was developed during this period and was adopted by ASTM as specification C 1293 in 1995. In this method, the original aggregates are mixed with 420 kg/m^3 highly-alkaline cement and samples are kept in 38 ^{o}C humid conditions for at least 1 year (2 years if a supplementary cementitious material is used). The purpose of the method is to reach more realistic conclusions compared with site performance [33, 34].

During the development of ASTM C 1293 researchers were focused on finding new accelerated testing methods. In 1986, an accelerated mortar bar test was developed by Oberholster and Davies [35]. Crushed aggregate is mixed with ordinary portland cement (OPC) and the mortar is cast in prismatic molds. After 24 h, the samples are placed in water at 80^{o}C and kept for another 24 h. Eventually the samples are put into a 1N NaOH solution at 80 ^{o}C and kept for 14 days. The test lasts a total of 16 days which saves a considerable amount of time for construction projects compared to other tests. This method was adopted by ASTM as specification C 1260 in 1994. ASTM C 1260 was intended to test the reactivity of aggregates and not to test the effectiveness of supplementary cementitious materials (SCM)s in mitigating ASR. However, over the years, many researchers have used ASTM C 1260 for exactly this purpose. Because of this misuse, ASTM eventually devised specification C 1567 in 2004, a test quite similar to ASTM C 1260 [36, 37].

Before and during this standardization period, several methods were suggested by researchers and international conferences on ASR were conducted to form a discussion platform on ASR and its testing methods. 24 h 80 ^{o}C accelerated hot curing of concrete blocks was suggested by Hudec and Larbi [38]. A chemical test method depending on OH^{-} ion decrease in a 70^{o}C KCl solution containing CaO and the sample aggregate was introduced. An acoustic emission method was suggested that measures crack detection instead of elongation length as expansion mechanism [39, 40, 41].

The Chinese researchers developed an autoclave method [42]. Although they had some success in identifying the potential reactivity of aggregate, small sample size and high temperature applied, (150^{o}C) made many researchers doubt the method.

On the other hand, for some aggregates, as relatively poor correlations between expansions of ASTM C 1293 and ASTM C 1260 were observed, researchers focused on new accelerated methods and a new test method, the Chinese accelerated mortar bar method (CAMBT) was developed [43]. In this method, a highly alkaline system is obtained by KOH addition and the test procedure is the same as in ASTM C 1260 except the initial length measurement is made after 4 h of immersion in

1N NaOH solution at 80^{o}C and the duration of the test is 7 days. Another test method, the modified CAMBT, was also developed by Lu et al. [42]. It is similar to ASTM C 1260 except for the aggregate gradation. The results of these studies showed good correlation between the CAMBT and C 1260. However, the correlations in expansions of both ASTM C1260 and CAMBT with ASTM C1293 are very poor. The best correlation was obtained between the 10-day expansion of the modified CAMBT and ASTM C 1293. In this modified method, 0.2-5.0 mm single-sized aggregate is used [42].

Using existing field performance is possibly the most reliable means of detecting ASR. Especially in the case of SCM usage, it is quite difficult to foresee the external effect of site conditions. Even current standards have some contestable points. It is generally accepted that the principal mechanism by which pozzolanic materials suppress ASR is by reducing the quantity of alkali hydroxides in the pore solution. It should be recognized that the mechanisms by which SCMs control the concentration of alkali hydroxides in ASTM C 1293 and ASTM C 1260 are somewhat different. In ASTM C 1293, the source of alkalis is internal and SCMs deplete the alkalis in solution by dilution and by binding sodium and potassium in the hydration products. In ASTM C 1260, the predominant source of alkalis is external and SCMs work by both retarding the rate of ingress of alkalis into the mortar bar and by binding a portion of alkalis in solution. Thus, any correlation that exists between the results of the two tests is fortuitous [33]. Besides, specimen size has a large impact on expansion and this effect can be largely ascribed to leaching of the alkalis from smaller specimens. Thus, additional alkali is applied in ASTM C 1293 to get the alkali ratio of site concretes after leaching. However, in the accelerated method ASTM C 1260, specimens are kept in a water bath at 80^{o}C for 24h. It is widely accepted that alkali leaching from the sample to the bath water occurs during this period. Although it was demonstrated by some researchers that there was a reasonable correlation between the 14-

day expansion in ASTM C 1260 and the two year expansion in ASTM C 1293 and a 0,10% expansion limit is sufficient for ASR, some researchers prefer to use 28-day expansion measurements to compare with the chosen limiting value. The correlation between alkali emission and expansion were studied by Thomas et al. [44]. Figure 4 shows the finding of that study, where SF is silica fume and FA is fly-ash.

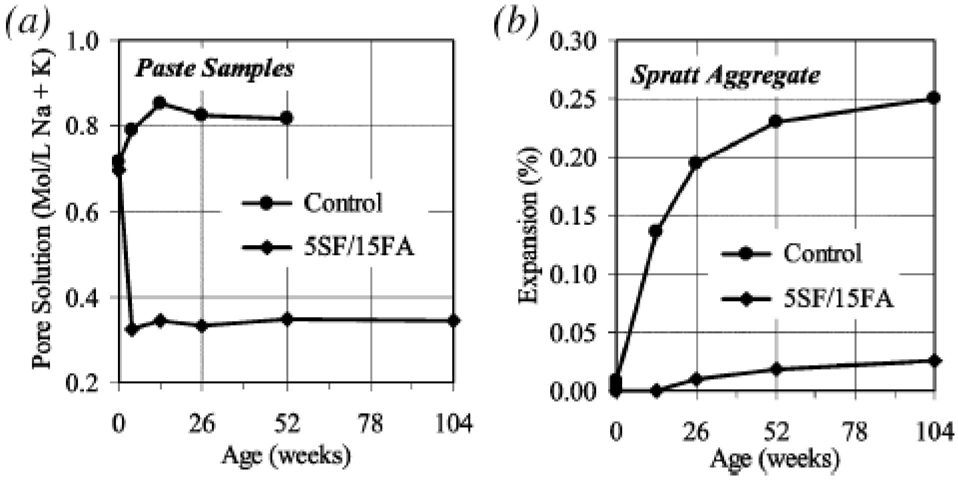


Figure 4. Pore Solution Analysis [44]

It is clearly seen in Figure 4 that, especially when SCMs are used, pore solution alkalinity differs remarkably. Thus it is noted in the modified ASTM C 1260, namely ASTM C 1567, that due to alkali leaching problems, this method is not applicable for SCMS's containing sodium oxide equivalent of greater than 4 %.

2.6 ACTIVATION

When literature on the general concept of activation is combed to better understand the activation of pozzolanic materials, it is possible to find numerous definitions and equations on the subject. The term 'activation' in this study is meant to imply one of or a combination of several methods to stimulate the pozzolanic reactions or to release the latent cementitious properties of inorganic materials. Several methods have been suggested by researchers including; calcination, mechanical method (grinding), thermal method (elevated-temperature curing) and addition of chemical activators.

Calcination is the burning of material in order to drive off the combined water in clay or other minerals resulting in a quasi–amorphous material which possesses pozzolanic properties. The gain of pozzolanic properties by calcination is attributed to both changes in the structure of the material and an increase in surface area during the calcination process. Lateritic and bauxitic soils and shales are some of the soils that had pozzolanic properties only after proper burning [8].

Grinding may be labeled as another effective way of activating the pozzolanic properties of materials thus many results indicate that the early strength of a hardened cement paste is directly proportional to the fineness of the cement. However, fineness does not increase ultimate strength. In contrast, excessively high fineness may increase water requirement and cause a reduction in ultimate strength [45]. Shrinkage may also be aggravated by increased cement fineness. Applying elevated temperature curing to the cement pastes may result in them reaching their maximum strength within several hours. However, ultimate strength of the samples exposed to thermal curing have been shown to decrease with increasing curing temperature [46]. Insufficiency of time and water to form proper components at high temperatures is given as an explanation of this phenomenon.

The previously mentioned methods have not attracted as much attraction as chemical methods since the results obtained from chemical activation were more satisfactory as well as more applicable and more economical. Another advantage of chemical activation over other methods is that, both mechanical and thermal methods are focused on accelerating existing cementitious properties whereas, in the chemical method, it is aimed to initiate the pozzolanic reaction without the help of any other materials such as portland cement clinker. However, since even the hydration reactions of plain cement are not completely understood, making trials of chemical activation of cementitious materials, is an enterprise based much more on trial and error than theoretical concepts.

2.6.1 Chemical and Thermal Activation

The accepted definition of an activator is “a substance that changes the speed of a chemical reaction without undergoing any chemical change itself ” [47]. In the case of alkali activation, since a reactant or a product may also be an activator, the definition suggested by Bell may be used instead: “An activator is a substance which appears in the rate expression to a power higher than that to which it appears in the stoichiometric equation” [48]. However, from a practical point of view, an activator is a substance that changes the rate of a desired reaction, regardless of the fate of the activator itself [51].

Most of the activation research to date has been conducted on the alkali activation of slags, owing to their self-cementing value. The possibility of producing slag-alkali cements without the addition of portland cement clinker which would result in more durable, more economical and perhaps most importantly more environmentally-friendly concretes, raises the importance of slags.

The term ‘alkali-activated’ is used by those who believe that R^+ (alkali) ions in such materials play a catalytic role in the early stages, then at a later stage they are combined into the structure to form zeolite-like phases [52].

Some references outlining eminent steps in the development of alkali–activated and alkaline cementitious mixtures are given in the Table 6 [52].

Table 6. Development of Alkali-Activated Cementitious Mixtures List of References

Author (s)	**Year**	**Significance**
Feret	1939	Slags used for cement
Purdon	1940	Alkali-slag combinations
Glukhovsky	1959	Theoretical bases and development of alkaline cements
Glukhovsky	1965	First named 'alkaline cements' because natural substances used as components
Davidovits	1979	“Geopolymer” term first used -emphasizes greater polymerization
Malinowski	1979	Ancient aqueducts characterized
Forss	1983	F-cement (slag-alkali-superplasticizer)
Langton and Roy	1984	Ancient building materials characterized (Roman - Greek- Cypriot)
Davidovis and Sawyer	1985	Patent leading to 'pyrament'
Krivenko	1986	D.Sc. Thesis , R_2O-RO-R_2O_3-SiO_2-H_2O
Malolepsyz and Petri	1986	Activation of synthetic melilite slag
Malek et al.	1986	Slag cement-low level radioactive waste forms
Davidovits	1987	Ancient and modern concretes compared
Deja and Malolepsy	1989	Resistance to chloride shown
Kaushal et al.	1989	Adiabatically cured nuclear waste forms from alkaline mixture including zeolite form.
Roy and Langton	1989	Ancient concrete analogs
Majumder et al.	1989	$C_{12}A_7$-slag activation
Talling and Brandstetr	1989	Alkali-activated slag
Wu et al.	1990	Activation of slag cement
Roy et al.	1991	Rapid setting alkali-activated cements
Roy and Silsbee	1992	Alkali-activated cements: overview
Palomo and Glasser	1992	CBC with metakaolin
Roy and Malek	1993	Slag cement
Glukhovsky	1994	Ancient, modern and future concretes
Krivenko	1994	Alkaline cements
Wang and Scrivener	1995	Slag and alkali-activated slag microstructure

The strength of cement and concrete materials is the most widely used and perhaps the most important overall measure of quality. The following factors can be listed as critical for the strength gain of concrete ;

- The nature of cementitious materials and activators
- Dosage of activators,
- Water/cementitious material ratio,
- Curing temperature,
- Fineness of cementitious materials,
- Timing of the addition of activators,
- Other additives,
- Compaction pressure

Jimenez [53] concluded that the most important factors affecting mechanical strengths are, from most significant to least, the nature of alkaline activator, activator concentration, curing temperature and specific surface of slag.

2.6.1.1 Activation of Slags

It was reported by Malolepszy [49] that Na_2CO_3 is especially suitable for activating slags rich in C_2MS, where M is an alkali metal, and NaOH is a good activator for slags rich in C_2AS. Activation of different systems with NaOH, Na_2CO_3 and $NaO.SiO_2$ was examined by Krivenko [50] and it was found that $Na_2O.SiO_2$ is the most effective for $CaO\text{-}SiO_2$,$CaO\text{-}Al_2O_3$, $CaO\text{-}Al_2O_3\text{-}SiO_2$ and $CaO\text{-}MgO\text{-}SiO_2$ systems, and Na_2CO_3 is the most effective for $CaO\text{-}Al_2O_3$ system. Many studies have confirmed that Na_2SiO_3 (sodium silicate or water glass) is a very effective activator [54].

As for the activation of portland-slag cements by Na_2SiO_3, Na_2CO_3, NaOH and Na_2SO_4.Na_2SiO_3 is the most and Na_2SO_4 is the least effective activator. However, in another study, it was mentioned that the addition of 4% Na_2SO_4 into a cement containing 50% blast furnace slag could significantly increase the strength of the cement [52].

In another study [54], it was shown that 4 %Na_2SO_4 and 4%$CaCl_2.2H_2O$ addition to lime-slag pastes cured at 50°C shows a large activation effect. Up to 90 days, $CaCl_2$ shows a greater activation effect on slag than Na_2SO_4.

Jiang [47] conducted another comprehensive study on alkali-activated cementitious materials. He showed the effect of different activators on compressive strength of cement-slag mortars. For a constant molar concentration of sodium, 2M, the comparative strength diagram is given in Figure 5. The most effective activator was 2M sodium silicate, which confirms the findings of Wang and Scrivener [55] that the use of soluble sodium and potassium silicate solution produced the highest strengths.

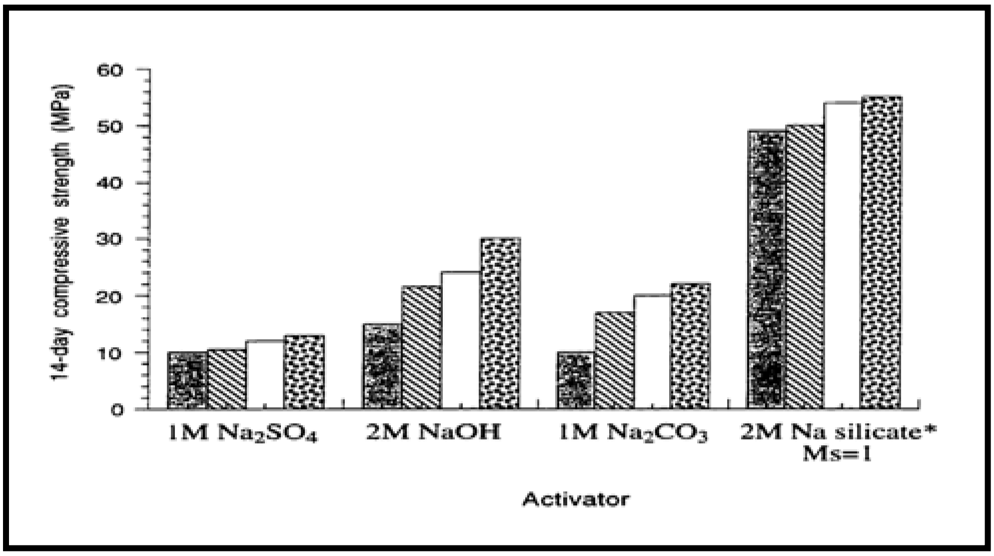


Figure 5.Different Activators vs. the14-day Compressive Strength of Mortars with OPC:slag=50/50 [47]

In the same study, the effect of heat treatment from 95-100^oC on the compressive strength of alkali-activated slag was also reported. The optimum range was obtained as 8-10 h heat treatment for the 2M NaOH activator case.

In another study, the activation of slag in gypsumless portland cement was researched. Addition of Na_2CO_3 from 1 %to 3 % resulted in an increase of strength in both ground slag and portland cement clinker-added ground slag mixtures [56].

Atiş et al. [57] studied the feasibility of using Turkish slags to produce a mortar without portland cement. Sodium silicate solution, sodium hydroxide and sodium carbonate were used as activators following the work by Bakherev et al. [58] on Australian slag cements. Although the best strength was obtained by sodium silicate solution, sodium carbonate was recommended considering the shrinkage properties of the mortars. It was reminded that heat treatment considerably accelerates strength development, but at later ages the compressive strength was reduced compared to concrete cured at room temperature [57].

Another study by Krizan and Zivanovic [59] showed that alkali slag cements activated with water glass with a (SiO_2/Na_2O) ratio between 0,6 and 1,5 show higher ultimate strengths than portland cement.

In the activation study of Brough and Atkinson et al. [60] it was concluded that higher strengths were developed rapidly by activating slag with 1,5 M $(Na_2O).(SiO_2)_2$ water glass solution when compared with ordinary portland cement and thermal activation of water glass systems is significant. Heat curing for 12 h at 80^oC gave rise to high early strength.

2.6.1.2 Activation of Fly Ash

The activation of low-calcium fly ash (LFA) and high-calcium fly ash (HFA) lime mixtures with 4% $CaCl_2$ and 4% Na_2SO_4 addition was studied by Shi [45] at a 50 ^oC curing temperature. In general, the action of Na_2SO_4 and $CaCl_2$ on lime-LFA pastes was almost the same as that on lime-natural pozzolan pastes: 1) The presence of Na_2SO_4 improves the early strength significantly; 2) $CaCl_2$ doesn't improve the early strength but increases the later strength significantly.

Addition of $CaCl_2$ lowers the alkalinity of the solution and slows down the dissolution of fly ash. The presence of $CaCl_2$ accelerates the dissolution of $Ca(OH)_2$ and favors the generation of $C_3A.CH.12H$ in the pastes is consumed very quickly. No more CH is found at 7 days and thereafter. The pastes have less C-S-H and more $C_3A.CH.12H$ compared with the control pastes. C-S-H acts as a binder and C_3A $.CA(OH)_2.12H_2O$ as a reinforcement. Thus, $CaCl_2$ containing pastes may show lower strength at early ages due to less C-S-H. As C-S-H increases, the $CaCl_2$ pastes possess high strength due to the reinforcement effect of $C_3A.CH.12H$.

Addition of Na_2SO_4 raises the alkalinity of the solution and accelerates the early hydration of lime-LFA. Both the acceleration of hydration and the formation of more Af_t give lime-LFA pastes high early strength [45].

Also for portland-fly ash cements, alkali sulfates are very effective activators when the portland cement content is greater than 20%. Microstructural examinations conducted by Lee et al. [61] also indicated that the use of Na_2SO_4 or K_2SO_4 as an activator clearly increased the consumption of $Ca(OH)_2$ and the formation of ettringite. Actually, it was observed that K_2SO_4 was more effective than Na_2SO_4 in reducing the total porosity and pore size.

When cement content is less than 20%, waterglass can be a very effective activator for cement. The addition of a certain amount of gypsum can also enhance the activation effect, however excessive gypsum will decrease the strength of the mixture drastically [54].

Activation of fly ash in different blended cement systems such as lime-fly ash, lime-fly ash-slag and portland-fly ash was investigated in a study by Qian et al.[62]. The activating effect of Na_2SO_4 was proven both for fly ash-lime and fly ash-slag-lime mixtures. The activation of fly ash-portland cement mixtures with CaO was less effective than activation withNa_2SO_4. However, addition of both CaO and Na_2SO_4 showed a cumulative activation effect.

A method of fly ash activation with the addition of CH and a small quantity of Na_2SiO_3 was studied by Fan et al. [63]. An activated fly ash (AFA) was obtained by homogeneously mixing FA, CH and Na_2SiO_3 , holding the mixture at a constant temperature of 55 ^oC until the CH disappears, then keeping at this temperature for another 8 hours, wet grinding the mixture for 40 minutes and drying at a temperature of 120^{o}C. The compressive strengths of AFA pastes were greater than FA pastes in all cases. Na_2SiO_3 addition increased the early strength of the pastes from 3 to 28 days but ultimate strength of AFA with Na_2SiO_3 was lower than those without Na_2SiO_3. The best activation was obtained with fly ashes that had high reactive SiO_2 and Al_2O_3 contents and $(Si/Al)_{reactive}$ ratios below 2 [64, 65].

In the patented study of Bainton [66] unwashed acidulated pozzolans were investigated and it was concluded that acidulated fly ash cubes at the age of 3 days had 129 % more strength when compared with untreated cubes incorporating 10 % portland cement and 90 % fine aggregate. In this example, even though fly ash was used as a pozzolanic filler material, the strength gain is obvious.

2.6.1.3 Activation of Natural Pozzolans

Despite natural pozzolans being some of the oldest construction materials, the disadvantages of prolonged setting time and slow strength development of lime-natural pozzolan pastes restrict their use. Also the tendency to increase the mixing water requirement for concrete is an additional obstacle for their use in blended cements. Thus, most of the activation trials are on natural pozzolan-lime mixtures.

Shi [45] investigated the activation of different pozzolans with Na_2SO_4, $CaCl_2$, $CaSO_4$ and NaCl as activators. Use of NaCl had no significant effect on strength gain whereas hemihydrate gypsum ($CaSO_4.0,5H_2O$) had a varied increase on strength. Na_2SO_4 increased both the early and later strength and the effect at early and later ages was higher than that at later ages; $CaCl_2$ increased strength significantly after 3 days with 50^oC curing. Surprisingly, increasing the curing temperature from 23^oC to 65 ^oC, resulted in a decrease of ultimate strength of both control and activated (Na_2SO_4 and $CaCl_2.2H_20$) mixtures. However, the rate of initial strength development increases as curing temperature increases. Several studies have confirmed that elevated temperature curing is very helpful in increasing the early strength of lime-pozzolan cements. For example, mortars made with Santorin earth did not show any strength at 7 and 28 days at 0 ^oC , but they did show high strength when cured at 35^oC [5]. In another study [54], lime-pozzolan pastes cured at ambient temperatures and tested at 7 days gave strengths of about 0,8 MPa , but gave 6MPa when cured at 52 ^oC.

Allahverdi [67] studied the effect of some chemical activators and set accelerators on setting and strength behaviors of lime–natural pozzolan cement containing 70% pumice and 30% hydrated lime. Na_2SO_4, Na_2CO_3, NaCl, $CaCl_2.2H_2O$, NaOH and OPC were used as activators. Na_2SO_4 was found to be the most effective chemical activator. Addition of 6% Na_2SO_4 to the studied lime natural pozzolan cement increased the 90-day compressive strength more than twice the control value. Addition of 4 % NaOH significantly decreased both the initial and final setting times.

In a study of Alexander [68], it was mentioned that the addition of NaOH increased the early strength of both lime pozzolan and portland pozzolan cements. On the other hand, in studies by Johansen [69] and Jawed and Skalny [70] the addition of alkalis to portland cement resulted in a reduction of strength after 3 or 7 days, because the hydration chemistry and the morphology of the hydration products were changed due to the presence of alkalis.

Alexander [68] showed that the reactivity of an effective pozzolan could be greatly increased, particularly at early ages, by acid treatment. The degree of activation depends on the concentration of the acid, and reaches a maximum in the region of 10 N in the case of HCl. No further activation was produced by raising the temperature of the acid. The experimental results indicated that acid treatment processes were more effective than prolonged grinding or the addition of NaOH to mixing water. Other researchers suggested that acid treatment can only increase the pozzolanic reactivity of low-calcium pozzolan; In high-calcium pozzolan, calcium is dissolved and its pozzolanic reactivity is reduced [45]. Also, it was noted that the addition of both NaOH and acid treatment together may be dangerous during operation.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

As indicated in the previous chapters, with its high silica content and natural pozzolan structure, perlite is thought to be useful for ASR suppressing purposes. Despite the affirmative results obtained in previous studies, it is still not clear whether the current accelerated test method for determining ASR, is applicable to perlite or not. ASTM C 1567 was developed for concrete and mixtures containing SCMs. However, while the alkali content of many pozzolans vary within the range of 2-3 %, perlite contains 6-8% alkalis in its structure. In ASTM C 1567, before preparing a 1N NaOH solution, samples are put into tap water at 80^{o}C for 24 h. It has been claimed and shown that during this water bath period, alkali leaching from the samples can occur. The acceptable point is that, after immersion in the NaOH solution, samples regain their alkalis. However, if perlite is being used, there is a conflicting point. Due to the high alkali content of perlite, roughly 30% replacement of cement with perlite will result in a higher alkali content than in a 1N NaOH solution, assuming all alkalis in perlite are soluble in water. In this case, it is likely to result in lower expansion measurements in ASTM C 1567 readings when compared to real site conditions in which no initial leaching would occur. In order to evaluate the adequacy of current standards to determine the effect of ground perlite addition on ASR before popularizing perlite usage in the cement and concrete sector some comparative tests would need to be conducted. In this context, both current methods should be repeated and alternative methods should be employed. If supporting results are obtained, these tests may form a larger database for encouraging the use of perlite to mitigate ASR. If the results are not compatible with the previous studies, new research may be needed prior to the using perlite in the cement sector.

On the other hand, the slow strength gain and excessive water requirement of natural pozzolans-containing cements are other handicaps that restrict their use in blended cements and mixtures. In this context, the activation of perlite-containing mixtures was attempted using chosen chemicals. The compressive and flexural strengths of the samples were determined according to the relevant standards.

3.2 MATERIALS

3.2.1 Cement

In all mixtures of both alkali–silica tests and activation trials, CEM I 42,5R type portland cement conforming to the Turkish Standard TS-EN 197-1, and obtained from Set Ankara Cement Factory, was used. The chemical characterization obtained by X-ray fluorescence and physical properties determined according to ASTM C 188 and ASTM C 204 are given in the following chapter.

3.2.2 Perlite

The perlite used in the study was obtained from a quarry in Erzincan, in sieved form. In order to provide the fineness requirements of ASTM C 618 which indicates not more than 34 % of the pozzolan should be retained on the 45 µm sieve in the case of wet sieving, comparative grinding-fineness tests were conducted. An optimum grinding time of 4 hours was obtained for the use of natural pozzolans as an addition in blended cements satisfying a Blaine fineness according to ASTM C 204 compatible with the definition of ASTM C 618. For grinding, a ball mill of 57780 cm^3 volume was used having a grinding media of both steel balls and steel cylpebs. The diameter of steel balls were within the range of 30 mm to 70 mm and they had a total weight of 84 kg. The dimensions of cylpebs (diameter x length) differed between 100 mm^2 to 900 mm^2 and cylpebs had a total weight of 14 kg. The chemical characterization obtained using X-ray fluorescence and physical properties determined as per the standards ASTM C 188 and ASTM C 204 are given in the following chapter.

3.2.3 Chemical Admixtures / Activators

In light of the results of previous activation studies, NaOH, $CaCl_2$, Na_2SiO_3, Na_2SO_4 and HCl were chosen as activators for the initial chemical activation attempts. 2 %, 4 % and 6 % addition of chemicals into the mixing water were tested. However, due to ineffective strength results, NaOH addition was discontinued after being used in the 25 % perlite-containing mortars.

NaOH was also used in the alkali-silica tests of ASTM C 1567, ASTM C 1293 and derived alternative test methods. KOH and NaOH were used in preparing standard solutions for determining the alkalinity of batch waters by flame photometry.

3.2.4 Aggregates

Three kinds of aggregates were used in the experimental part of this thesis. In the preparation of the mortars to be activated, CEN standard sand conforming to EN 196-1 was used. For ASTM C 1293 tests, 2 different reactive aggregates was used. The same aggregate sources were used also for ASTM C 1567 tests. Aggregates were crushed to a fineness providing the specified gradation in the standards. The physical properties of the aggregates were determined according to ASTM C 127, ASTM C 128, and ASTM C 29.

3.3 MIXTURE PREPARATION

3.3.1 Mixtures for Alkali-Silica Tests

For determining the alkali-silica reactivity of perlite-containing mixtures, two different testing methods were used. Concrete samples were prepared for the ASTM C 1293and mortar samples for ASTM C 1567 test, concrete samples were prepared, whereas for the tests based on ASTM C 1567, mortar samples were prepared. In all mixtures, perlite replacement levels were chosen as 5 %, 15 % and 25 % in order to observe the effect of increasing perlite content more clearly compared to the previous studies on perlite-containing cements.

3.3.1.1 Concrete Samples

In conformance with ASTM C 1293, the cementitious materials content of the concrete was kept constant at 420 kg/m^3 and water-to-cementitious (w/c) ratio at 0,43. Replacement amount of portland cement with perlite by 5 %, 15 % and 25 % is calculated on weight basis and rounded to the nearest integer. The dry mass of coarse aggregate per unit volume of concrete was equaled to 0,70 of its dry-rodded bulk density and the missing volume of the calculated concrete was completed with sand. Gradation of coarse aggregate was arranged according to the grading requirement of the standard. NaOH was dissolved in the mixing water in order to bring the alkali content of the concrete mixture up to 1,25 %of cement. A hand mix concrete is prepared and poured into the 75 mm cross-sectioned molds. 3 samples were prepared for each batch.The mixing and curing of concrete was performed as described in Practice C 192/C 192/M. Properly-compacted samples were kept in their molds for 24 hours and after taking the initial length measurement immediately put into the moist cabinet having a temperature of 38 ^{o}C .

Table 7. Mixture Proportions of Alkali-Silica Test Concretes

MIXTURE	OPC	PERLITE	NaOH	WATER	COARSE AGGREGATE	SAND
	(g)	(g)	(g)	(g)	(g)	(oven dry-g)
1(Control)	3030	0	13,69	1300	8700	3820
2(5% perlite)	2880	150	13,01	1300	8700	3770
3(15%perlite)	2580	450	11,66	1300	8700	3700
4(25%perlite)	2270	760	10,26	1300	8700	3625

The samples of ASTM C 1293 test method were identified with 2 numbers, (XY). X represents the batch of the specimen, and Y represents the order of the specimen. For instance, specimen number '32' represents the 2nd specimen of 15 % perlite-containing mixture.

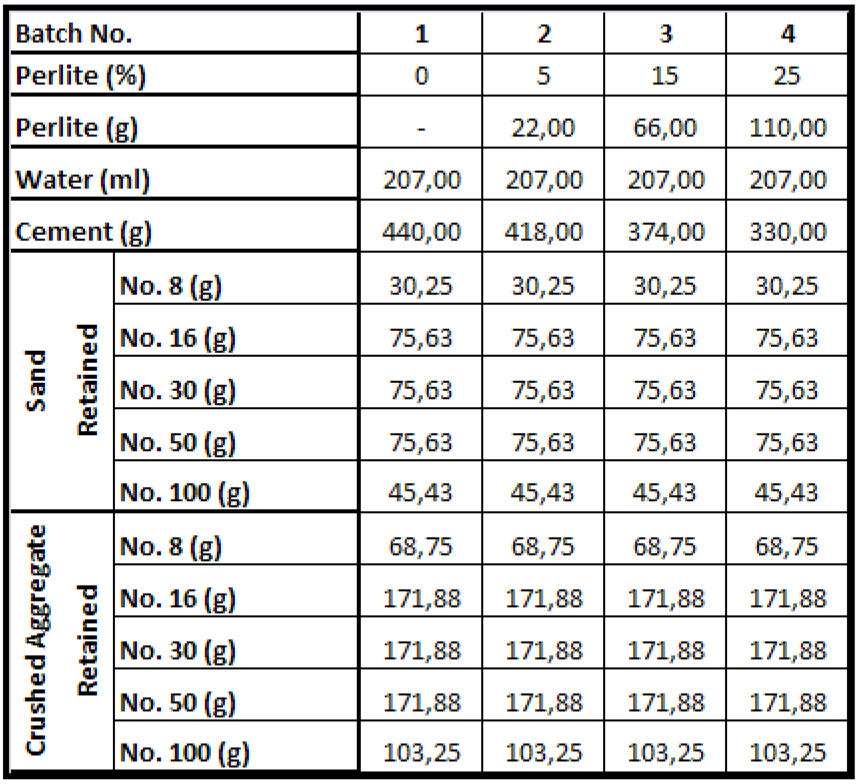
3.3.1.2 Mortar Samples

As indicated in ASTM C 1567, proportion of dry materials for the test mortar is adjusted using 1 part of cementitious materials (hydraulic cement plus pozzolan) to 2,25 parts of graded aggregate by mass for aggregates with a relative density (OD) above 2,45. The proportions of graded aggregate mixture from 2 different aggregate source were adjusted similar to the proportions of concrete test samples so as to have a comparable base. Water to cementitious material ratio is kept constant at 0,47 by mass and the mixture is prepared in accordance with the requirements of Practice C 305. After filling the 16 cm^2 cross-sectioned molds, samples were kept at ambient temperature for 24 hours. Immediately after removing the samples from the molds and taking the initial length measurements, they were placed in tap water at 80 ^{o}C and kept for another 24 h. Then for the reminder of the test the samples were kept in a 1N NaOH solution at 80^{o}C. Also, variants of this testing method were tried abiding by the mixture proportions but changing the solutions in which the samples were kept for 24 h upon demolding.

In the first variant, after demolding the mortar bars, samples were kept in a 1N NaOH solution and for the second variation, in a 2N NaOH solution.

The samples of ASTM C 1567 test method and its variants were also labeled similar to ASTM C 1293 test samples. The first of the two consecutive letters (e.g XY), represents the batch the specimen belongs to, and the second character represents the order of the specimen within the batch. The test method of which the specimen belongs to, is identified in the beginning of the informative table or figure.

Table 8. Mixture Proportions of Alkali-Silica Test Mortars



Batch No.			1	2	3	4
Perlite (%)			0	5	15	25
Perlite (g)			-	22,00	66,00	110,00
Water (ml)			207,00	207,00	207,00	207,00
Cement (g)			440,00	418,00	374,00	330,00
Sand	Retained	No. 8 (g)	30,25	30,25	30,25	30,25
		No. 16 (g)	75,63	75,63	75,63	75,63
		No. 30 (g)	75,63	75,63	75,63	75,63
		No. 50 (g)	75,63	75,63	75,63	75,63
		No. 100 (g)	45,43	45,43	45,43	45,43
Crushed Aggregate	Retained	No. 8 (g)	68,75	68,75	68,75	68,75
		No. 16 (g)	171,88	171,88	171,88	171,88
		No. 30 (g)	171,88	171,88	171,88	171,88
		No. 50 (g)	171,88	171,88	171,88	171,88
		No. 100 (g)	103,25	103,25	103,25	103,25

3.3.2 Mixtures for Activation Tests

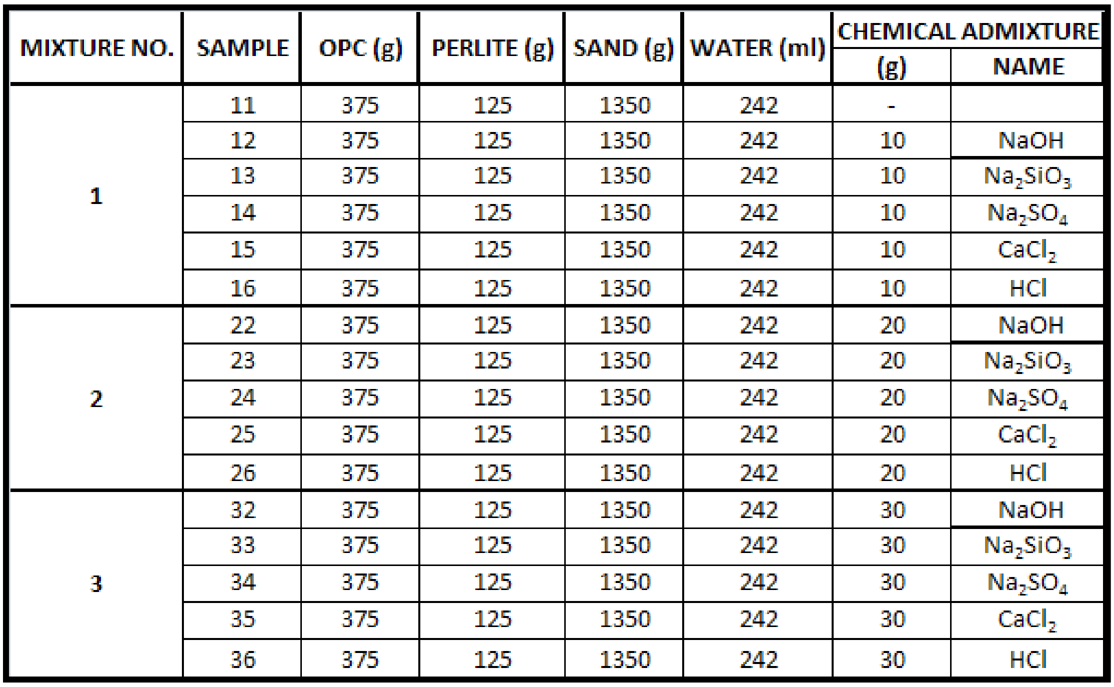
Based on a survey of the literature existing on activation of pozzolan incorporating portland cement mortar and concrete mixtures it was decided to try well-known alkali activators such as Na_2SiO_3 (water glass), NaOH, Na_2SO_4 as well as $CaCl_2$ and HCl.

$CaCl_2$ which is known to be an effective set accelerator had been tried in activation attempts previously and found to be effective especially on the early strength gain of portland-pozzolan cements. However, its use in the mortars is restricted due to the corrosion forming effect of Cl^- ions by breaking down the passive film on the rebar. On the other hand HCl had been suggested as an effective activator for low-Ca pozzolans that would be appropriate for perlite mineral. It must be noted that HCl may also exacerbate rebar corrosion.

In order to examine the effect of chemical activators on perlite containing cements, 25 % and 50 %perlite replacement was applied with an addition of chemicals at a content of 2%, 4% and 6% by mass of the total cementitious materials. For each replacement level, one control sample containing no chemical admixture was cast and compared with the 100 % OPC mortar specimen. Mortar prisms having dimensions of 4x4x16 cm were cast and kept in a moist room until the test day. Mixture proportions of the activated mortars at ambient conditions and at thermal conditions are given in the Table 8, 9, 10 and 11. Samples were tested at ages of 1day, 3 days, 7 days, 28 days and 56 days. 4 mixes were prepared for each batch. For the 1 and 3 day tests, 2 samples were deemed to suffice due to the consistently small difference between the results obtained. Another 2 specimens were kept for 56 day strength.

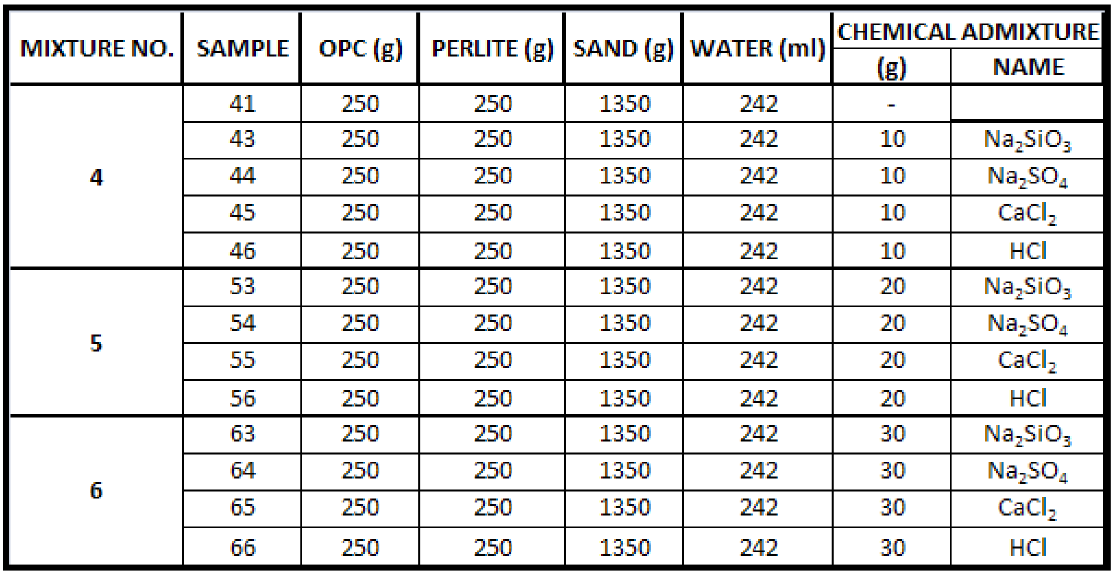
Non-marketable chemicals in building trade were used in amounts of 2, 4 and 6%. Although no activation trial of perlite exists in the literature, most of the researchers kept activator content less than 8 % due to the inefficacity and uneconomical nature of the activation process. Hrazdira [56] showed the decreasing strength of slag mortars with increasing Na_2CO_3 content after 2%. As per the study of Jimenez et al. [53] on the effect of activator concentration on strength gain of slags with Na_2O, the activator values recommended were between 3 and 5%. Also in the study of Shi and Day [71] on lime-pozzolan mortars, 4% dosage of Na_2SO_4 addition was found as the optimum amount. Thus, an increasing activator content from 2% to 6 % was decided in this study.

Table 9. Mixture Proportions of 25% Perlite-Containing Mortars



MIXTURE NO.	SAMPLE	OPC (g)	PERLITE (g)	SAND (g)	WATER (ml)	CHEMICAL ADMIXTURE	
						(g)	NAME
1	11	375	125	1350	242	-	
	12	375	125	1350	242	10	NaOH
	13	375	125	1350	242	10	Na_2SiO_3
	14	375	125	1350	242	10	Na_2SO_4
	15	375	125	1350	242	10	$CaCl_2$
	16	375	125	1350	242	10	HCl
2	22	375	125	1350	242	20	NaOH
	23	375	125	1350	242	20	Na_2SiO_3
	24	375	125	1350	242	20	Na_2SO_4
	25	375	125	1350	242	20	$CaCl_2$
	26	375	125	1350	242	20	HCl
3	32	375	125	1350	242	30	NaOH
	33	375	125	1350	242	30	Na_2SiO_3
	34	375	125	1350	242	30	Na_2SO_4
	35	375	125	1350	242	30	$CaCl_2$
	36	375	125	1350	242	30	HCl

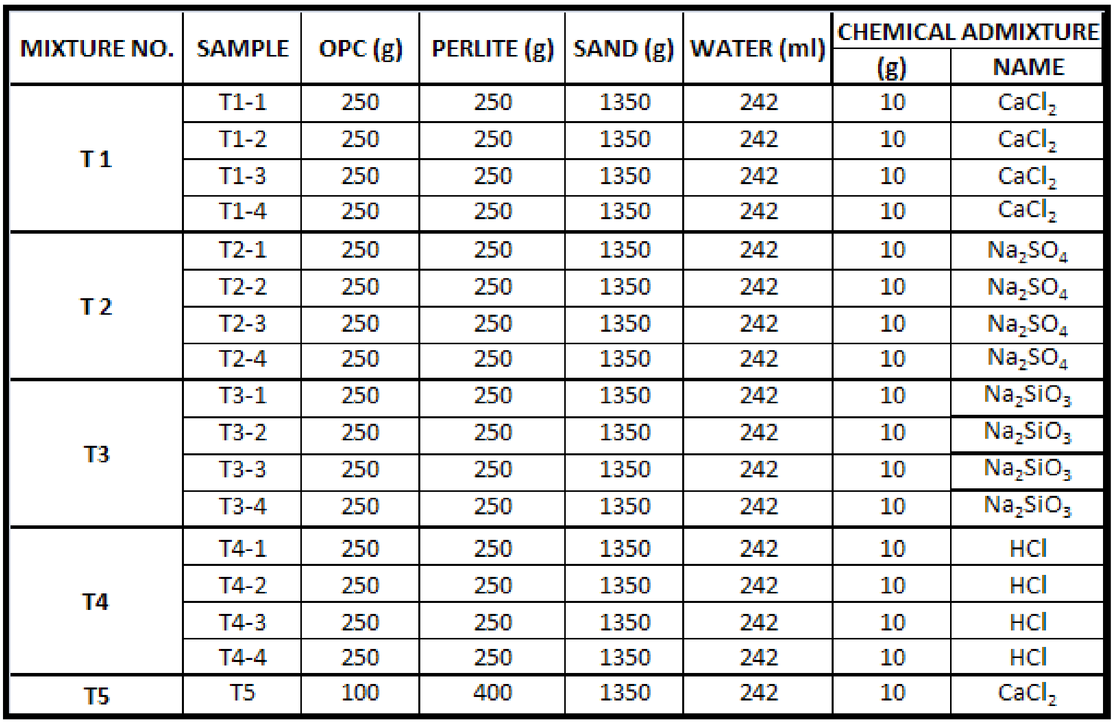
Table 10. Mixture Proportions of 50% Perlite-Containing Mortars



MIXTURE NO.	SAMPLE	OPC (g)	PERLITE (g)	SAND (g)	WATER (ml)	CHEMICAL ADMIXTURE	
						(g)	NAME
4	41	250	250	1350	242	-	
	43	250	250	1350	242	10	Na_2SiO_3
	44	250	250	1350	242	10	Na_2SO_4
	45	250	250	1350	242	10	$CaCl_2$
	46	250	250	1350	242	10	HCl
5	53	250	250	1350	242	20	Na_2SiO_3
	54	250	250	1350	242	20	Na_2SO_4
	55	250	250	1350	242	20	$CaCl_2$
	56	250	250	1350	242	20	HCl
6	63	250	250	1350	242	30	Na_2SiO_3
	64	250	250	1350	242	30	Na_2SO_4
	65	250	250	1350	242	30	$CaCl_2$
	66	250	250	1350	242	30	HCl

Two characters were used for the labeling of the activated mortars. The first character stands for the mixture number of the specimen that changes depending on the admixture content and perlite replacement level, and the second number represents the order of the specimen that is directly related with admixture type. For instance, sample name ‘55’ means the fifth specimen of a 50 % perlite and 4 % (20 g) admixture containing mixture.

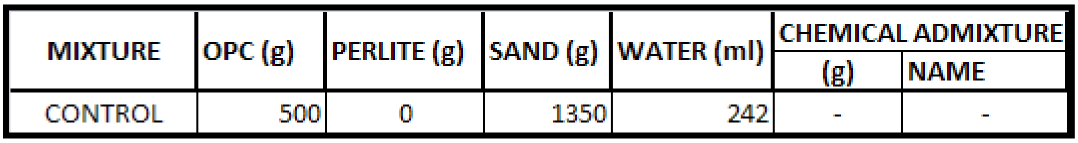
Table 11. Mixture Proportions of Thermally Cured Mortars



MIXTURE NO.	SAMPLE	OPC (g)	PERLITE (g)	SAND (g)	WATER (ml)	CHEMICAL ADMIXTURE	
						(g)	NAME
T 1	T1-1	250	250	1350	242	10	$CaCl_2$
	T1-2	250	250	1350	242	10	$CaCl_2$
	T1-3	250	250	1350	242	10	$CaCl_2$
	T1-4	250	250	1350	242	10	$CaCl_2$
T 2	T2-1	250	250	1350	242	10	Na_2SO_4
	T2-2	250	250	1350	242	10	Na_2SO_4
	T2-3	250	250	1350	242	10	Na_2SO_4
	T2-4	250	250	1350	242	10	Na_2SO_4
T3	T3-1	250	250	1350	242	10	Na_2SiO_3
	T3-2	250	250	1350	242	10	Na_2SiO_3
	T3-3	250	250	1350	242	10	Na_2SiO_3
	T3-4	250	250	1350	242	10	Na_2SiO_3
T4	T4-1	250	250	1350	242	10	HCl
	T4-2	250	250	1350	242	10	HCl
	T4-3	250	250	1350	242	10	HCl
	T4-4	250	250	1350	242	10	HCl
T5	T5	100	400	1350	242	10	$CaCl_2$

For identification of thermally cured mortars, the letter ‘T’ was used prior to the mix number which changes according to the admixture type, and the second number stands for the different heat and curing time conditions.

Table 12. Mixture Proportions of Control Samples



MIXTURE	OPC (g)	PERLITE (g)	SAND (g)	WATER (ml)	CHEMICAL ADMIXTURE	
					(g)	NAME
CONTROL	500	0	1350	242	-	-

3.4 TESTING OF MATERIALS

3.4.1 Tests of Aggregates

Density, relative density (specific gravity), and absorption of coarse and fine aggregates were found in accordance with ASTM C 127 and C 128. Water contents of the aggregates were calculated. As described in ASTM C 1293, aggregates were graded in 3 groups and calculations were made on this basis. The intended gradations of aggregates in ASTM C 1567 and ASTM C 1293 were obtained by using a mechanically operated sieve.

3.4.2 Tests of Powders

Ground perlite and portland cement were the only powders of this study. An x-ray fluorescence analysis for chemical characterization of each material was conducted. The specific gravities of the powders were determined in accordance with ASTM C 188.

Finenesses of the powders were determined by using a manually operated Blaine air permeability apparatus described in ASTM C 204 test method A. Since the porosity of perlite powder greatly differed from that of reference cement, the required adjustments were made to get a porosity of 0,5. Calculations were done on the basis of the 7th equation given in the standard for materials other than portland cement and having a test temperature within ±3 °C temperature of calibration test.

The equation used in calculations is:

$$S=[S_s.\rho_s.(b_s-\epsilon_s)\sqrt{\epsilon^3}.\ \sqrt{T}]/[\ \rho.(b-\epsilon).\ \sqrt{\epsilon_s^3}.\sqrt{T_s}] \qquad \textbf{Eq.(1)}$$

where;

S = Specific surface of the test sample, m^2/kg

S_s = Specific surface of the standard sample used in calibration of the apparatus, m^2/kg

T = Measured time interval, s, of manometer drop for test sample

T_s = Measured time interval, s, of manometer drop for standard sample used in calibration of the apparatus

Є = Porosity of the prepared bed of test sample

$Є_s$= Porosity of the prepared standard sample used in calibration of apparatus

ρ = Density of test sample

ρ_s = Density of standard sample used in calibration of apparatus

b= b_s= 0,9 a constant.

In determining the fineness of perlite powder, a comparative method is applied. A sample amount of perlite was sieved through 63µm sieve and the material passing was subjected to Blaine fineness test.

Another sample of perlite was ground for 4 hours and then a Blaine fineness test conducted. The fineness of the latter is expected to be finer than first one to satisfy the requirements of ASTM C 618.

3.5 TESTING OF MIXTURES

Four different testing methods were applied to determine the length change of samples due to the alkali-silica reaction. Concrete specimens were tested in accordance with ASTM C 1293, whereas mortar bars were tested in accordance with ASTM C 1567 and its variants, which were essentially identical to ASTM C 1567 except having a different alkalinity of the bath water. Instead of tap water, 1N NaOH and 2N NaOH solutions were used as the first 24-hour waiting solution in the derived testing methods. In order to evaluate the alkali leaching of mortars in water, alkalinity of batch water was determined, before and after 24-hour wait period.

In addition to the alkali silica tests, the effectiveness of activation of mixtures using different chemical admixtures were examined with compressive and flexural strength tests for different replacement levels of portland cement with different amounts of chemical addition and under different thermal curing conditions.

3.5.1 Determination of Length Change of Concrete Due to Alkali-Silica Reaction

Actually, ASTM C 1293 is the only test method that can be used for materials containing an equivalent alkaline greater than 4 % [37]. The requirement to keep the specimens under controlled conditions for periods up to 2 years, supplementary cementitious material containing specimens, restricts the use of this testing method.

The test set up was prepared as described in the standard and sealed with a plastic film in order to prevent any considerable loss of enclosed moisture due to evaporation. The bottom of each polyethylene containers was filled with water without allowing it to pass over the supports of the apparatus and the inside walls of the containers were covered with an absorbent fabric so that a homogeneous humidity environment was provided. A length gauge having a sensitivity of 0,0001 in. was used. Depending on the length of the specimens, the length measurements were made with or without a small metallic piece (pin) attached to the measurement opening of the gauge.

Figure 6. The ASTM C 1293 Testing Setup – Open View

Figure 7. The ASTM C 1293 Testing Setup – Sealed View

3.5.2 Determination of the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method)

The ASTM C 1567 and modified ASTM C 1567 (as explained in section 3.3.1.2) tests were applied to the prepared mortar bars to determine the potential alkali-silica reactivity of perlite-containing mortars. In ASTM C 1567, after demolding the specimens, they were kept in containers filled with tap water at 80^oC for 24 hours whereas for the modified ASTM C 1567 tests specimens were kept in, in order of, 1N and 2N NaOH solutions at 80^oC. After the first 24 hours they were kept in a 1N NaOH solution for an additional 14 days. During this period, successive length measurements were taken. A length gauge with a sensitivity of 0,0025 mm was used for the measurements.

3.5.3 Determining the Alkalinity of Specimen Bath Waters

In order to control the alkali leaching of the specimens in different solutions and to compare the amounts leached from the specimens containing different amounts of perlite, alkali measurements of bath waters were taken before and after the initial 24-hour wait period in the container at 80^oC. A Jenway model PFP7 flame photometer was used to determine the concentrations of Na^+ and K^+ ions in the bath waters. Solution samples were tested immediately after taking the reading of standard calibration solutions.

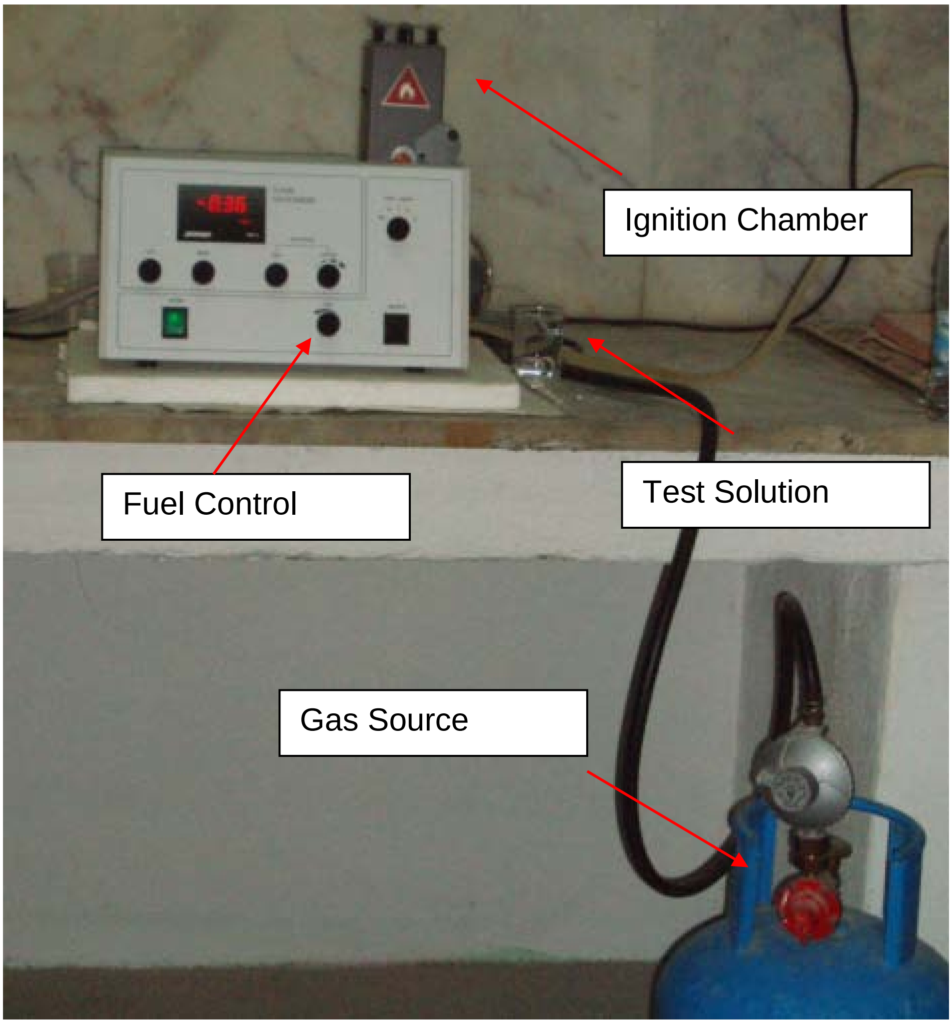


Figure 8. Flame Photometer

3.5.4 Flexural Strength Tests

The flexural strengths of the mortar prisms, prepared for the evaluation of activation process of perlite-containing blended cements, were determined as described in TS EN 196-1 by using a universal test machine. Prisms with nominal dimensions of 4cm x 4cm x 16 cm were tested in a three-point bending test having a support span of 10 cm. The maximum applied load prior to breaking (in kN) was determined and the flexural strength Rf was calculated through equation 2.

$$Rf=3PL/2bd^2 \qquad \textbf{Eq.(2)}$$

3.5.5 Compressive Strength Tests

Compressive strengths of the mortars were determined in accordance with TS EN 196-1. The two halves of the prism specimen obtained after the flexural strength test were tested individually, in compression. The maximum applied load (in kN) and compressive strength for a 4 cm x 4 cm loaded area was automatically obtained from the machine.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

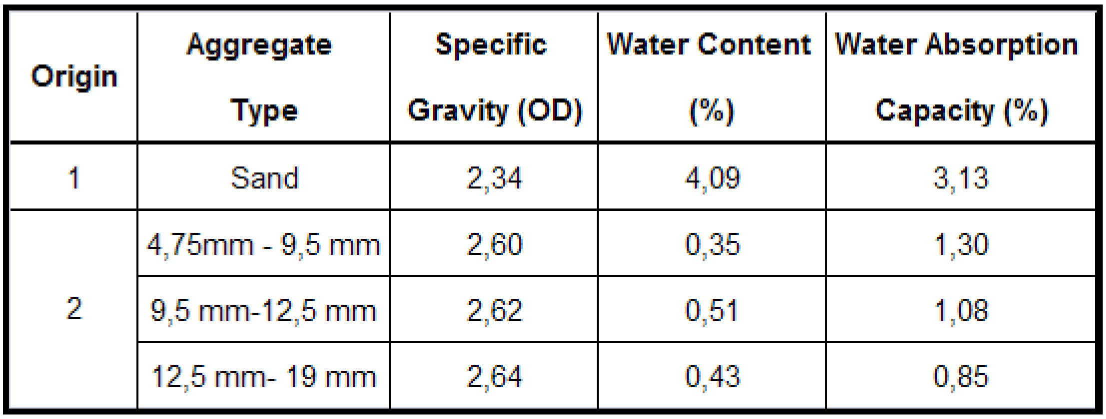
In this section results obtained from alkali-silica tests and tests to evaluate the effect of chemical and thermal activation on strength are presented. A comparison between the expansion of specimens during various standard and devised alkali silica tests and the determination of alkali leaching in each test method, and finding an effective activator for perlite-containing blended mortars were aimed.

4.2 CHEMICAL AND PHYSICAL PROPERTIES OF USED MATERIALS

4.2.1 Physical Properties of the Aggregates Used

The physical properties such as the specific gravity, bulk density and moisture content of aggregates from two different sources, used in alkali-silica expansion tests on concrete and mortar specimens are presented in Table 13. The aggregate gradation given in ASTM C 1293 was also used to prepare the sample for determining the physical properties of aggregates.

Table 13. Physical Properties of Aggregates



Origin	Aggregate Type	Specific Gravity (OD)	Water Content (%)	Water Absorption Capacity (%)
1	Sand	2,34	4,09	3,13
2	4,75mm - 9,5 mm	2,60	0,35	1,30
	9,5 mm-12,5 mm	2,62	0,51	1,08
	12,5 mm- 19 mm	2,64	0,43	0,85

OD: Oven Dry

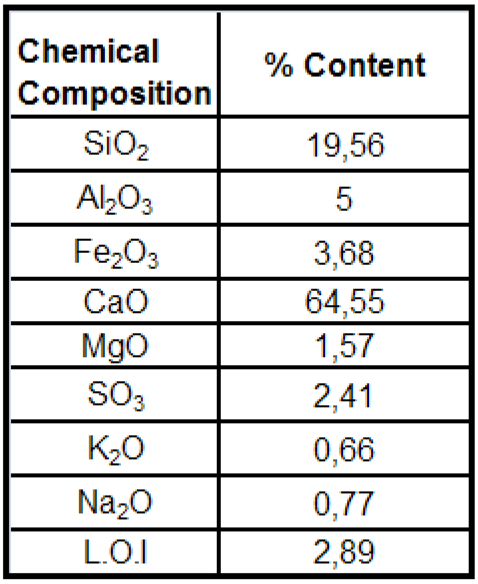
4.2.2 Physical and Chemical Properties of the Powder Materials

The chemical compositions of the expanded ground perlite and CEM-I 42,5 R type cement are presented in Table 14 and 15. The rather high SiO_2 content of perlite is as if to prove its pozzolanic characteristic at first glance.

Table 14. X-Ray Fluorescence Analysis of the Perlite Used

Chemical Composition	Content (%)
SiO_2	71,1
Al_2O_3	13
Fe_2O_3	1,6
CaO	1,6
MgO	0,5
SO_3	1,6
K_2O	3,8
Na_2O	4,2
MnO	0,1
BaO	0,1
P_2O_5	<0.1
TiO_2	<0.1

Table 15. X-Ray Fluorescence Analysis of the Cement Used

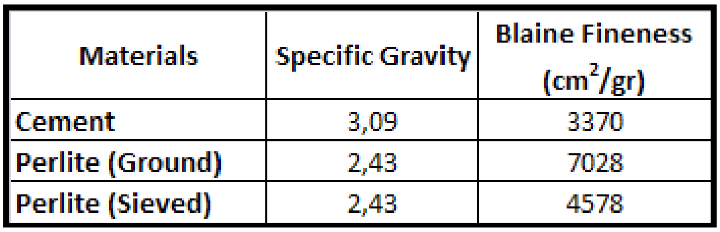


Chemical Composition	% Content
SiO_2	19,56
Al_2O_3	5
Fe_2O_3	3,68
CaO	64,55
MgO	1,57
SO_3	2,41
K_2O	0,66
Na_2O	0,77
L.O.I	2,89

L.O.I: Loss on Ignition

The finenesses of the materials determined using the Blaine air-permeability test and specific gravity determined using volume displacement in a Le Chatelier flask, are presented in Table 16. As can be seen, finer perlite could be obtained by extended grinding.

Table 16. Physical Properties of the Cement and Perlite Used



Materials	Specific Gravity	Blaine Fineness (cm^2/gr)
Cement	3,09	3370
Perlite (Ground)	2,43	7028
Perlite (Sieved)	2,43	4578

4.3 INVESTIGATIONS ON THE ALKALI–SILICA REACTIVITY OF PERLITE-CONTAINING MORTARS

It was previously mentioned that, four different methods were employed to evaluate the alkali-silica reactivity of perlite-containing mixtures in our study. The first aim of this, was to obtain more realistic results about the behaviour of perlite-containing cements undergoing alkali-silica reactions. Since ASTM 1567 is not a method applicable to materials containing high amounts of alkalis such as perlite, it would be appropriate to use the only suitable and most realistic standard method, ASTM C 1293, to test perlite-containing cementitious mixtures. Although, the duration of this test for pozzolan containing mixtures is 2 years, which is a very forcing time for a master thesis, we aimed to obtain at least 1-year length measurement results for the concrete samples to get an understanding of the general influence of different amounts of perlite addition to concrete. However, we were not able to obtain results for even 6 months. After putting the samples into the oven at 38°C, it was observed that the plexiglass and steel supports had warped and corroded after several months. It was decided that this happened due to a decrease in the elastic moduli of the material at the higher than room temperature inside the oven and the subsequent creep of the load-carrying parts of the support. Besides, an electrical power failure caused the oven to turn off, and the problem was discovered only after several days. Since the weather conditions during test period were not adequate to compensate a 10-day interruption at ambient temperature, it was decided to retry the test and put a newly-prepared set of samples in the oven only a few months prior to the writing of the thesis. A continuous decrease in the oven water pool depth caused from by humidity losses (not in the specimen containers but from the oven environment), resulted in non-homogeneous heat dispersion between the two separate parts of the oven from time to time. Thus, it was occasionally not possible to achieve exactly 38^{o}C constant ambient temperature inside the oven. Despite all these setbacks, we found it helpful to continue the experiment for an additional time interval longer, at least to get a general idea about the influence of perlite addition to concrete mixtures on alkali-silica reactivity.

4.3.1 ASTM C 1293 Test Results

As previously mentioned in Chapter 3.3.1.1, concrete samples for evaluating alkali-silica reactivity, were prepared as per the mixture proportions suggested in ASTM C 1293.

Four successive measurements were taken over a 3-month period and are presented in the Appendix. The measurements shown in green were canceled due to disaccordance with the other 2 samples. Length changes of the samples were calculated and given in Table A1. Length changes are visualized in Figure 9.

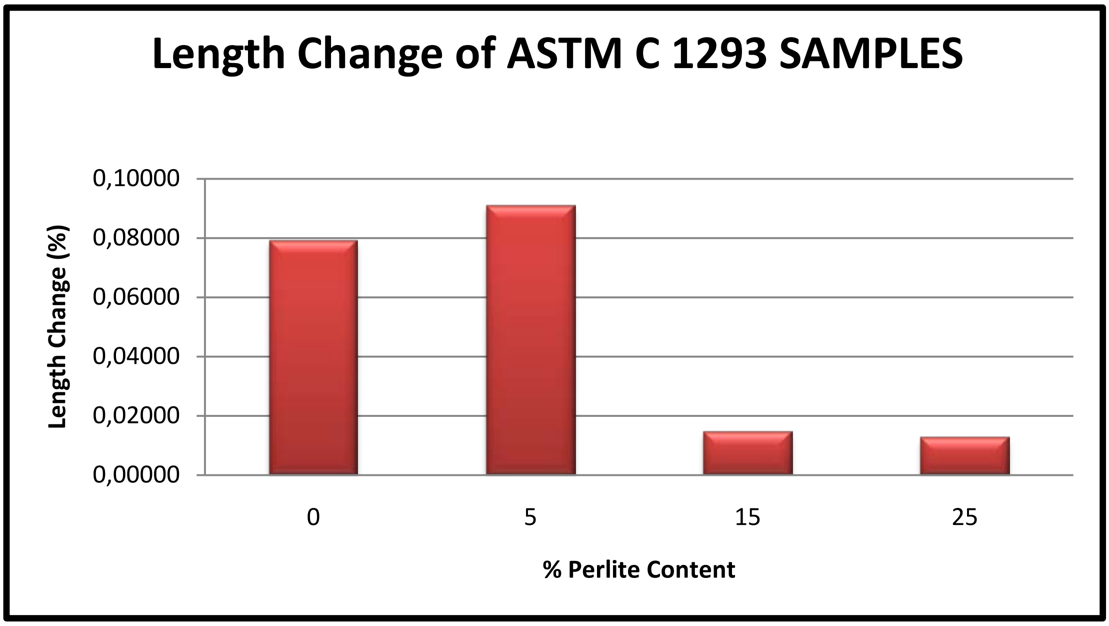


Figure 9. Length Changes of the ASTM C 1293 Samples in 3 Months

In Table A1, ‘k’ corresponds to 0,001 in. As shown in Figure 9, use of perlite decreased the expansion of the samples due to alkali-silica reaction. The expansion increase in the case of 5 % perlite replacement may be attributed to pessimum effect of pozzolan replacement on alkali-silica reaction as indicated by Bektaş et al. [23] previously. Also, the equipment problems which occurred during the test period and inconsistency of testing conditions reduce the reliability of test results. However, to reiterate the purpose of this study which was to evaluate the effect of perlite addition on alkali-silica reaction related expansions, while whether an expansion occurs for low mass fraction perlite replacement is debatable, it is clear that high replacement volumes of perlite mitigate the expansive effect of this reaction.

4.3.2. ASTM C 1567 Test Results

Mortar bars for evaluating the alkali-silica reactivity of perlite-containing mixtures, were prepared as per the mixture proportions suggested in ASTM C 1567.

Five length measurements were taken within the 14-day duration of the test and are presented in Appendix. It should be noted that, some of the tests samples cracked during demolding and had to be discarded. Length changes of the samples were calculated and are given in Table A2. The length changes are shown in graphical format in Figure 10.

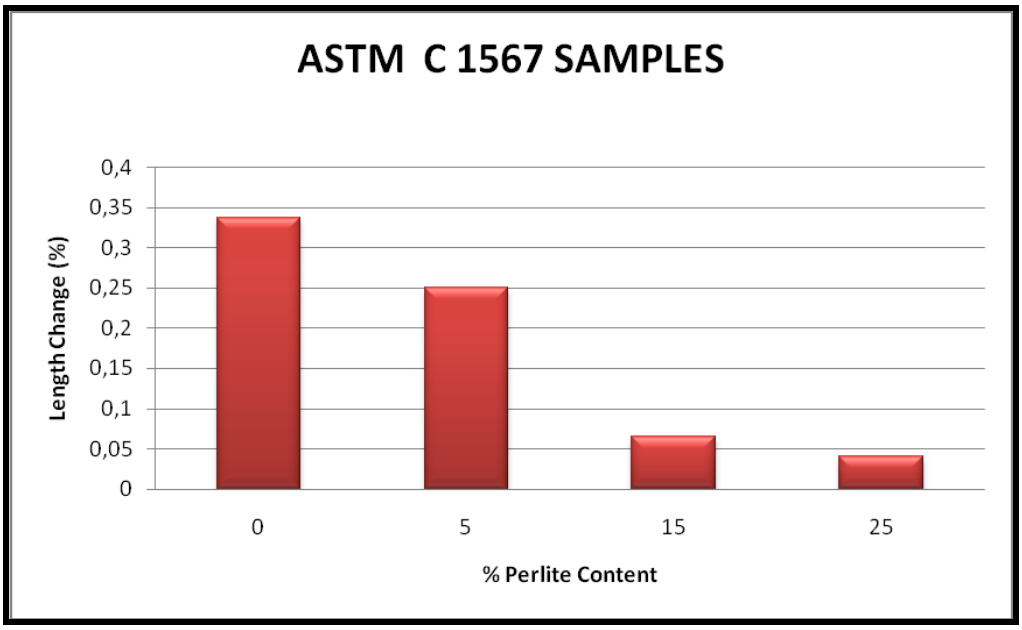


Figure 10. Length Changes of the ASTM C 1567 Samples

In Table A2, ‘k’ corresponds to 4 x 0,0025 mm for all measurements of ASTM C 1567 and its variants test methods.

According to the results of this testing method, it is seen that, even 5% use of perlite was efficient for mitigating the alkali-silica expansions of the mortars. However, for more effective results, perlite content should be increased. The results of ASTM C 1567 support the results of ASTM C 1260 tests conducted by Bektaş et al. [23] and Erdem [20]. All studies show that, increasing perlite content decreases the alkali-silica expansions.

4.3.3 ASTM C 1567- 1N Modified Test Results

The procedure of the ASTM C 1567- 1N modified test was mentioned previously. Six length measurements were taken during test duration and are listed in Appendix. Length changes of the samples were calculated as in Table A3. Due to problems with the 3rd batch, the readings shown in green were canceled.

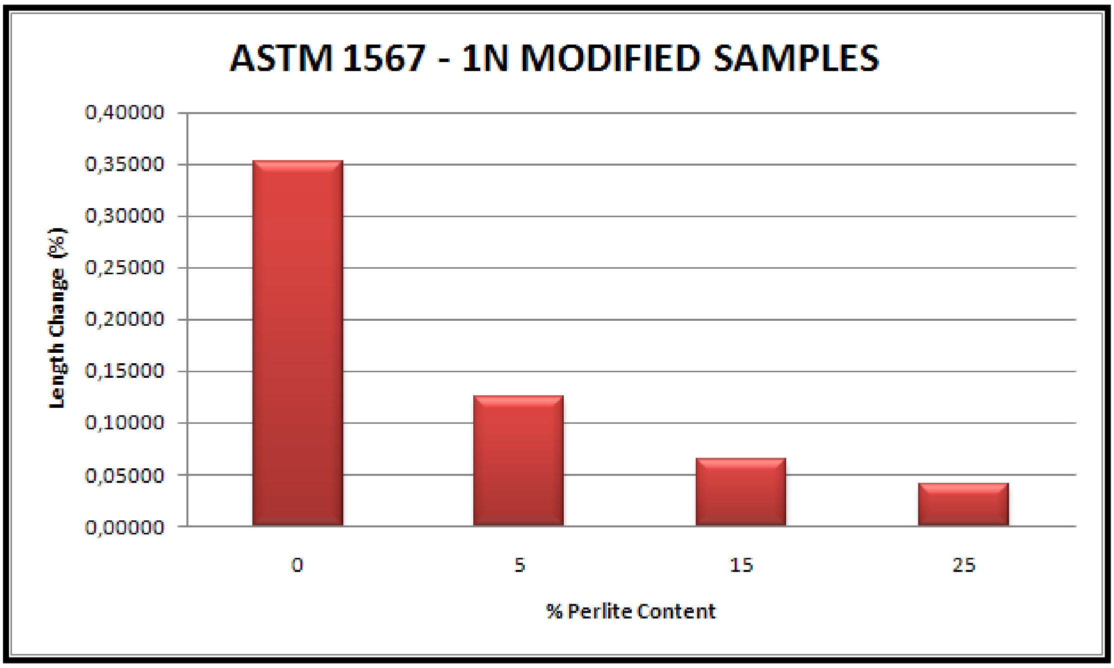


Figure 11. Length Changes of the ASTM C 1567-1N Modified Samples

As seen in Figure 11, use of perlite still decreases the alkali-silica expansions. The variation between the results of mortar bars of the same batch may be caused by hairline cracks which formed during demolding of the samples.

4.3.4 ASTM C 1567-2N Modified Test Results

ASTM C 1567-2N Modified test method was conducted as explained in previous chapters. Length measurements of the mortar bars are given in Appendix. Length changes were calculated as and are depicted graphically in Figure 12.

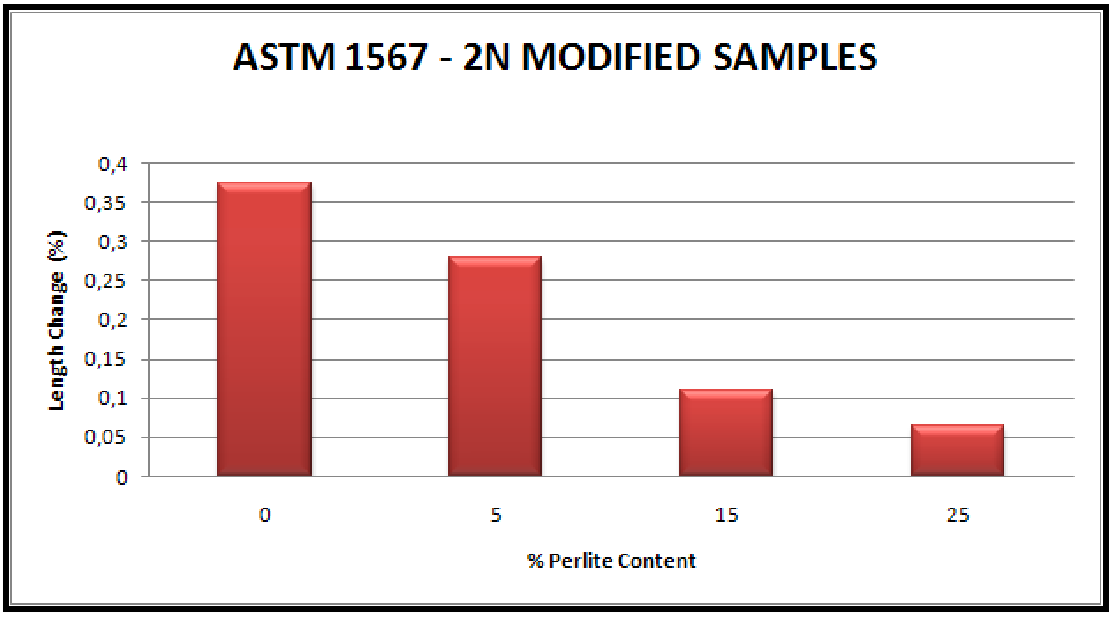


Figure 12. Length Changes of the ASTM C 1567-2N Modified Samples

The effect of perlite addition content on alkali-silica reaction does not change in the 2N Modified method, either. Increasing perlite addition results in a decrease in alkali-silica expansion.

4.3.5 Comparison of Different Alkali-Silica Tests

When expansion results of ASTM C 1567, ASTM C 1567- 1N Modified and ASTM C 1567- 2N Modified are compared for mixtures containing identical amounts of perlite, Figures 13 - 16 are obtained.

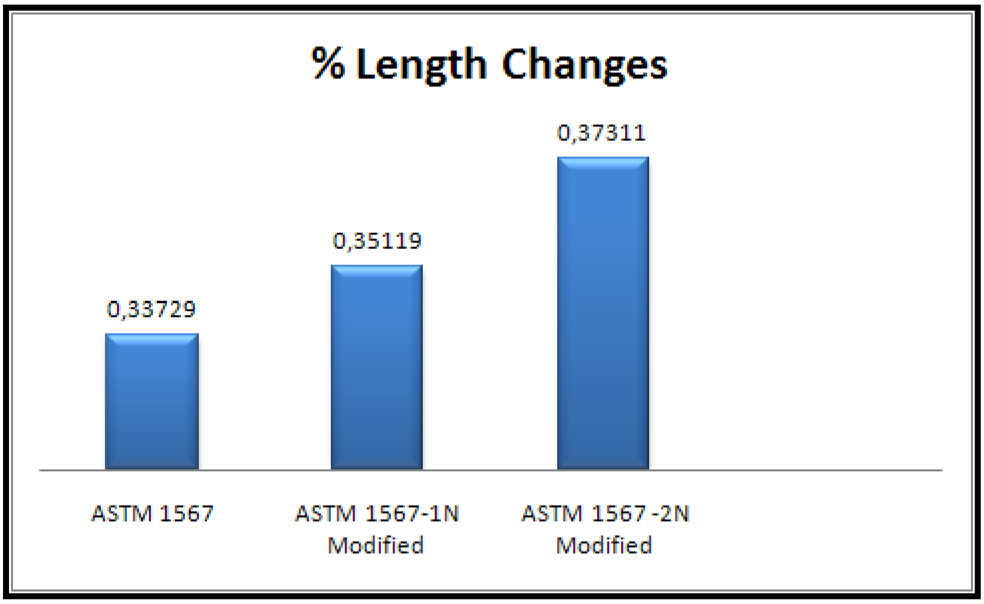


FIGURE 13. Comparison of Alkali-Silica Tests of 0% Perlite Specimens

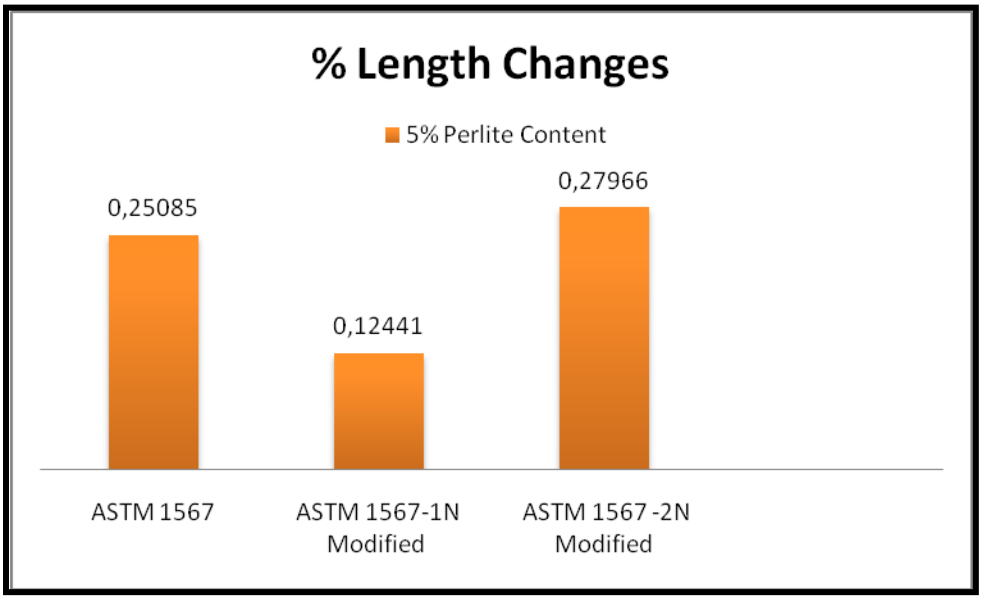


FIGURE 14. Comparison of Alkali-Silica Tests of 5 % Perlite-Containing Specimens

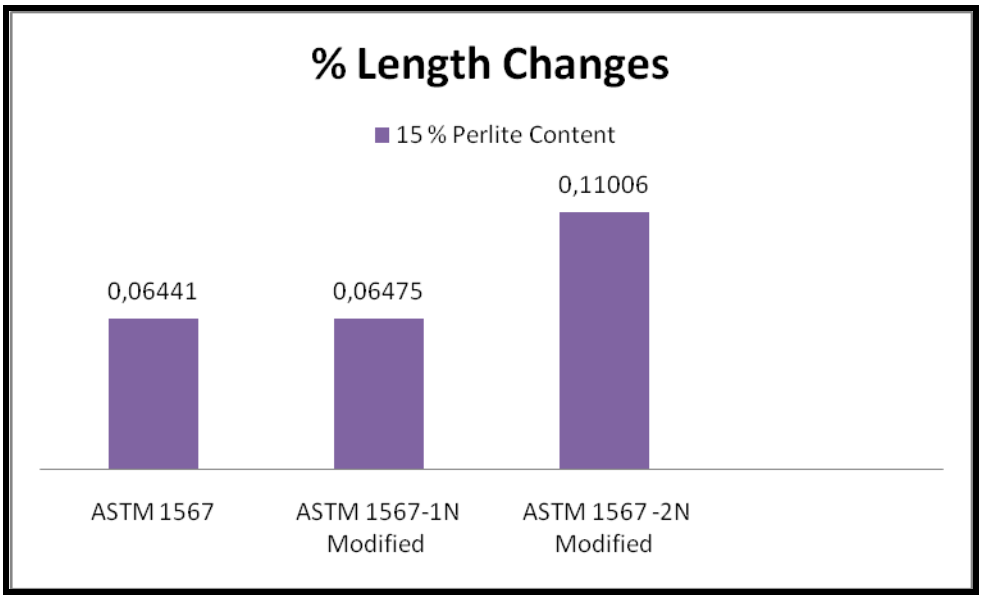


FIGURE 15. Comparison of Alkali-Silica Tests of 15 %Perlite-Containing Specimens

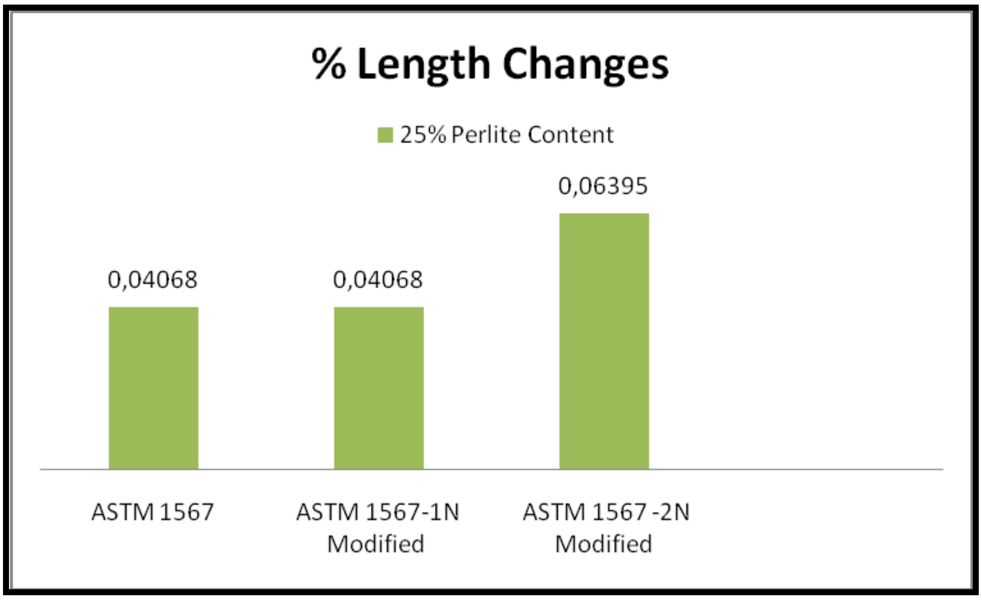


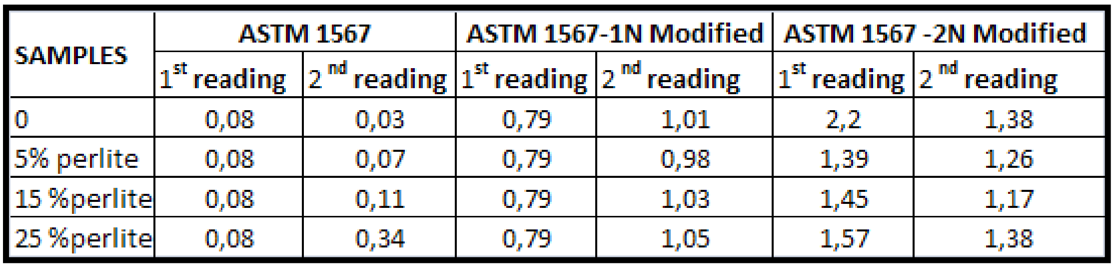
FIGURE 16. Comparison of Alkali-Silica Tests of 25 %Perlite-Containing Specimens

Apart from the 5 % perlite-containing mixtures, in all cases it was observed that expansion is increased with increasing alkalinity of the bath water, anticipated. Because, even if all the alkalis of perlite are assumed to be water-soluble and the alkalis of pore solutions, which are not able to leach to the bath water, are neglected, it is still not possible to have an alkali leaching from samples to bath water up to 15 % replacement level. In the case of 25 % perlite-containing samples, alkali leaching is expected up to 1N alkali-concentrated solution. However, for the 2N alkali-containing solution, samples are expected to absorb alkalis from water. If alkali leaching from samples is not observed, or a relatively lower alkali leaching is observed in 1N and 2N solutions, more expansion can be expected in these solutions. The exception of 5 % perlite-containing mixtures may be due to erroneous measurements (or cracked samples), as well as, due to pessimum behaviour. Pessimum behaviour may be observed in samples depending on the amount of reactive silica. Also, in a study of Bektaş et al. [23], for 4 % replacement of cement with expanded perlite, higher expansions than control samples of 100% OPC were obtained.

4.4 INVESTIGATIONS ON THE ALKALINITY OF SPECIMEN BATH WATERS

The aim of this test is to get an idea about the alkaline motion of the samples that were kept in 1N, 2N and non-alkaline solutions, which would be helpful to understand the expansion mechanism of the samples under different alkalinity conditions. Sodium ion measurements of the bath waters are given in Table 17. Potassium ion measurements of bath waters are given in Table 19. 1st readings were taken from bath waters prior to putting samples into the containers and 2nd readings were taken after 24 h waiting period. Obtaining the nearest linear equation of ion concentration (ppm) vs. photometer reading from Figures 17 and 19, ion concentration of solutions were obtained as shown in Table 18 and 20.

Table 17. Na^+ Ion Measurements Using Flame Photometry



SAMPLES	ASTM 1567		ASTM 1567-1N Modified		ASTM 1567 -2N Modified	
	1st reading	2 nd reading	1st reading	2 nd reading	1st reading	2 nd reading
0	0,08	0,03	0,79	1,01	2,2	1,38
5% perlite	0,08	0,07	0,79	0,98	1,39	1,26
15 %perlite	0,08	0,11	0,79	1,03	1,45	1,17
25 %perlite	0,08	0,34	0,79	1,05	1,57	1,38

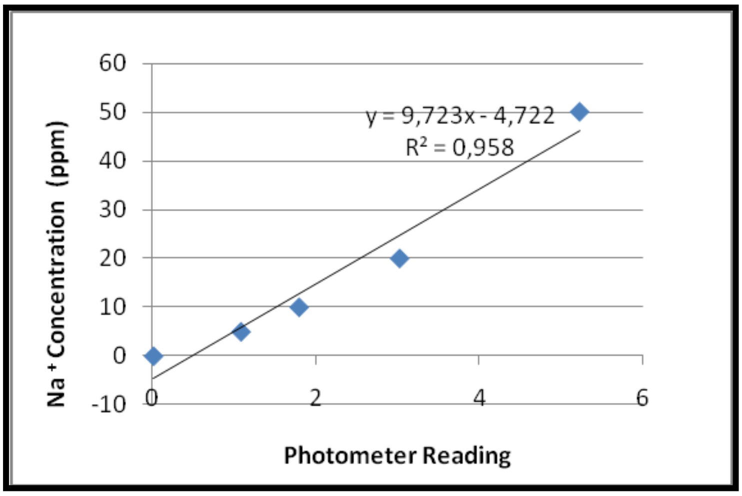


Figure 17. Linear Equation of Na^+ Concentration vs. Photometer Reading

Table 18. Na+ Ion Concentration of Bath Waters

SAMPLES	ASTM 1567		ASTM 1567-1N Modified		1567-2N Modified	
	1st ppm	2nd ppm	1st ppm	2nd ppm	1st ppm	2nd ppm
0	-39441,60	-44303,10	29591,70	50982,30	166686,00	86957,40
5% perlite	-39441,60	-40413,90	29591,70	48065,40	87929,70	75289,80
15 %perlite	-39441,60	-36524,70	29591,70	52926,90	93763,50	66539,10
25 %perlite	-39441,60	-14161,80	29591,70	54871,50	105431,10	86957,40

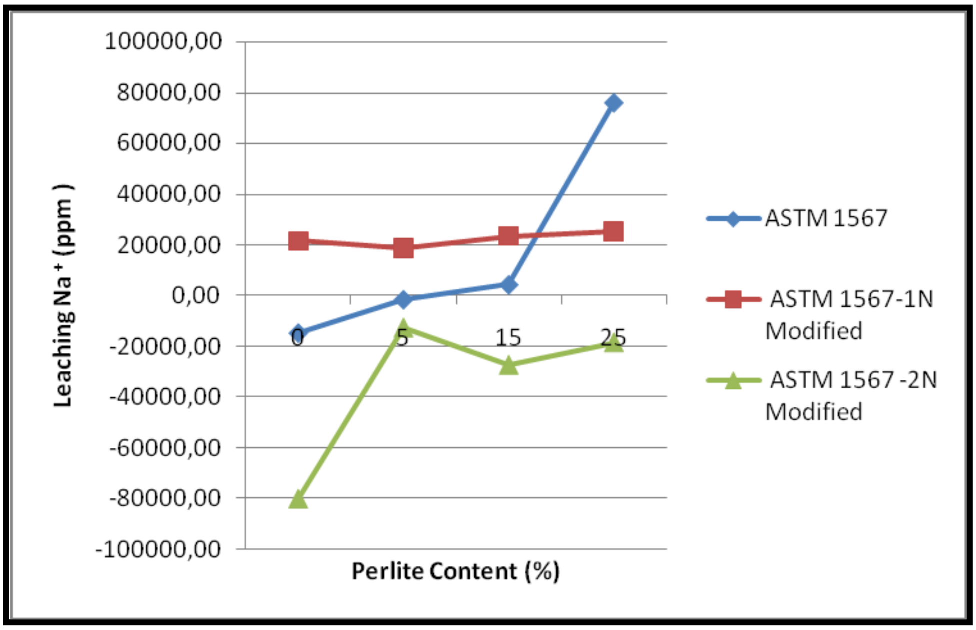


Figure 18. Na$^+$ Ion Leaching from Samples to the Bath Water

Similar to the Na + concentration calculation K$^+$ ion concentrations were obtained from diluted bath waters.

Table 19. K$^+$ Ion Measurements Using Flame Photometry

Sample	ASTM 1567		ASTM 1567-1N Modified		ASTM 1567-2N Modified	
	1st reading	2 nd reading	1st reading	2 nd reading	1st reading	2 nd reading
0	-0,36	-0,36	-0,24	-0,03	-0,03	-0,24
5% perlite	-0,36	-0,38	-0,24	-0,02	-0,02	-0,25
15 %perlite	-0,36	-0,35	-0,24	-0,03	-0,03	-0,24
25 %perlite	-0,36	-0,34	-0,24	-0,02	-0,03	-0,25

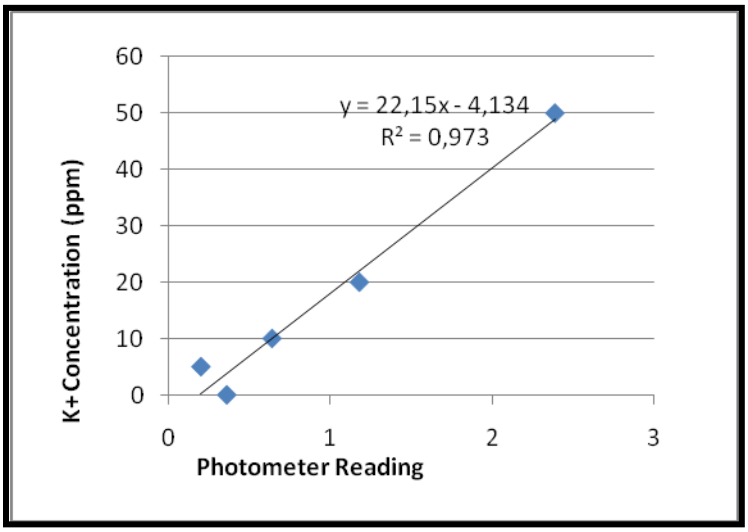


Figure 19. Linear Equation of K^+ Concentration vs. Photometer Reading

Table 20. K^+ Ion Concentration of Bath Waters

Sample	ASTM 1567		ASTM 1567-1N Modified		1567-2N Modified	
	1st ppm	2nd ppm	1st ppm	2nd ppm	1st ppm	2nd ppm
0	-121080	-121080	-94500	-47985	-47985	-94500
5% perlite	-121080	-125510	-94500	-45770	-45770	-96715
15 %perlite	-121080	-118865	-94500	-47985	-47985	-94500
25 %perlite	-121080	-116650	-94500	-45770	-47985	-96715

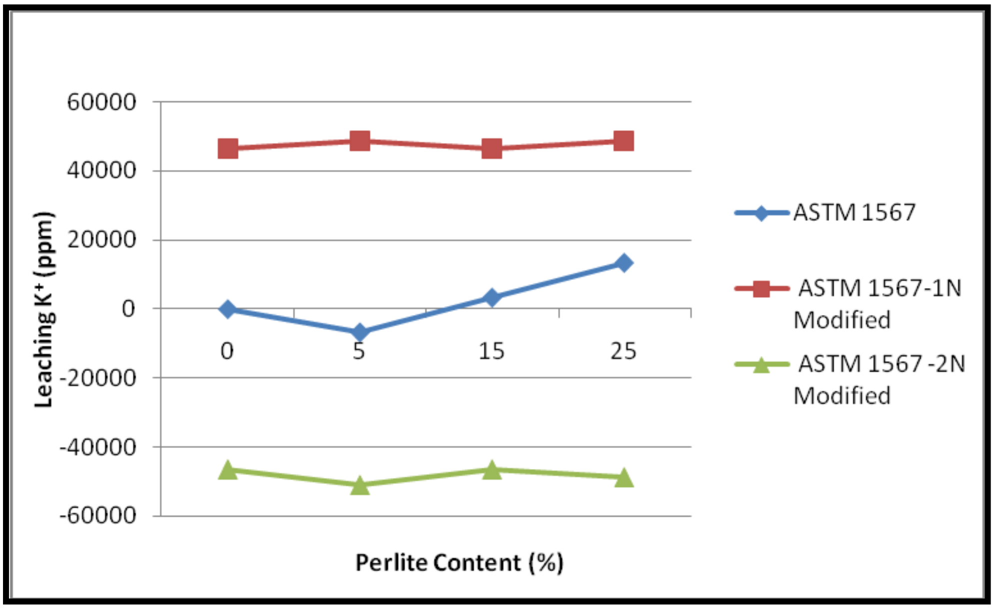


Figure 20. K^+ Ion Leaching from Samples to the Bath Water

Looking at the above-given results and graphs obtained by flame photometry, the following observations may be made;

❖ Being away from the expected/real values based on the known concentration of the bath waters at the start of the test, only the tendencies of mixture to gain or lose alkalis were obtained.

❖ Extrapolation of reading values, especially for the points near to the origin and peak values, may show higher faults. Despite the photometer readings were in accordance with each other's relatively, ppm concentrations of real bath waters (not diluted ones) were very far from a comparative base. For 2N solutions, roughly twice the value of 1N solutions alkalinity was measured from the photometer. However, calculated real values were quite different.

❖ The most reasonable result of alkali determination by photometer in this study is that; in the case of keeping samples in 2N solution, for 4 replacement levels, samples absorbed alkali from bath water whereas for 1N solution all samples were leaching alkali to the bath water.

❖ It is basically seen that, both for Na^+ and K^+ ions determinations, the most leaching was obtained in ASTM C 1567-1N Modified method in contrary to the expectations.

4.5 INVESTIGATIONS ON ACTIVATION OF PERLITE-CONTAINING PORTLAND CEMENT MORTARS

The main objective of this part of the study was to obtain the best activator especially from a strength-gain point of view even if it could result in a decrease in durability. In the case that a substantial strength gain of perlite-containing mixtures was detected, the mixtures could be used in blockwork mortars etc.

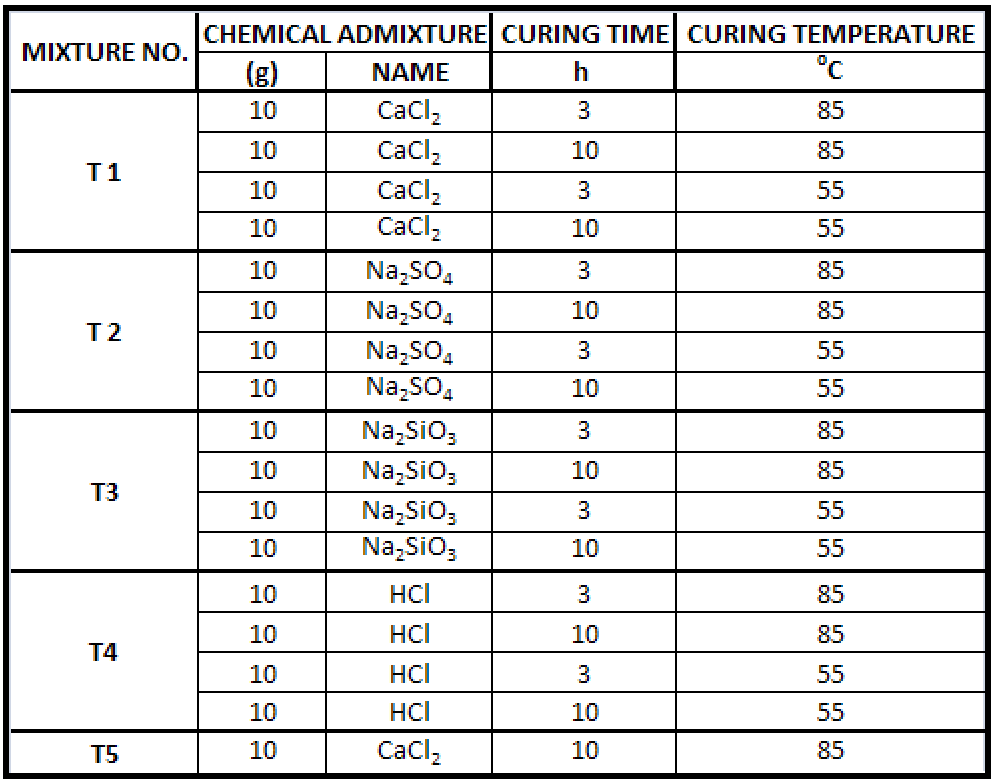
Within the activation concept of perlite, different amount of perlite additions were attempted, using different chemicals and also by changing the amounts of chemical admixtures. The activation study can be grouped into 3 parts as;

1) 25 % replacement level of cement with perlite
2) 50 % replacement level of cement with perlite
3) Thermal curing trials

Mixture proportions of all groups were given in Chapter 3. NaOH was found to be less effective than the other chemical admixtures and its use was eliminated in the 50 % perlite containing mixtures.

The studies of Lea [72] and Day [73] showed that thermal curing is very helpful for initial strength gain of cementitious materials. The studies of Deng et al. [74] on slag activation showed that, increasing temperature from 25 to 40 ^{o}C and 40 to 80 ^{o}C increased initial strength very significantly. However, no further strength gain was obtained when temperature was increased up to 100 °C. Also in the study of Talling [75], temperatures higher than 60 °C do not increase the initial strength regardless of the activator type. Considering the related studies, thermal curing temperatures were chosen as 55°C and 85 °C with two different curing time of 3 h and 10 h. Applied curing time and temperature to the mortars are listed in the Table 21.

Table 21. Curing Conditions of Thermally Cured Mortars



MIXTURE NO.	CHEMICAL ADMIXTURE		CURING TIME	CURING TEMPERATURE
	(g)	NAME	h	°C
T 1	10	$CaCl_2$	3	85
	10	$CaCl_2$	10	85
	10	$CaCl_2$	3	55
	10	$CaCl_2$	10	55
T 2	10	Na_2SO_4	3	85
	10	Na_2SO_4	10	85
	10	Na_2SO_4	3	55
	10	Na_2SO_4	10	55
T3	10	Na_2SiO_3	3	85
	10	Na_2SiO_3	10	85
	10	Na_2SiO_3	3	55
	10	Na_2SiO_3	10	55
T4	10	HCl	3	85
	10	HCl	10	85
	10	HCl	3	55
	10	HCl	10	55
T5	10	$CaCl_2$	10	85

4.5.1 Results of Strength Tests

Flexural and compressive strength tests were applied to the samples of 1, 3, 7, 28 and 56 days. The test results for all mixtures of all ages with their ranges and variances are given in the Appendix. Only the classified and graphed results are given in this chapter.

TABLE 22. Effect of Activator Content on 25 % Perlite-Containing Mixtures at 1 Day

Activator Type	% Activator Content			
	2	4	6	
None-25 % perlite	8,77	8,77	8,77	The 1-day Compressive Strength (MPa)
NaOH	7,42	4,62	4,30	
Na_2SiO_3	6,47	6,87	8,42	
Na_2SO_4	12,63	13,20	11,65	
$CaCl_2$	12,27	8,72	6,78	
HCl	5,80	6,90	4,03	
Control	13,43	13,43	13,43	

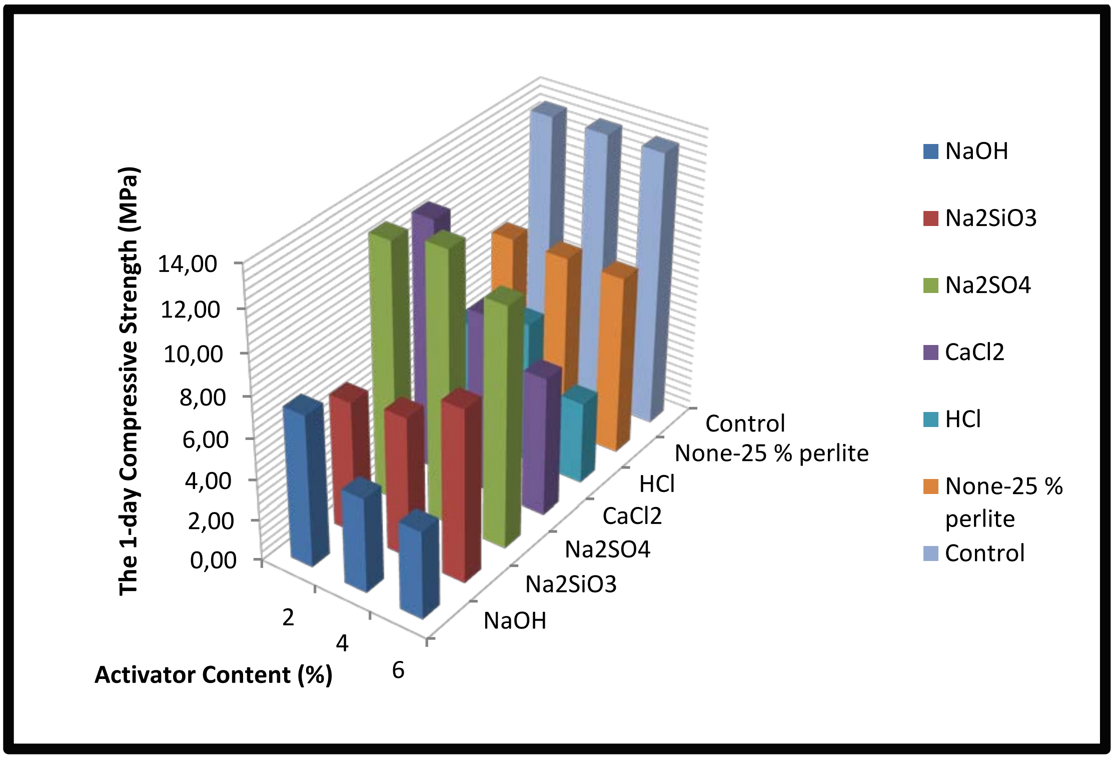


FIGURE 21. Effect of Activator Content at 1 Day- 25 % Perlite

It is deducted from Table 22 and Figure 21 that, 25 % perlite addition to cement mortars results in about 35 % decrease at 1-day strength of the control samples.However, the early strength activation effect of Na_2SO_4 and $CaCl_2$ is clear. The optimum amount of admixture addition is determined as 2 % for $CaCl_2$ and 4 % for Na_2SO_4 .

TABLE 23. Effect of Activator Content on 25 % Perlite-Containing Mixtures at 3 Days

Activator Type	% Activator Content			
	2	4	6	
None.-25 %perlite	23,12	23,12	23,12	The 3-day Compressive Strength (MPa)
NaOH	12,60	7,05	5,70	
Na_2SiO_3	19,65	18,45	16,75	
Na_2SO_4	25,23	22,43	22,48	
$CaCl_2$	29,73	17,23	14,92	
HCl	24,55	18,62	13,08	
Control	24,50	24,50	24,50	

It can be drawn that, even no admixture is added to 25 % perlite containing mixtures, the 3-day compressive strength of control sample is achieved by 94 %. Such an accelerated strength gain of perlite containing mixtures, is of vital importance especially for demonstration of its pozzolanic properties. Na_2SO_4 and $CaCl_2$ are again seen as the best activators. For 2 % addition they gave higher strengths than control sample.

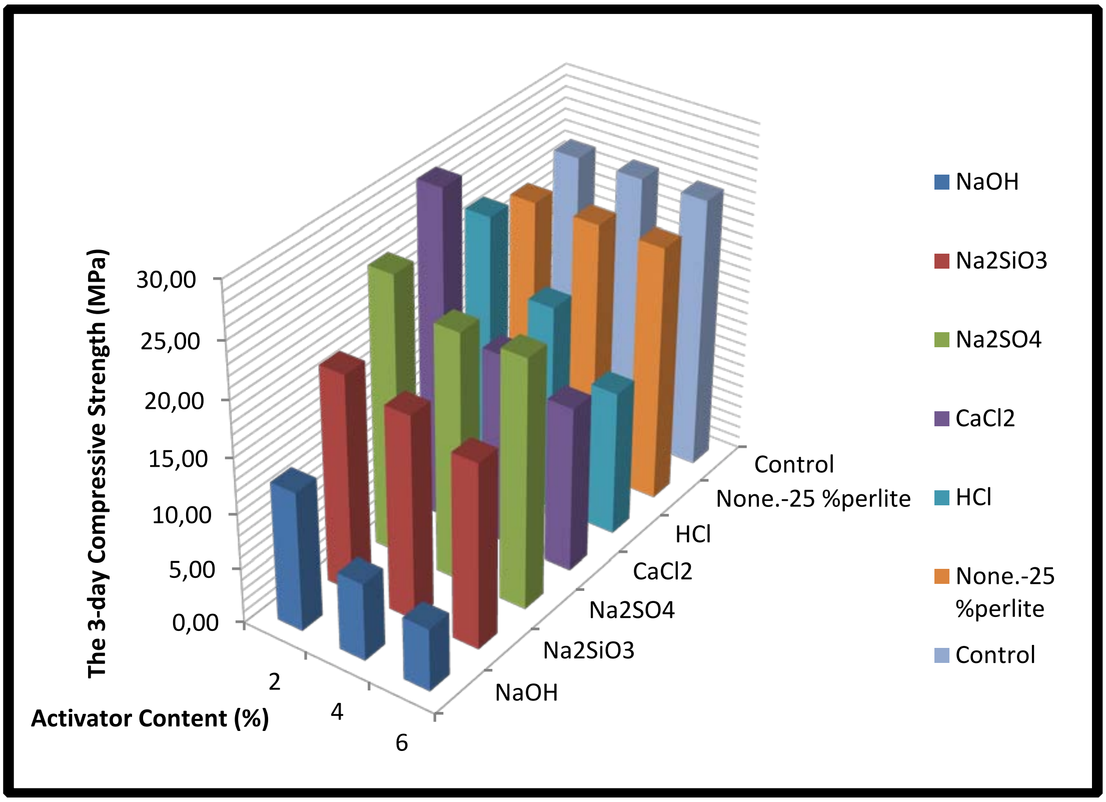


FIGURE 22. Effect of Activator Content at 3 Days - 25 % Perlite

TABLE 24. Effect of Activator Content on 25 % Perlite-Containing Mixtures at 7 Days

Activator Type	**% Activator Content**			
	2	**4**	**6**	
None-25 %perlite	31,70	31,70	31,70	**The 7-day Compressive Strength (MPa)**
NaOH	14,55	10,12	7,28	
Na_2SiO_3	28,18	23,88	23,05	
Na_2SO_4	31,80	27,80	29,25	
$CaCl_2$	35,98	25,50	23,30	
HCl	33,55	30,60	22,63	
Control	34,53	34,53	34,53	

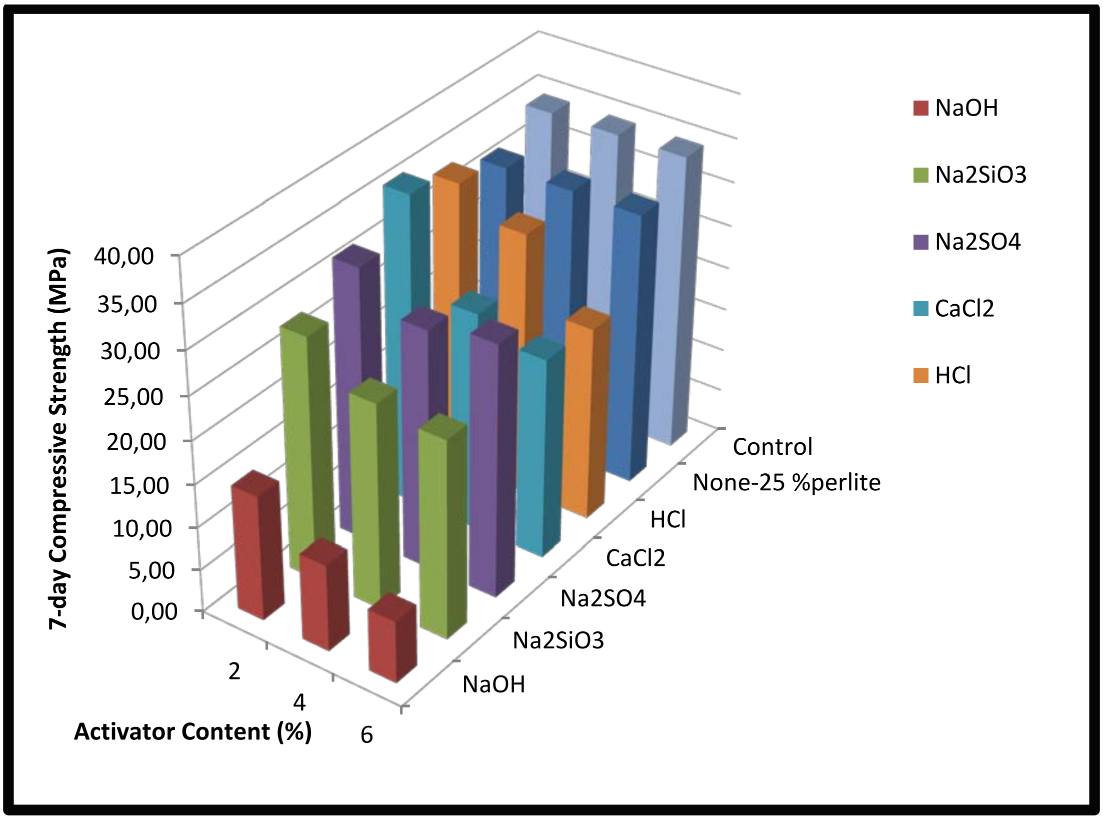


FIGURE 23. Effect of Activator Content at 7 Days - 25 % Perlite

As per the results obtained from 7-day strength tests, it is seen that the effect of HCl addition on strength gaining properties increases by the age of the samples. At this age, HCl gives better strength results than Na_2SO_4. However, the best and the only activator that gave higher than control sample, is still $CaCl_2$.

TABLE 25. Effect of Activator Content on 25 % Perlite-Containing Mixtures at 28 Days

Activator Type	% Activator Content			
	2	4	6	
None-25 %perlite	42,88	42,88	42,88	The 28-day Compressive Strength (MPa)
NaOH	24,20	16,68	13,95	
Na_2SiO_3	41,73	32,55	32,70	
Na_2SO_4	39,30	35,78	37,30	
$CaCl_2$	57,10	40,48	43,38	
HCl	52,90	48,45	44,88	
Control	44,93	44,93	44,93	

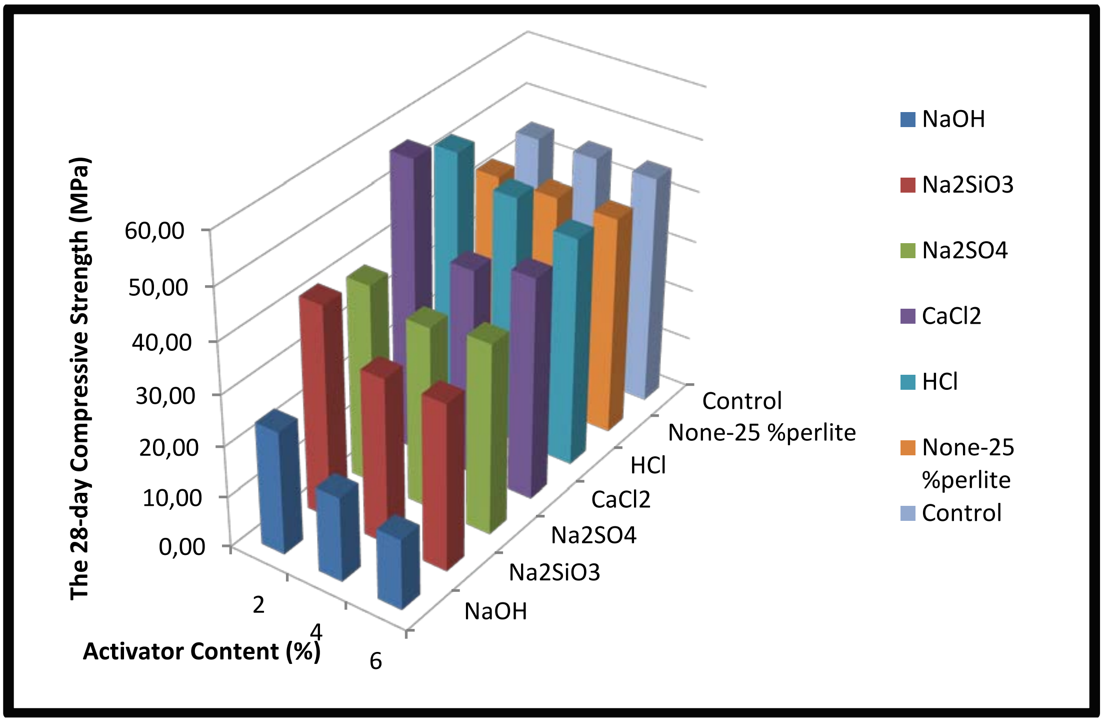


FIGURE 24. Effect of Activator Content at 28 Days - 25 % Perlite

The increasing effect of HCl addition is more obvious at 28-day strengths. $CaCl_2$ is again found as the best activator for 25 % replacement level. For 28-day strength, it gave 28 % higher strength than control samples.

TABLE 26. Effect of Activator Content on 25 % Perlite-Containing Mixtures at 56 Days

Activator Type	% Activator Content			
	2	4	6	
None-25 %perlite	55,00	55,00	55,00	The 56-day Compressive Strength (MPa)
NaOH	29,38	22,83	14,35	
Na_2SiO_3	47,18	39,20	44,77	
Na_2SO_4	47,60	45,93	49,00	
$CaCl_2$	58,63	51,85	50,90	
HCl	55,83	60,83	49,30	
Control	51,81	51,81	51,81	

It is seen from Table 26 that, the pozzolanic properties of perlite becomes more apparent. Even any chemicals were not added; only 25 % perlite addition to cement mortars resulted in a greater compressive strength than control samples at 56 days. The activation effect of $CaCl_2$ and HCl is pointed out from beginning to end.

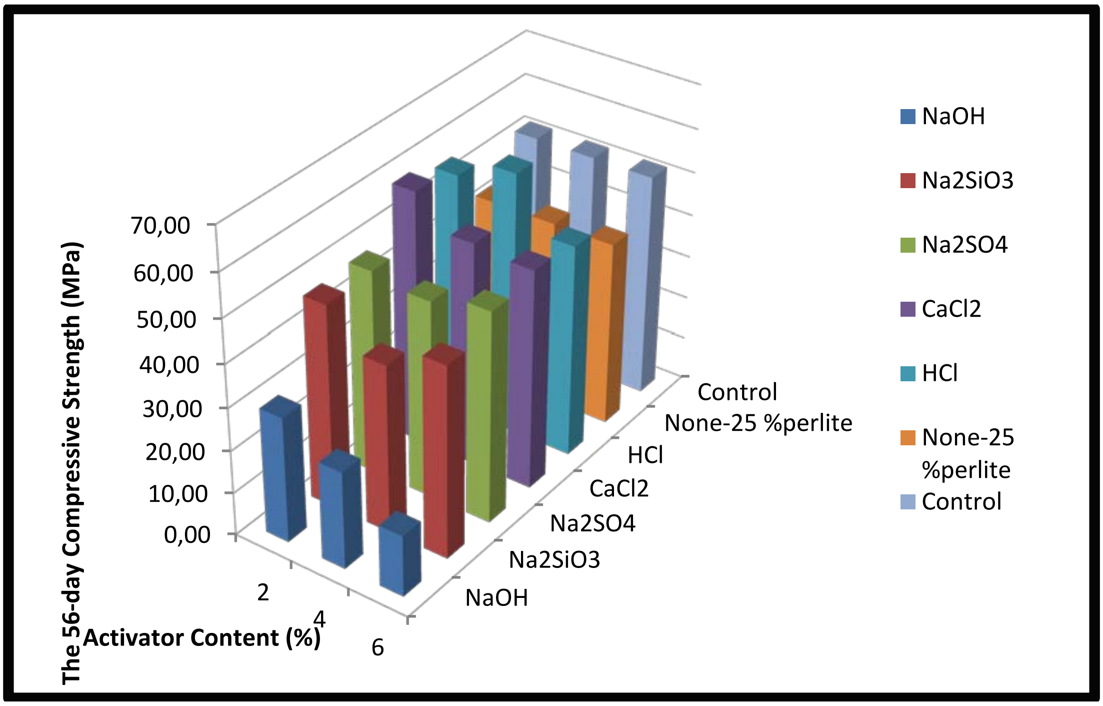


FIGURE 25. Effect of Activator Content at 56 Days - 25 % Perlite

For all ages, NaOH is found as unfavorable. Only half of the strength of inactivated mortars could be achieved by NaOH addition. Thus, NaOH admixture was not used in the remaining of the activation trials.

TABLE 27. Effect of Activator Content on 50 % Perlite-Containing Mixtures at 1 Day

Activator Type	% Activator Content			
	2	4	6	
None-50 %perlite	6,62	6,62	6,62	The 1-day Compressive Strength (MPa)
Na_2SiO_3	4,52	5,50	5,87	
Na_2SO_4	7,08	9,72	8,47	
$CaCl_2$	5,90	5,42	5,20	
HCl	4,28	3,62	3,43	
Control	13,43	13,43	13,43	

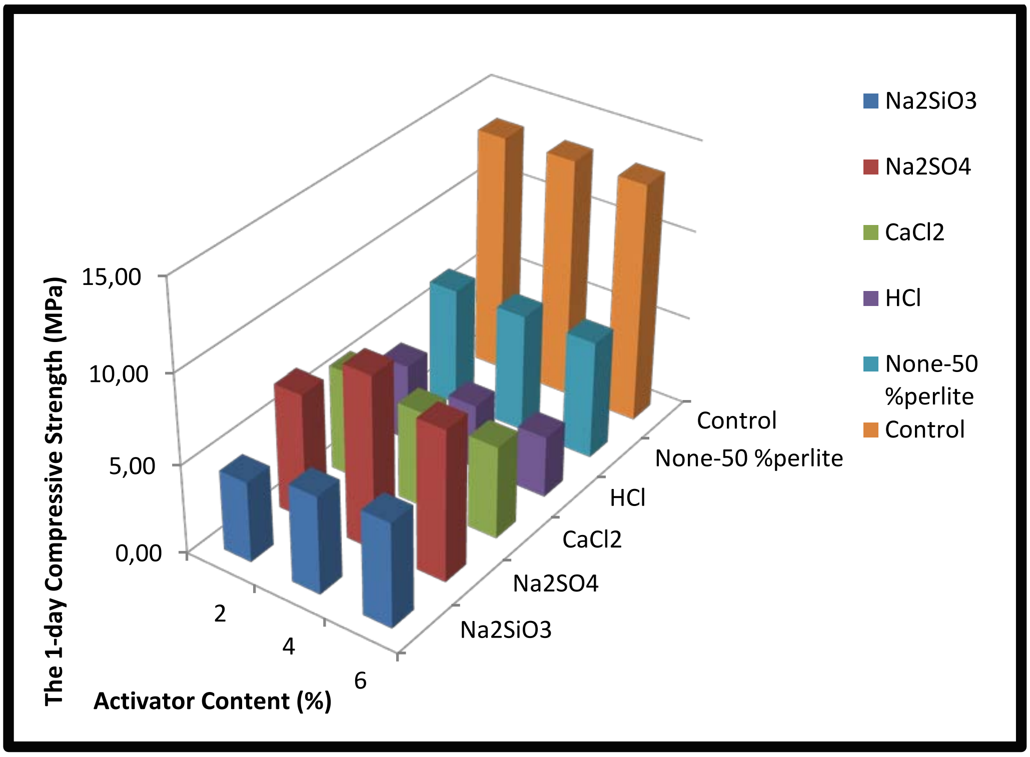


FIGURE 26. Effect of Activator Content at 1 Day - 50 % Perlite

50 % replacement of cement with perlite resulted in a sudden decrease in 1-day compressive strength as expected. The effects of activators for 1 day are similar to the ones for 25 % replacement level. Na_2SO_4 and $CaCl_2$ are the most effective activators. However, no activator could achieved to exceed 72 % strength of the control samples.

TABLE 28. Effect of Activator Content on 50 % Perlite-Containing Mixtures at 3 Days

Activator Type	% Activator Content			
	2	4	6	
None-50 %perlite	15,58	15,58	15,58	The 3-day Compressive Strength (MPa)
Na_2SiO_3	13,80	11,95	10,28	
Na_2SO_4	15,88	15,02	13,35	
$CaCl_2$	12,75	8,65	8,88	
HCl	11,60	9,20	7,37	
Control	24,50	24,50	24,50	

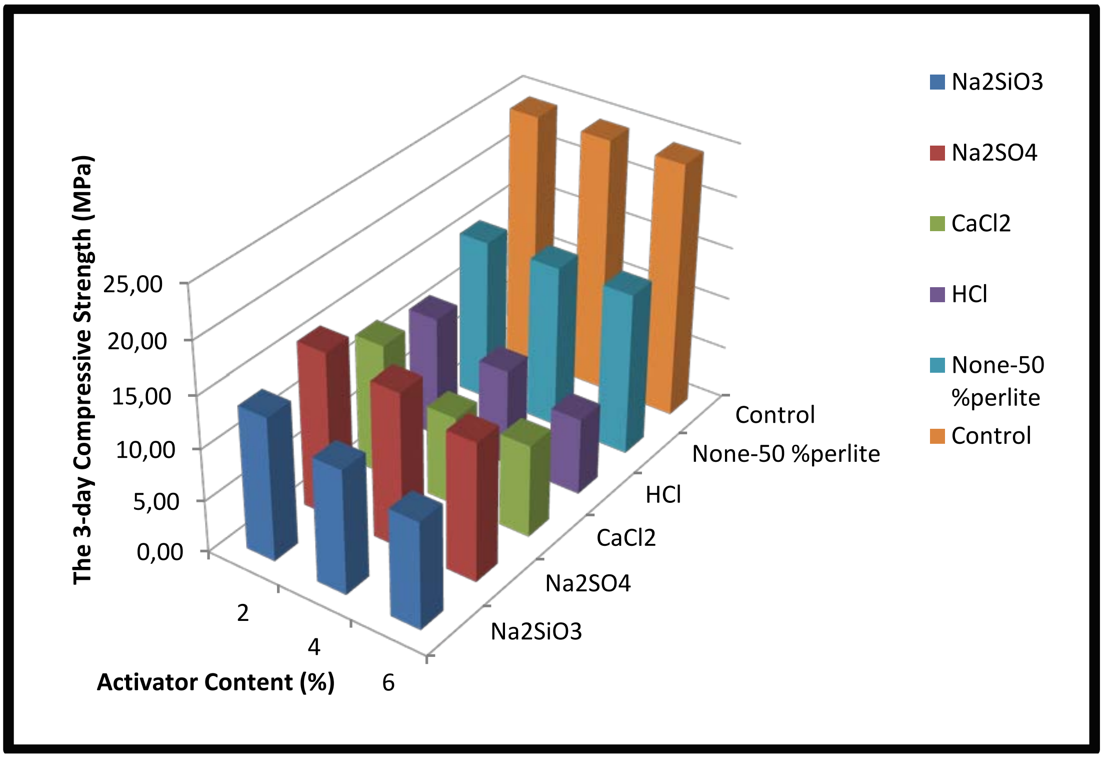


FIGURE 27. Effect of Activator Content at 3 Days-50 % Perlite

Even though Na_2SO_4 is the only activator that showed a positive effect on 3-day strength of 50 % perlite containing inactivated samples, this effect is too small to be considered. Also, with the increase in the activator dosage, a drop in the strength values is observed.

TABLE 29. Effect of Activator Content on 50 % Perlite-Containing Mixtures at 7 Days

Activator Type	**% Activator Content**			
	2	**4**	**6**	**The 7-day Compressive Strength (MPa)**
None-50 %perlite	18,68	18,68	18,68	
Na_2SiO_3	16,58	14,08	14,60	
Na_2SO_4	19,90	22,43	21,35	
$CaCl_2$	18,38	13,08	12,95	
HCl	18,40	12,95	10,80	
Control	34,53	34,53	34,53	

As seen from the Table 29 and Figure 28, the common tendencies of the samples for 1 and 3 days do not change for 7 days either. Na_2SO_4 is the best and the only activator that surpasses the inactivated samples of 50 % replacement level and the highest strength was obtained with an addition of 4%.

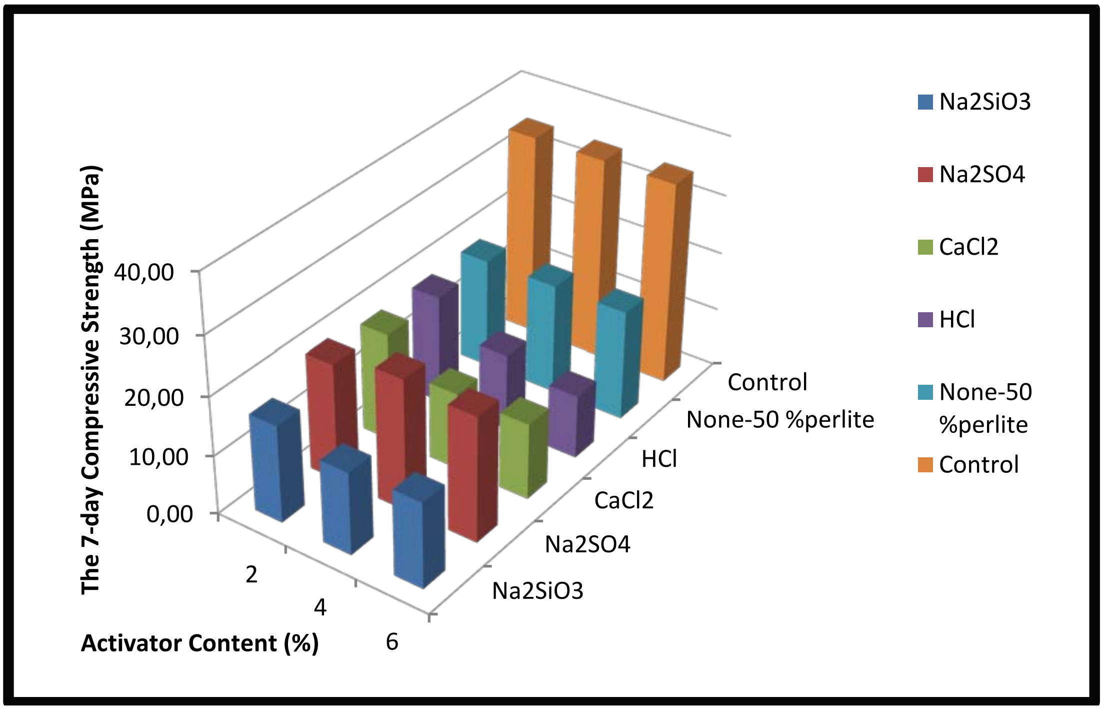


FIGURE 28. Effect of Activator Content at 7 Days - 50 % Perlite

TABLE 30. Effect of Activator Content on 50 % Perlite-Containing Mixtures at 28 Days

Activator Type	% Activator Content			
	2	4	6	
None-50 %perlite	30,45	30,45	30,45	The 28-day Compressive Strength (MPa)
Na_2SiO_3	31,53	25,18	26,45	
Na_2SO_4	31,83	35,08	32,23	
$CaCl_2$	33,15	28,55	29,45	
HCl	34,05	29,65	23,10	
Control	44,93	44,93	44,93	

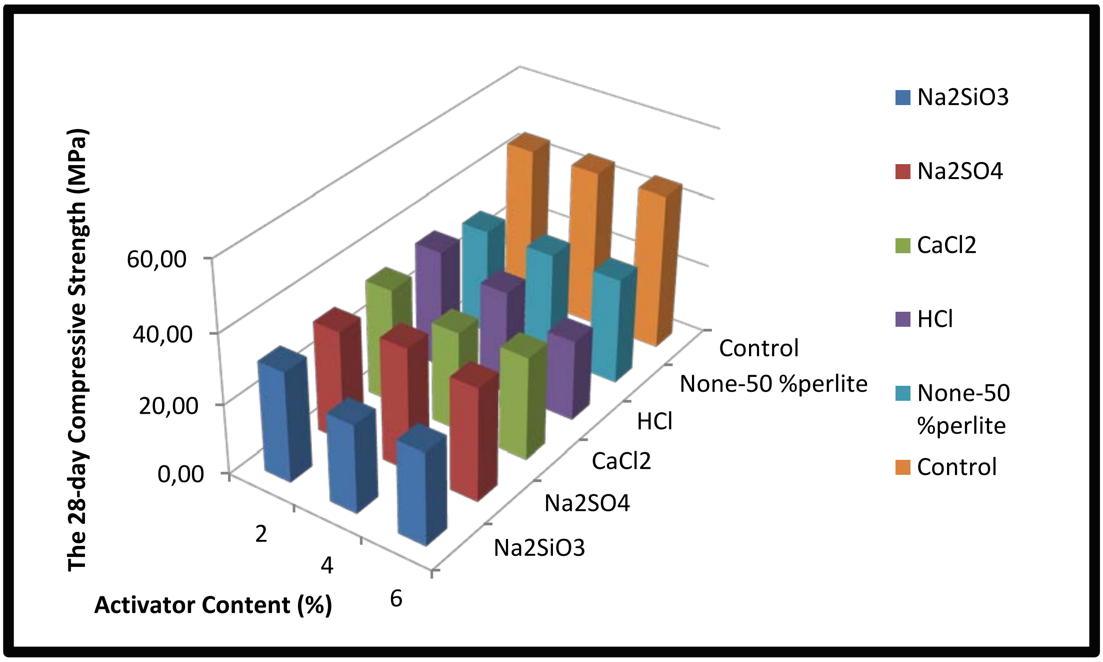


FIGURE 29. Effect of Activator Content at 28 Days - 50 % Perlite

After 28 days, chloride containing activators start to show their effect on strength gaining properties. $CaCl_2$ and HCl showed a great increase and had a 28-day strength of about 75 % of control sample, whereas they had a 7-day strength of about 50 %.

TABLE 31. Effect of Activator Content on 50 % Perlite-Containing Mixtures at 56 Days

Activator Type	% Activator Content			
	2	4	6	
None-50 %perlite	38,90	38,90	38,90	The 56-day Compressive Strength (MPa)
Na_2SiO_3	37,97	33,53	31,33	
Na_2SO_4	39,10	42,60	42,97	
$CaCl_2$	43,07	38,97	39,10	
HCl	43,37	34,43	35,87	
Control	51,81	51,81	51,81	

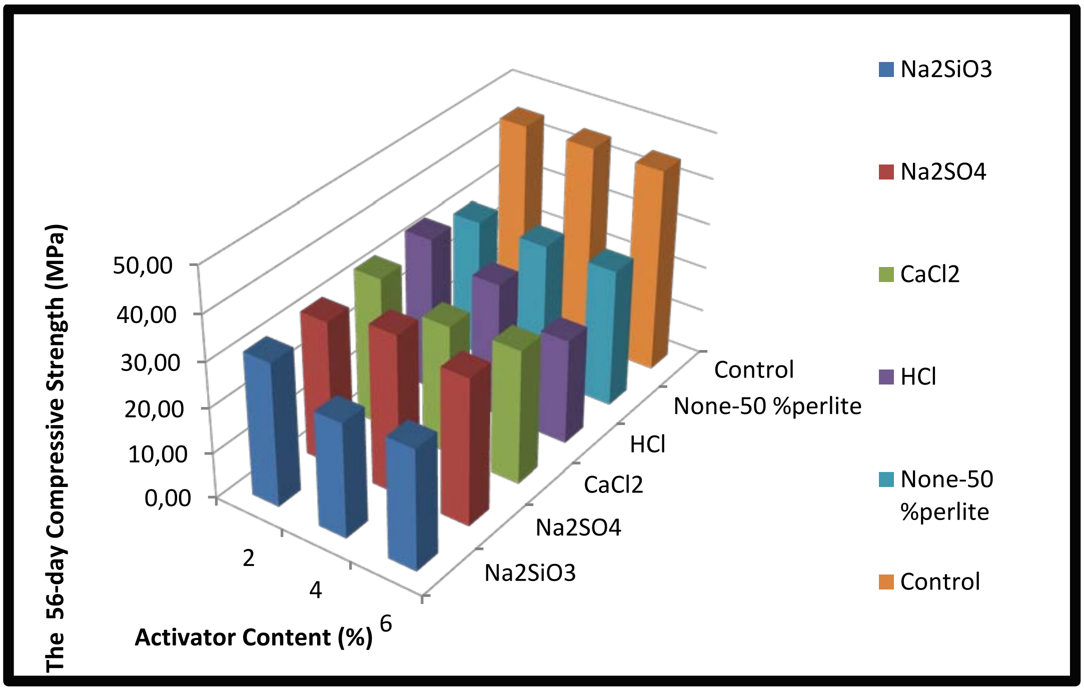
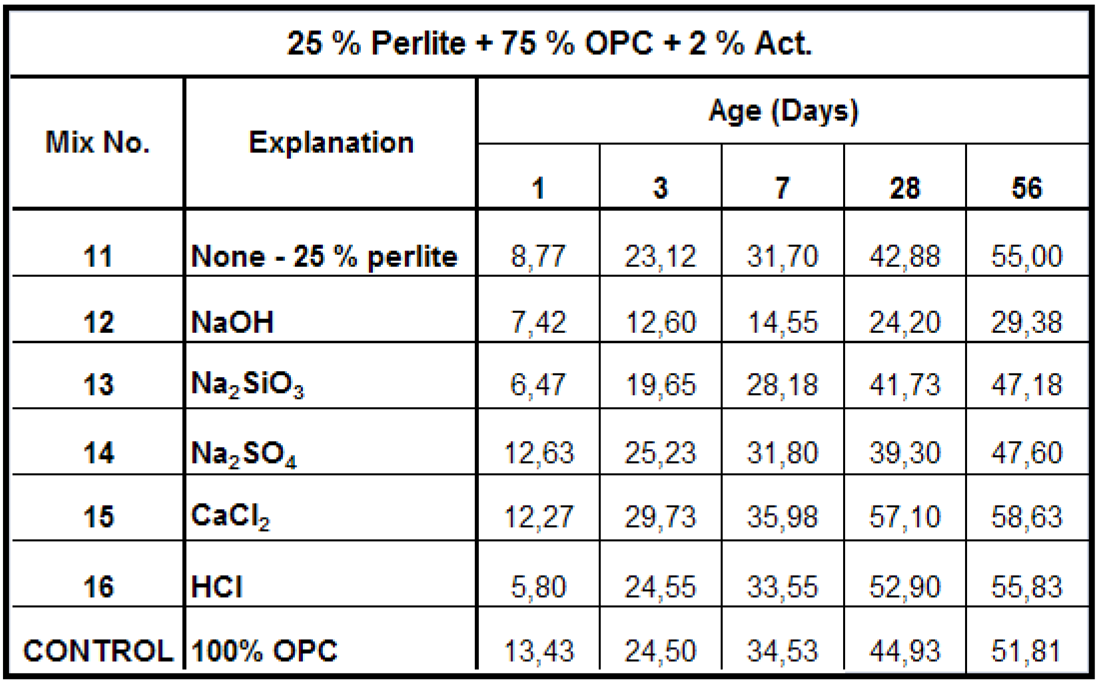


FIGURE 30. Effect of Activator Content at 56 Days - 50 % Perlite

The great pozzolanic property of perlite is manifested once more by the help of 56-day strength results.By the addition of HCl a strength of 84 % of control sample was obtained.

When overall ages of 50 %replacement level are considered, Na_2SO_4 for initial and chloride containing chemicals for later strength are found quite effective.

TABLE 32. Strength Gain of Mixtures Containing 25 % Perlite and 2 % Activator



25 % Perlite + 75 % OPC + 2 % Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
11	None - 25 % perlite	8,77	23,12	31,70	42,88	55,00
12	NaOH	7,42	12,60	14,55	24,20	29,38
13	Na_2SiO_3	6,47	19,65	28,18	41,73	47,18
14	Na_2SO_4	12,63	25,23	31,80	39,30	47,60
15	$CaCl_2$	12,27	29,73	35,98	57,10	58,63
16	HCl	5,80	24,55	33,55	52,90	55,83
CONTROL	100% OPC	13,43	24,50	34,53	44,93	51,81

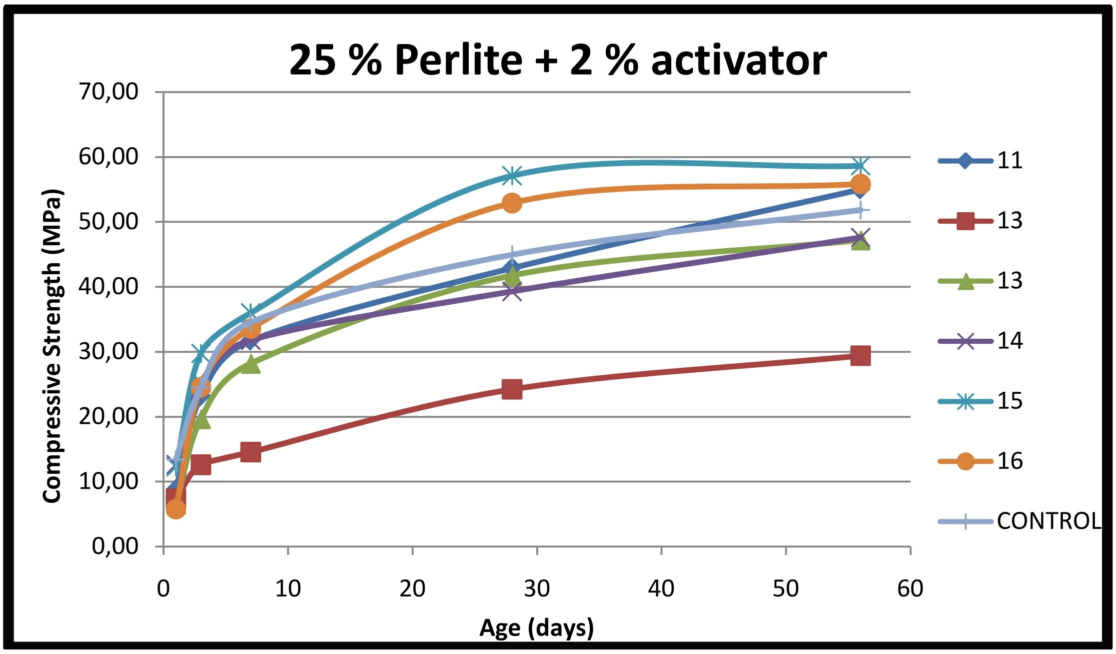


FIGURE 31. Strength Gain of Mixtures Containing 25 % Perlite and 2 % Activator

It is seen from Table 32 and Figure 31 that, one of the most effective activators, $CaCl_2$, shows a decrease in strength gaining slope beyond 40 days. Also the other chloride containing activator , HCl, nearly stops to gain strength after 28 days. On the other hand, the typical pozzolanic behaviour of perlite is emphasized by the increase in the strengths of inactivated perlite containing mixtures after 28 days.

TABLE 33. Strength Gain of Mixtures Containing 25 % Perlite and 4 % Activator

25 % Perlite + 75 % OPC + 4 % Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
11	None - 25 % perlite	8,77	23,12	31,70	42,88	55,00
22	NaOH	4,62	7,05	10,12	16,68	22,83
23	Na_2SiO_3	6,87	18,45	23,88	32,55	39,20
24	Na_2SO_4	13,20	22,43	27,80	35,78	45,93
25	$CaCl_2$	8,72	17,23	25,50	40,48	51,85
26	HCl	6,90	18,62	30,60	48,45	60,83
CONTROL	100% OPC	13,43	24,50	34,53	44,93	51,81

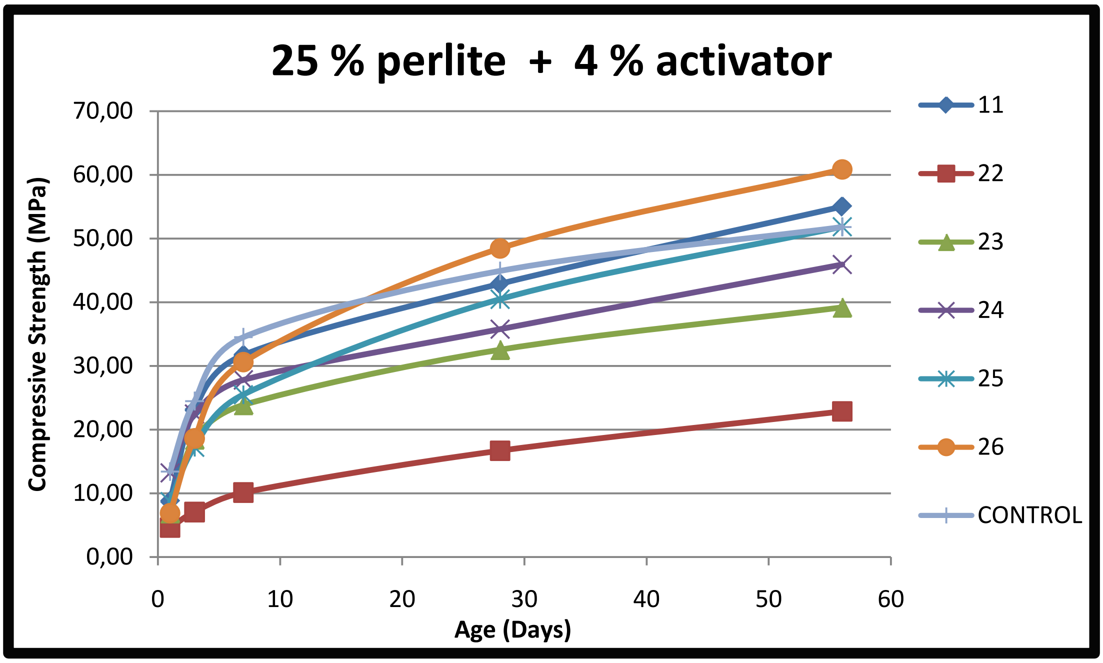


FIGURE 32. Strength Gain of Mixtures Containing 25 % Perlite and 4 % Activator

From Table 33 and Figure 32, it is observed that, the strength decrease after a certain time period for chloride contaning admixtures didn’t occur. All admixtures contribute to strength gain of mortars by parrallel increments. Similar to 2% admixture addition, Na_2SO_4 was quite effective at early strengths. However, final strengths were moderate. In contarary, chloride containing admixtures are moderate at early strengths but final strengths were, relativeley, fabulous. However, it is not possible to express the phenomena of this strength increments as ‘activation’ since the results are not considerably superior than inactivated ones. The apperant initial activation of Na_2SO_4 for all mixtures was probably due to rapid formation of ettringite as indicated in the previous literatures. Also, the decreasing effect of Na_2SO_4 at later ages is truistic.

Considering the results up to 28 days, an optimistic explanation of this insufficient strength results can be made as; for small amounts of admixture addition,a variable quantitiy of activation is observed, however, as the admixture dosage increases, generally, strength decreases.

TABLE 34. Strength Gain of Mixtures Containing 25 % Perlite and 6 % Activator

25 % Perlite + 75 % OPC + 6 % Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
11	None - 25 % perlite	8,77	23,12	31,70	42,88	55,00
32	NaOH	4,30	5,70	7,28	13,95	14,35
33	Na_2SiO_3	8,42	16,75	23,05	32,70	44,77
34	Na_2SO_4	11,65	22,48	29,25	37,30	49,00
35	$CaCl_2$	6,78	14,92	23,30	43,38	50,90
36	HCl	4,03	13,08	22,63	44,88	49,30
CONTROL	100% OPC	13,43	24,50	34,53	44,93	51,81

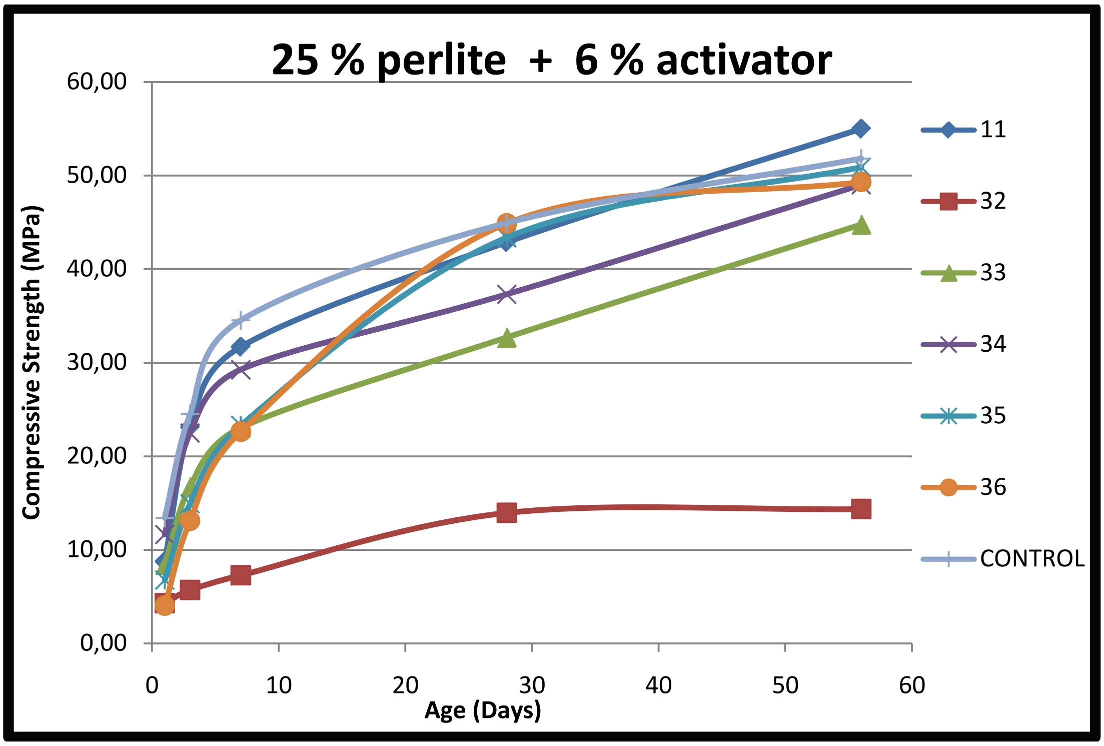
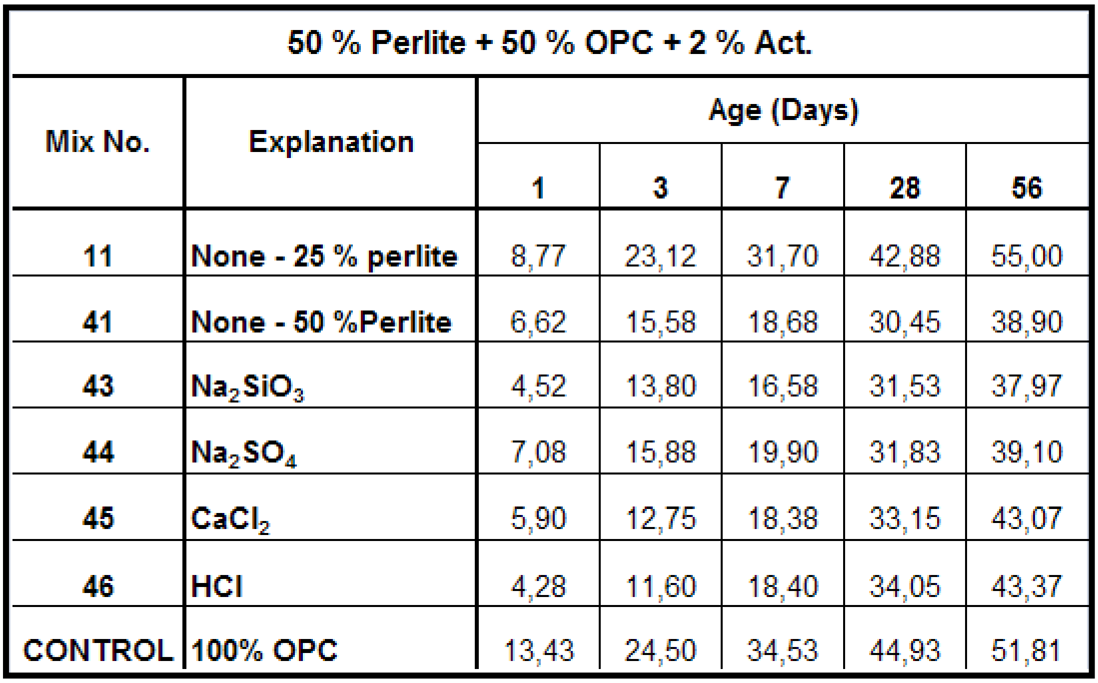


FIGURE 33. Strength Gain of Mixtures Containing 25 % Perlite and 6 % Activator

As the activator dosage increases, the justness of the comment’s for 4% admixture addition becomes more evident. As it is clearly seen from Table 34 and Figure 33, after 1 day tests, none of the chemicals could achieve the inactivated mortar’s strength.

TABLE 35. Strength Gain of Mixtures Containing 50 % Perlite and 2 % Activator



50 % Perlite + 50 % OPC + 2 % Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
11	None - 25 % perlite	8,77	23,12	31,70	42,88	55,00
41	None - 50 %Perlite	6,62	15,58	18,68	30,45	38,90
43	Na_2SiO_3	4,52	13,80	16,58	31,53	37,97
44	Na_2SO_4	7,08	15,88	19,90	31,83	39,10
45	$CaCl_2$	5,90	12,75	18,38	33,15	43,07
46	HCl	4,28	11,60	18,40	34,05	43,37
CONTROL	100% OPC	13,43	24,50	34,53	44,93	51,81

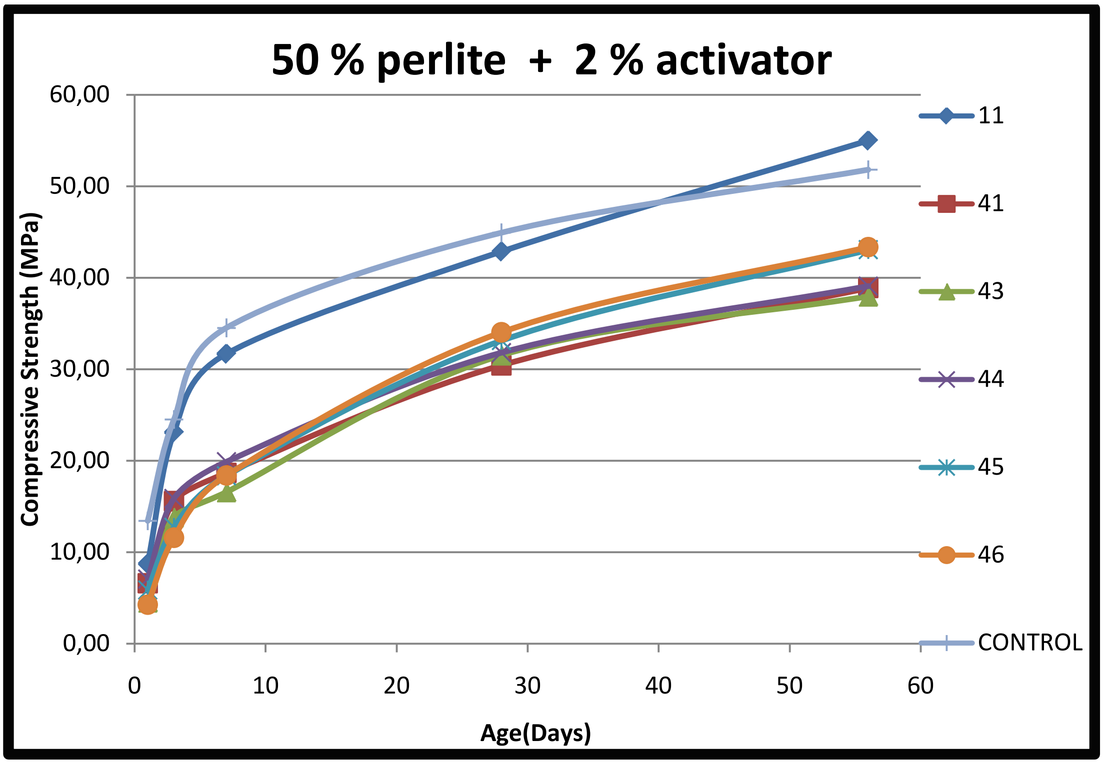


FIGURE 34. Strength Gain of Mixtures Containing 50 % Perlite and 2 % Activator

For 50% replacement level by 2% admixture content, it is not possible to mention about an activation effect. As it is seen from Figure 34, almost all perlite containing mixtures tending to increase their strengths especially after 28 days, in keeping with perlite’s pozzolanic behaviour.

TABLE 36. Strength Gain of Mixtures Containing 50 % Perlite and 4 % Activator

50 % Perlite + 50 % OPC + 4 % Act.						
Mix No.	**Explanation**	**Age (Days)**				
		1	**3**	**7**	**28**	**56**
11	**None - 25 % perlite**	8,77	23,12	31,70	42,88	55,00
41	**None - 50 % perlite**	6,62	15,58	18,68	30,45	38,90
53	**Na_2SiO_3**	5,50	11,95	14,08	25,18	33,53
54	**Na_2SO_4**	9,72	15,02	22,43	35,08	42,60
55	**$CaCl_2$**	5,42	8,65	13,08	28,55	38,97
56	**HCl**	3,62	9,20	12,95	29,65	34,43
CONTROL	**100% OPC**	13,43	24,50	34,53	44,93	51,81

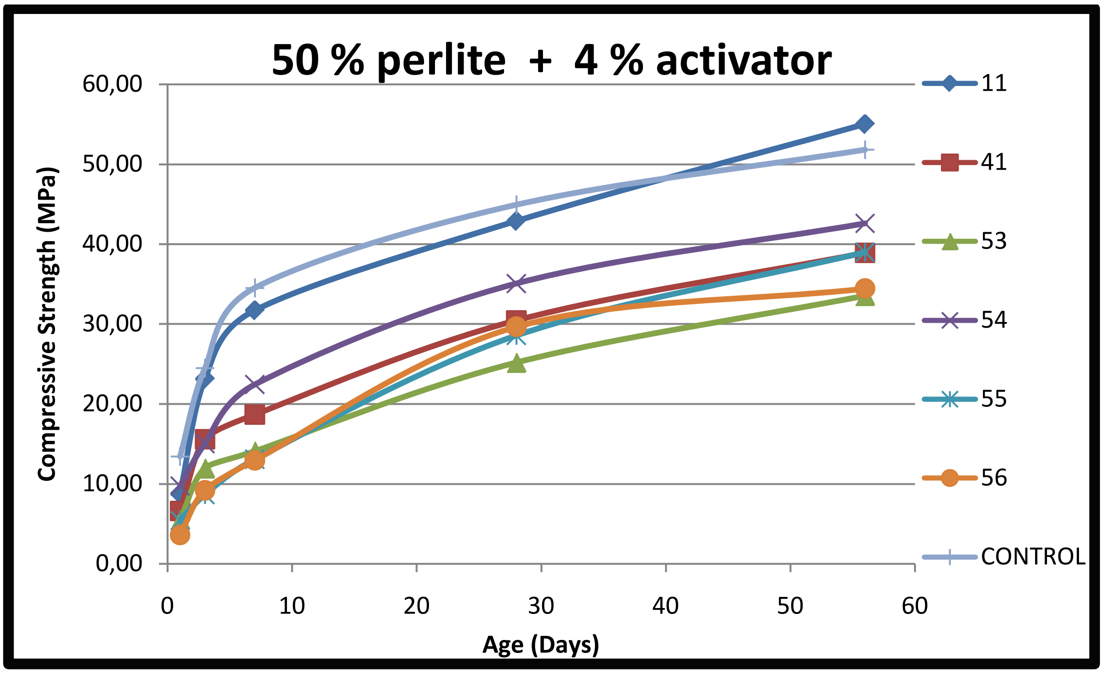
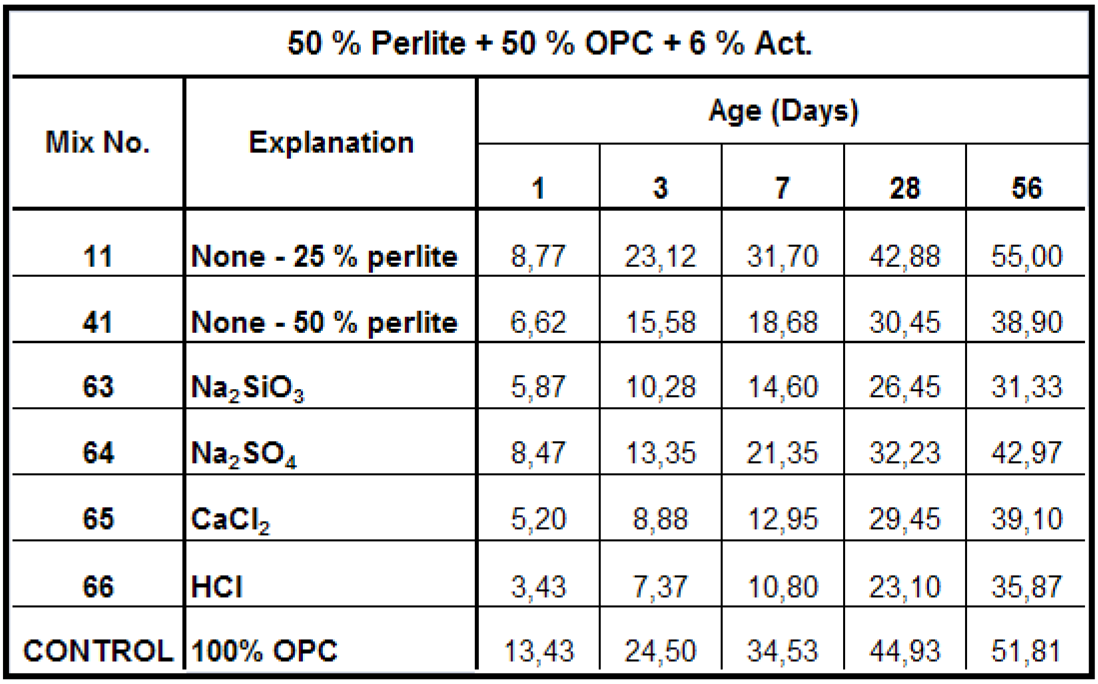


FIGURE 35. Strength Gain of Mixtures Containing 50 % Perlite and 4 % Activator

A different result was deducted for 4% admixture incorporated 50 % perlite mortars. In this case, the strength increasing effect of Na_2SO_4 was observed for both early and late ages.

TABLE 37. Strength Gain of Mixtures Containing 50 % Perlite and 6 % Activator



50 % Perlite + 50 % OPC + 6 % Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
11	None - 25 % perlite	8,77	23,12	31,70	42,88	55,00
41	None - 50 % perlite	6,62	15,58	18,68	30,45	38,90
63	Na_2SiO_3	5,87	10,28	14,60	26,45	31,33
64	Na_2SO_4	8,47	13,35	21,35	32,23	42,97
65	$CaCl_2$	5,20	8,88	12,95	29,45	39,10
66	HCl	3,43	7,37	10,80	23,10	35,87
CONTROL	100% OPC	13,43	24,50	34,53	44,93	51,81

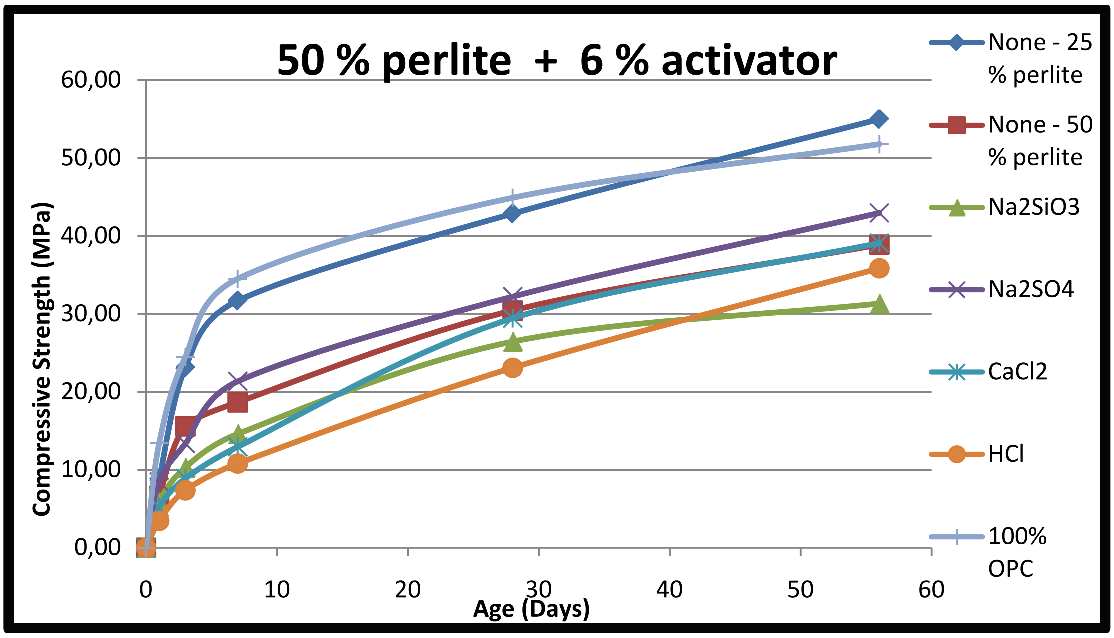
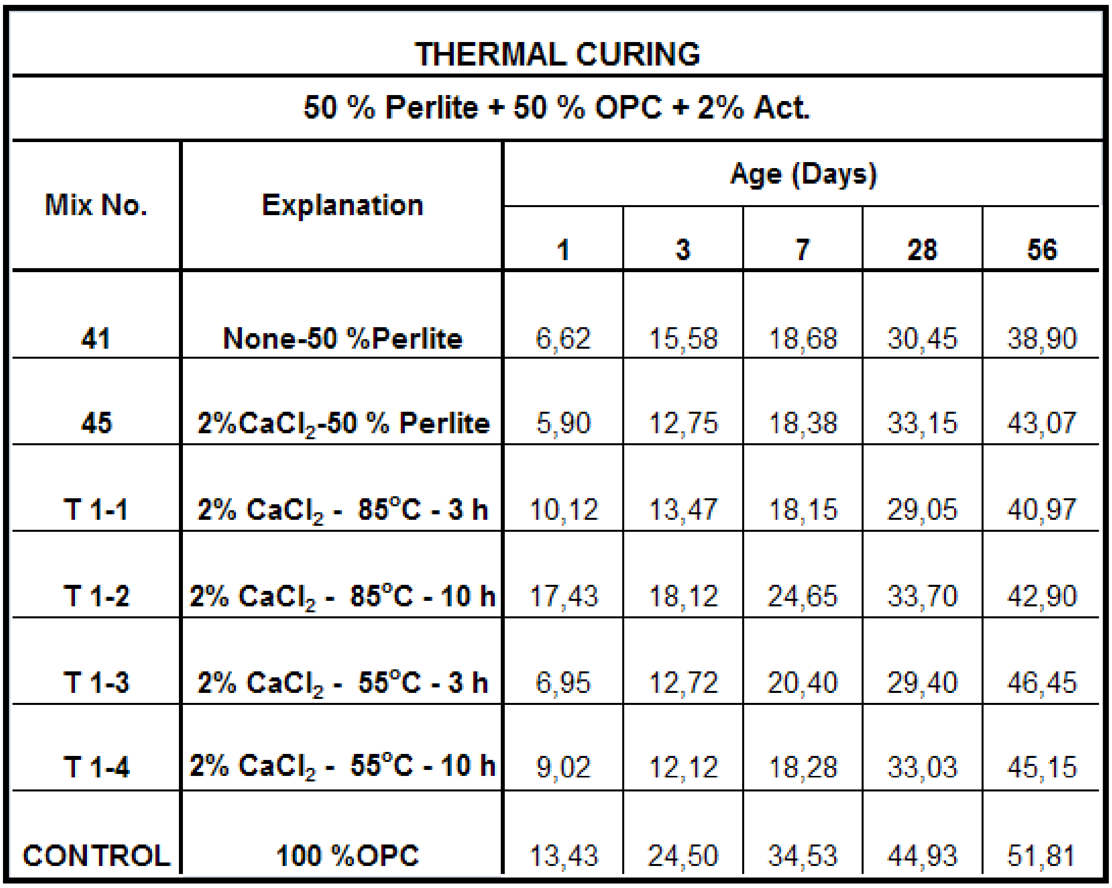


FIGURE 36. Strength Gain of Mixtures Containing 50 % Perlite and 6 % Activator

Similar to 4% admixture added case, the effect of Na_2SO_4 lasts up to final ages. Considering the results of Table 35 and 36 it may be generalized that, as perlite replacement level increases, the effect of Na_2SO_4 also increases. Since 2% admixture addition was found as the the most effective activator dosage, thermal curing trials were conducted with different admixtures but a constant dosage of 2% activator.

TABLE 38. Strength Gain of Thermally Cured Mixtures with $CaCl_2$



THERMAL CURING

50 % Perlite + 50 % OPC + 2% Act.

Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
41	**None-50 %Perlite**	6,62	15,58	18,68	30,45	38,90
45	**2%$CaCl_2$-50 % Perlite**	5,90	12,75	18,38	33,15	43,07
T 1-1	**2% $CaCl_2$ - 85°C - 3 h**	10,12	13,47	18,15	29,05	40,97
T 1-2	**2% $CaCl_2$ - 85°C - 10 h**	17,43	18,12	24,65	33,70	42,90
T 1-3	**2% $CaCl_2$ - 55°C - 3 h**	6,95	12,72	20,40	29,40	46,45
T 1-4	**2% $CaCl_2$ - 55°C - 10 h**	9,02	12,12	18,28	33,03	45,15
CONTROL	**100 %OPC**	13,43	24,50	34,53	44,93	51,81

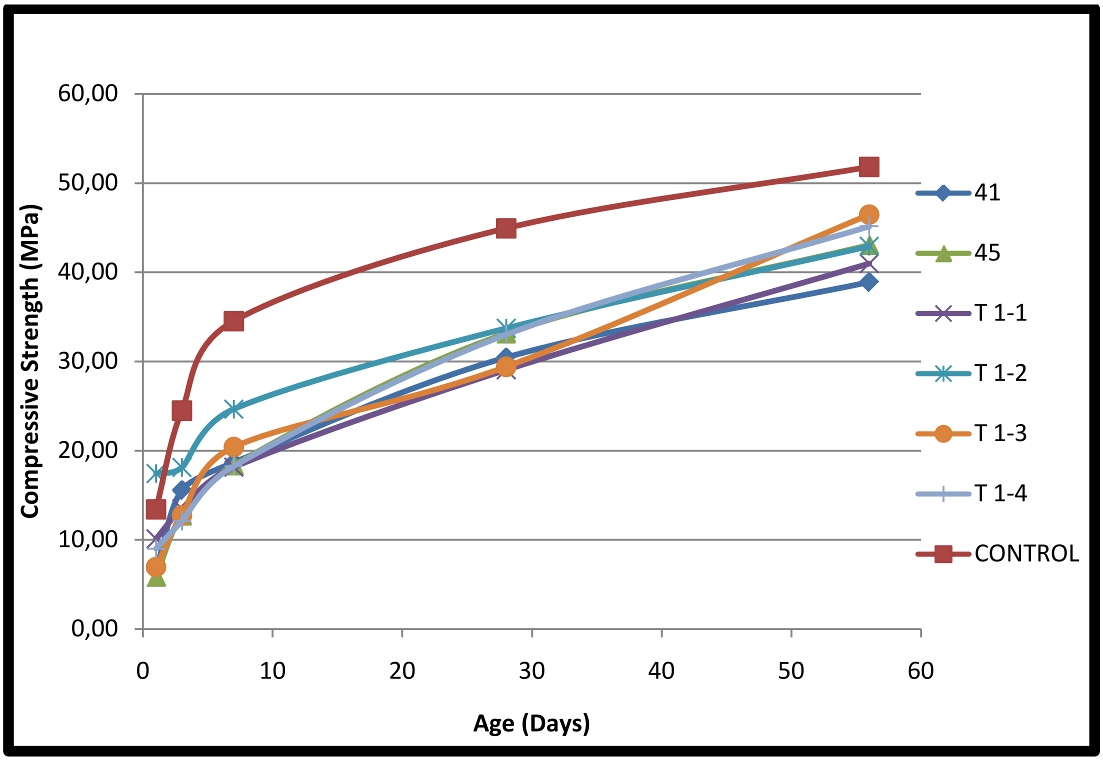
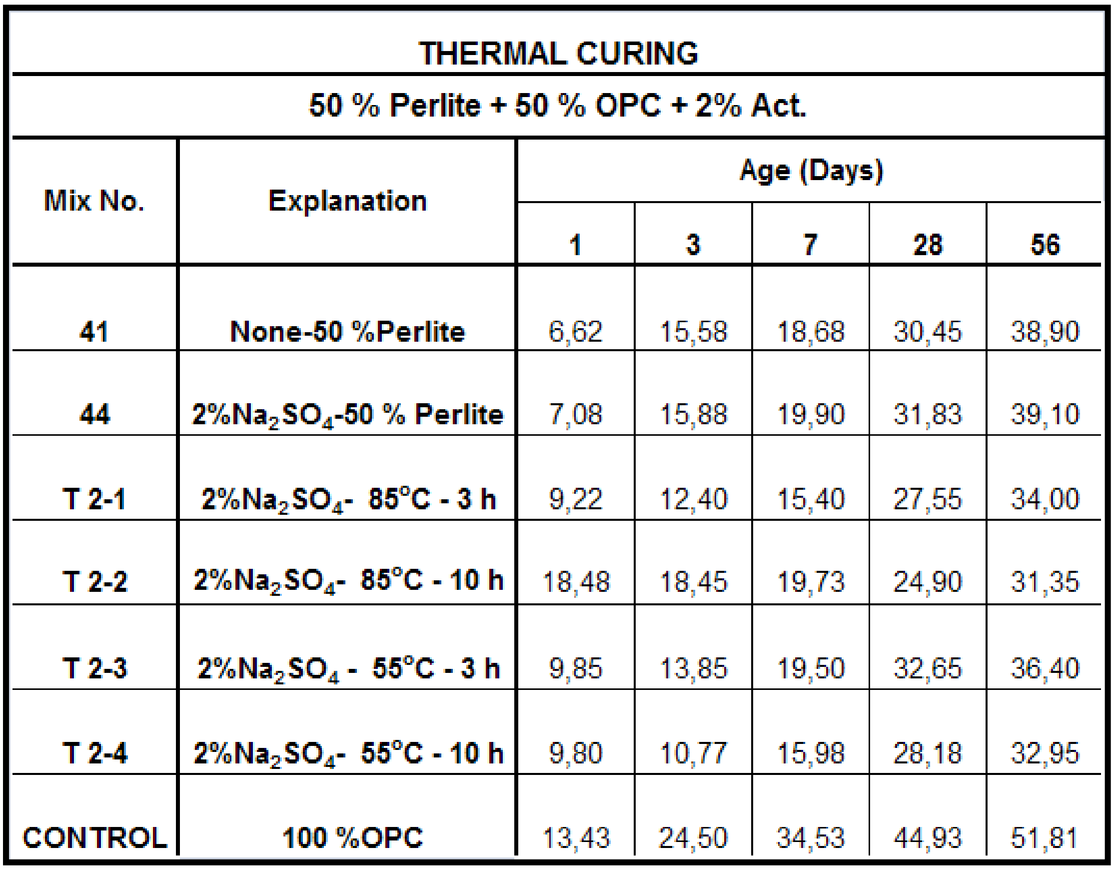


FIGURE 37. Strength Gain of Thermally Cured Mixtures with $CaCl_2$

The thermal curing trials of $CaCl_2$ containing mixtures are given in Table 38 and Figure 37. A high curing temperature of 85 ^oC for 10h , resulted in a sudden increase of 1-day compressive strength. The results of these samples which contain 50 % perlite, were found even higher than control samples. However, this dramatic increase in strength tempers by time.

On the other hand, thermal curing at lower temperatures is more effective at later ages. The highest strengths of 56-day tests were obtained from the samples of 55^{o}C, already. It is also seen that, all $CaCl_2$ containing samples of thermal curing, showed higher strengths than inactivated and not thermally cured ones.

TABLE 39. Strength Gain of Thermally Cured Mixtures with Na_2SO_4



THERMAL CURING						
50 % Perlite + 50 % OPC + 2% Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
41	None-50 %Perlite	6,62	15,58	18,68	30,45	38,90
44	2%Na_2SO_4-50 % Perlite	7,08	15,88	19,90	31,83	39,10
T 2-1	2%Na_2SO_4- 85°C - 3 h	9,22	12,40	15,40	27,55	34,00
T 2-2	2%Na_2SO_4- 85°C - 10 h	18,48	18,45	19,73	24,90	31,35
T 2-3	2%Na_2SO_4 - 55°C - 3 h	9,85	13,85	19,50	32,65	36,40
T 2-4	2%Na_2SO_4- 55°C - 10 h	9,80	10,77	15,98	28,18	32,95
CONTROL	100 %OPC	13,43	24,50	34,53	44,93	51,81

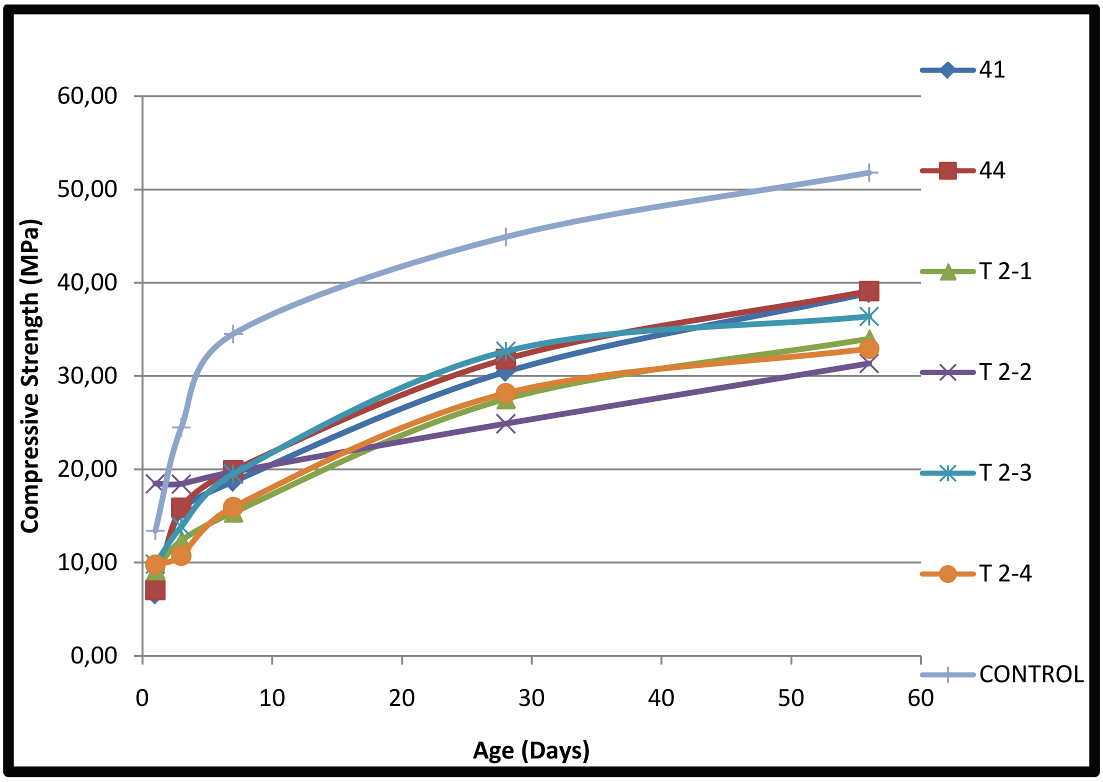
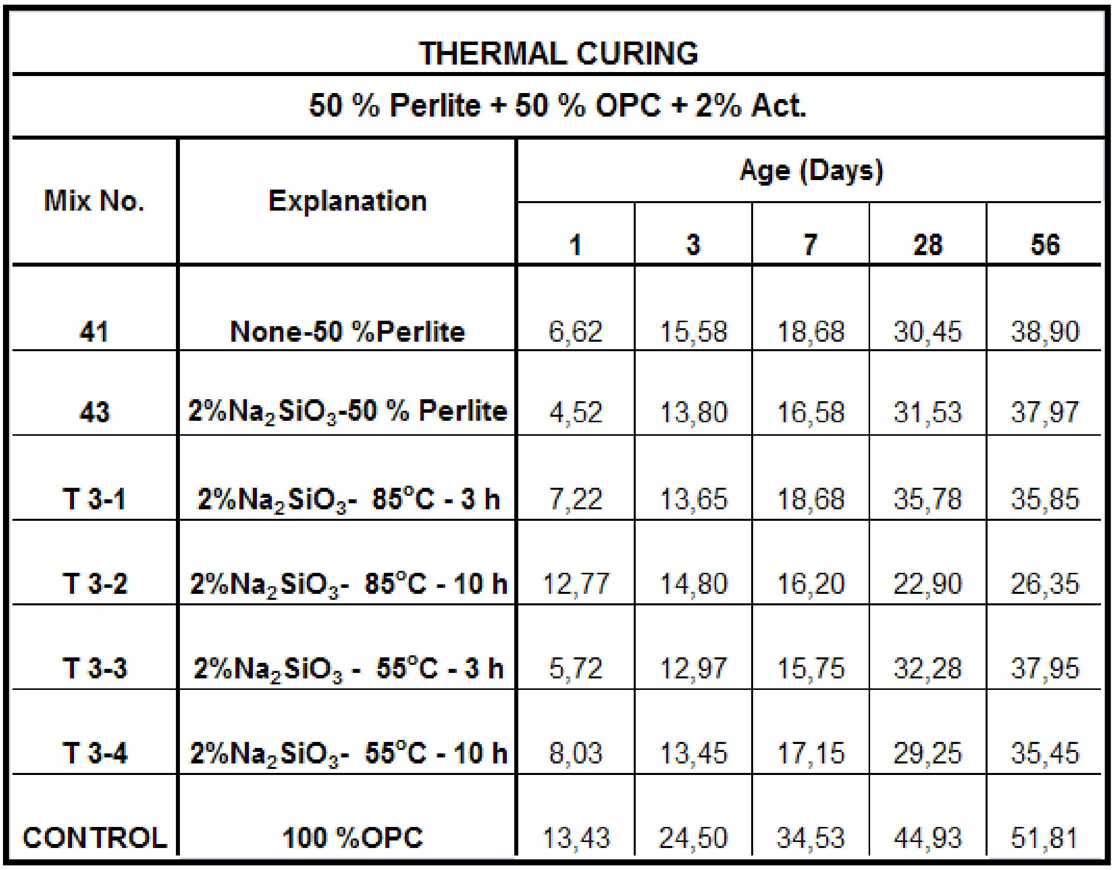


FIGURE 38. Strength Gain of Thermally Cured Mixtures with Na_2SO_4

As it is understood from Table 39 and Figure 38, Na_2SO_4 mixtures showed a dramatic increase at 1-day strength tests by thermal curing of 10h at 85 ^{o}C. However, this increasing effect couldn't be observed at later ages. All samples of thermal curing showed a lower strength than inactivated and not thermally cured ones.

TABLE 40. Strength Gain of Thermally Cured Mixtures with Na_2SiO_3



THERMAL CURING						
50 % Perlite + 50 % OPC + 2% Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
41	None-50 %Perlite	6,62	15,58	18,68	30,45	38,90
43	2%Na_2SiO_3-50 % Perlite	4,52	13,80	16,58	31,53	37,97
T 3-1	2%Na_2SiO_3- 85°C - 3 h	7,22	13,65	18,68	35,78	35,85
T 3-2	2%Na_2SiO_3- 85°C - 10 h	12,77	14,80	16,20	22,90	26,35
T 3-3	2%Na_2SiO_3 - 55°C - 3 h	5,72	12,97	15,75	32,28	37,95
T 3-4	2%Na_2SiO_3- 55°C - 10 h	8,03	13,45	17,15	29,25	35,45
CONTROL	100 %OPC	13,43	24,50	34,53	44,93	51,81

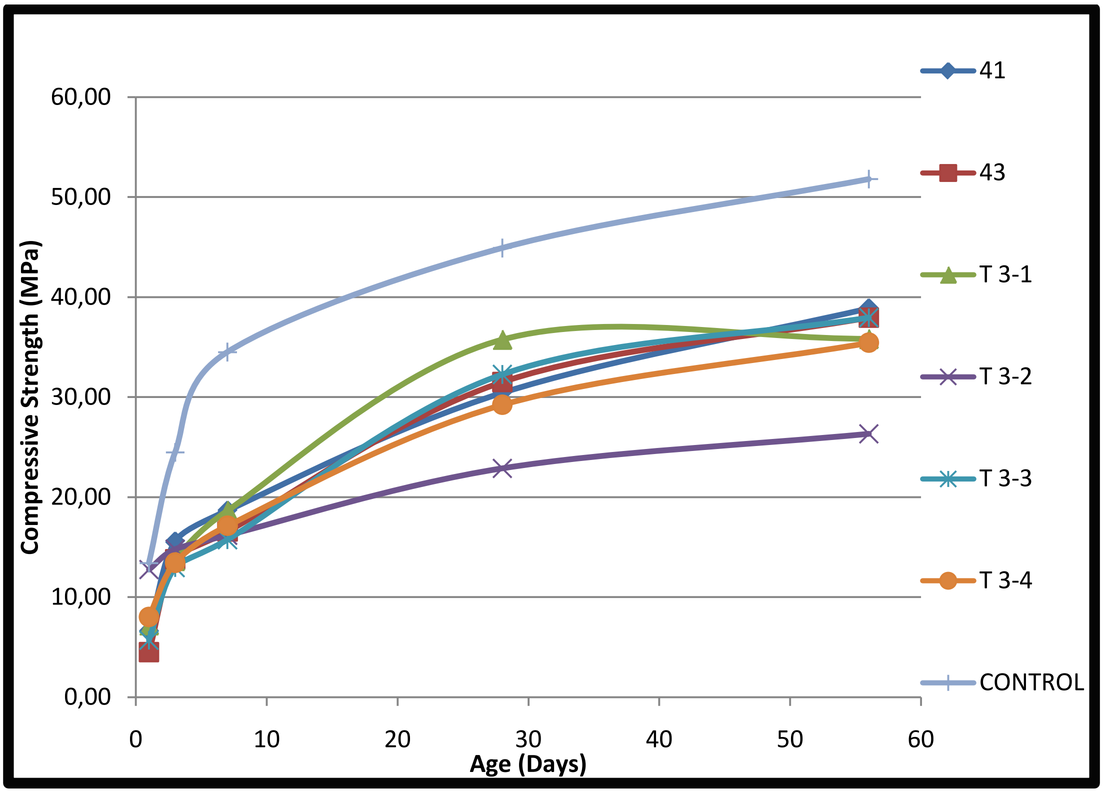
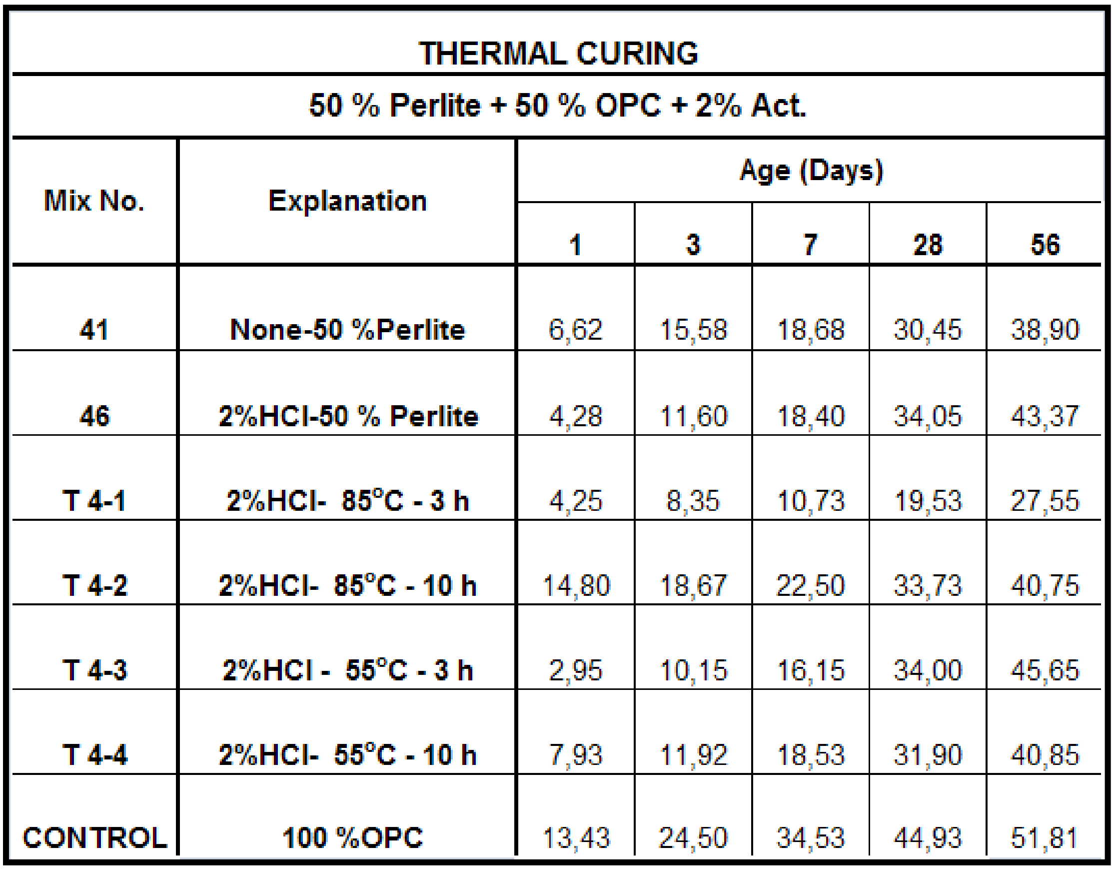


FIGURE 39. Strength Gain of Thermally Cured Mixtures with Na_2SiO_3

As it is seen from Table 40 and Figure 39, similar to Na_2SO_4 containing mixtures, the mixtures of Na_2SiO_3 are also showing high strengths at early ages.However the final strengths are lower than inactivated ones.

TABLE 41. Strength Gain of Thermally Cured Mixtures with HCl



THERMAL CURING						
50 % Perlite + 50 % OPC + 2% Act.						
Mix No.	Explanation	Age (Days)				
		1	3	7	28	56
41	None-50 %Perlite	6,62	15,58	18,68	30,45	38,90
46	2%HCl-50 % Perlite	4,28	11,60	18,40	34,05	43,37
T 4-1	2%HCl- 85°C - 3 h	4,25	8,35	10,73	19,53	27,55
T 4-2	2%HCl- 85°C - 10 h	14,80	18,67	22,50	33,73	40,75
T 4-3	2%HCl - 55°C - 3 h	2,95	10,15	16,15	34,00	45,65
T 4-4	2%HCl- 55°C - 10 h	7,93	11,92	18,53	31,90	40,85
CONTROL	100 %OPC	13,43	24,50	34,53	44,93	51,81

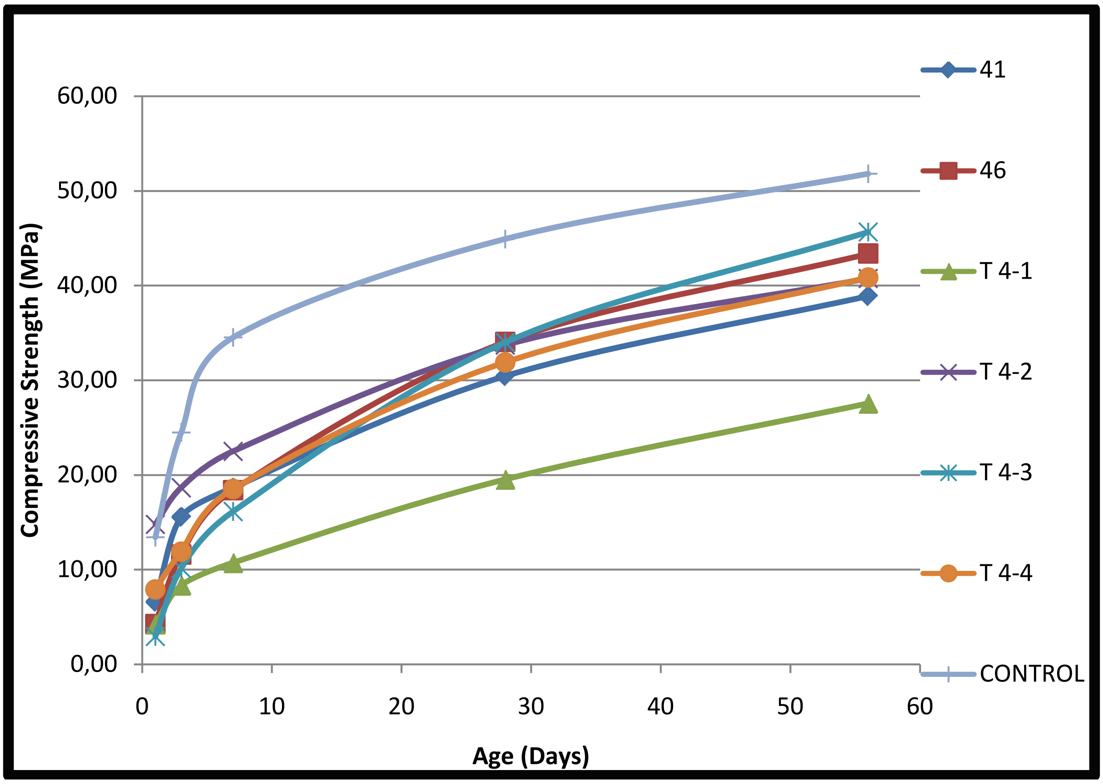


FIGURE 40. Strength Gain of Thermally Cured Mixtures with HCl

Behaviour of HCl containig mixtures are found to be quite similar to the mixtures of $CaCl_2$. The effectiveness of high temperature curing at early ages give place to low temperature curing by time.It is estimated to observe lower strengths by thermal curing at later ages beyond 56 days.

In the light of the above given test results, it can be said that $CaCl_2$ addition with thermal curing of 10 h at 85 ^{o}C, showed the highest performance at 1-day test results. In order to observe the level of strength gaining of higher amounts of perlite containing mixtures, one more mixture was prepared with 80 % replacement level. The results of the mixture is given in Table 41 in comparison with other $CaCl_2$ containing mixures.

TABLE 42. Strength Gain of Three Different Replacement Levels of Perlite with $CaCl_2$ Addition

Mix. No	Perlite Content (%)	Activator	CURING		COMPRESSIVE STRENGTH (MPa)				
			Temp. (°C)	Time (h)	1	3	7	28	56
15	25	2% $CaCl_2$	-	-	12,27	29,73	35,98	57,10	58,63
45	50	2% $CaCl_2$	-	-	5,90	12,75	18,38	33,15	43,07
T 1-3	50	2% $CaCl_2$	55	3	6,95	12,72	20,40	29,40	46,45
T 1-4	50	2% $CaCl_2$	55	10	9,02	12,12	18,28	33,03	45,15
T 1-1	50	2% $CaCl_2$	85	3	10,12	13,47	18,15	29,05	40,97
T 1-2	50	2% $CaCl_2$	85	10	17,43	18,12	24,65	33,70	42,90
T5	80	2% $CaCl_2$	85	10	6,60	6,57	6,88	11,73	13,35
CONTROL	0	-	-	-	13,43	24,50	34,53	44,93	51,81

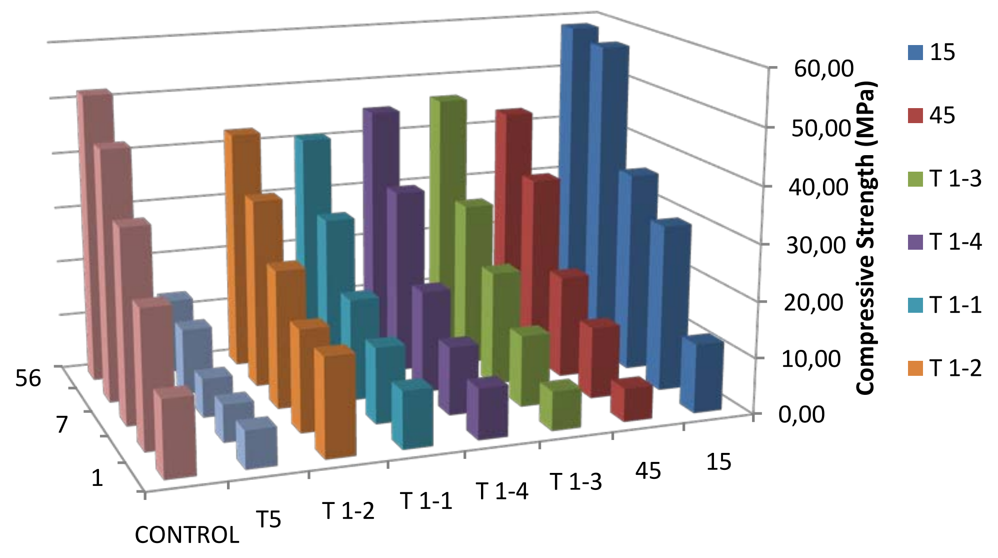


FIGURE 41. Comparison of Strength Gain for Different Amounts of Perlite Addition

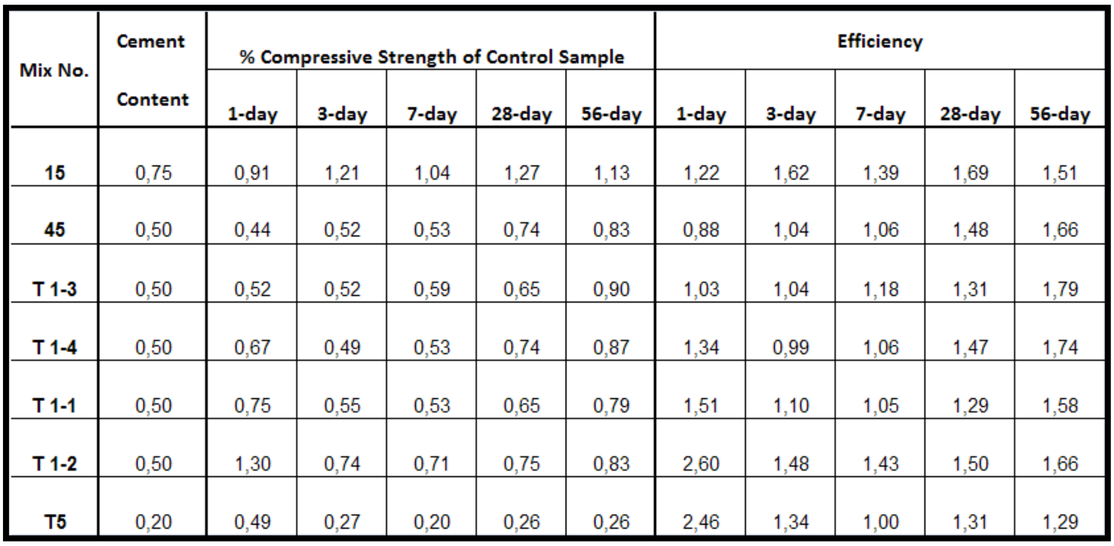
As it is seen from Table 42 and Figure 41, in the case that perlite content was increased up to 80 %, an initial strength of 50 % perlite containing mixture was exceeded, by the help of heat curing of 10 h at 85°C. However, between 1 day to 7 days, almost no strength gain was observed. Also 56-day strength of 80% perlite containing mixture was failed. The behaviour of higher amounts of perlite than 50 % containing mixtures is not fully understood due to lack of tests under unheated curing conditions.

After all these replacement and activation levels, another comparison in terms of efficiency can be made. Here, 'efficiency' is defined by Equation 3 ;

$$Efficiency = \frac{\%\ Compressive\ Strength\ of\ Control\ Sample}{\%\ Cement\ Content\ of\ Control\ Samples} \qquad \textbf{Eq. (3)}$$

The value of efficiency is thought to be helpful in the decision of cement replacement level and curing conditions and will offer an insight to prospective feasibility studies.

TABLE 43. Efficiency of Cement Replacement by Perlite under Different Conditions



Mix No.	Cement Content	% Compressive Strength of Control Sample					Efficiency				
		1-day	3-day	7-day	28-day	56-day	1-day	3-day	7-day	28-day	56-day
15	0,75	0,91	1,21	1,04	1,27	1,13	1,22	1,62	1,39	1,69	1,51
45	0,50	0,44	0,52	0,53	0,74	0,83	0,88	1,04	1,06	1,48	1,66
T 1-3	0,50	0,52	0,52	0,59	0,65	0,90	1,03	1,04	1,18	1,31	1,79
T 1-4	0,50	0,67	0,49	0,53	0,74	0,87	1,34	0,99	1,06	1,47	1,74
T 1-1	0,50	0,75	0,55	0,53	0,65	0,79	1,51	1,10	1,05	1,29	1,58
T 1-2	0,50	1,30	0,74	0,71	0,75	0,83	2,60	1,48	1,43	1,50	1,66
T5	0,20	0,49	0,27	0,20	0,26	0,26	2,46	1,34	1,00	1,31	1,29

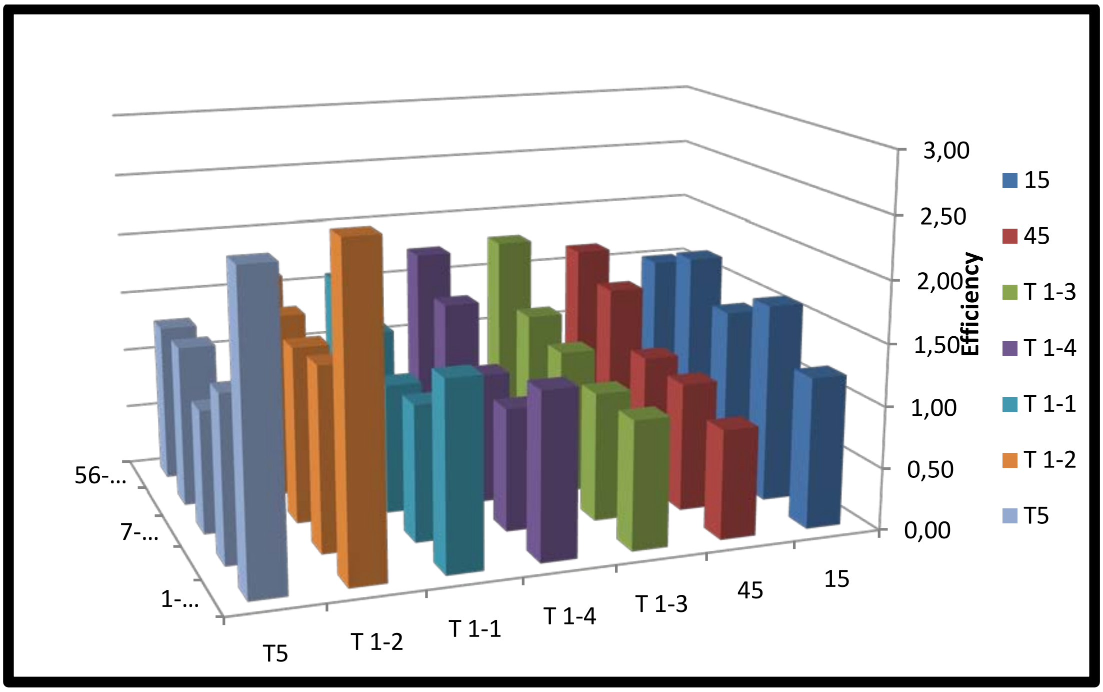


Figure 42. Efficiency of Cement Replacement by Perlite under Different Conditions

As seen from Table 43 and Figure 42, the efficiency of high curing conditions tempers as the age increases. Contrarily, the efficiency of moderate curing conditions increase by age. By thermal curing at 85 ^{o}C for 10 h, superior efficiencies were obtained for 1-day strengths.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The first requirement of encouraging the construction sector to produce perlite-containing cements and concretes is satisfactory technical research. The limited number of investigations on the use of ground perlite in the production of cement and concrete, unreliable methods of testing durability and the previously unattempted chemical and thermal activation of perlite inspired and compelled us to study perlite-containing mixtures.

From the findings of the study, the conclusions below can be drawn.

1- Findings of Alkali - Silica Tests

- Increasing alkali concentration of the waiting solution of 0% perlite-containing mixtures resulted in a small increase in the expansion length. Since the samples of this group do not contain any perlite, their alkalinity is relatively lower than the bath water. The increment in length measurements may be attributed to the alkali absorption of samples from water. However, this increment amount is negligible with the uncertainty of the testing method.

- The expansion measurements of 5% perlite-containing samples are quite far from estimations. It was expected to obtain larger expansions with increasing alkalinity of bath water. However, maximum expansion was obtained in the distilled water whereas minimum expansion was obtained in 2N solution.

- The discordant expansion findings of 5% perlite containing mixtures can be originated from errant measurement. However, a second probability is that, it may be due to pessimum behaviour of expansion mechanism depending on the reactive silica content. Also, The results of the study by Bektaş et al. [23], are in that vein.

- The results of ASTM C 1567 test that show a decrease in expansion by the increase in perlite content, are in accordance with the results of previous studies.

- The results obtained using flame photometry were relatively reasonable, however, far from real values of the solution's concentrations.

- According to the measurements obtained from flame photometer, surprisingly, the most leaching was experienced in the ASTM 1567-1N Modified test.

2- Findings of Activation Tests

- Activation by NaOH addition appears to be ineffective and detrimental to strength and the negative effect worsens with increasing concentration of it. Also, the percent drop in strength increases with specimen age.

- Na_2SiO_3, waterglass, addition does not seem to contribute to compressive strength either, with a greater drop caused in early-age strength than at later ages. Increasing the amount of the activator used tends to increase the early-strength to values close to that of the non-activated mixture but decreases ultimate strength to well below that of the non-activated mixture for 25 % replacement. Perhaps, the one exception to this is the 4% waterglass use in a 50 % replacement mixture where a strength increase more than 50 % over the non-activated mixture is observed at 1 day.

- Use of Na_2SO_4 however, increases early strength noticeably, compared to the non-activated case, for both the 25 % and the 50 % replacement mixtures. The greatest 1-day strength gain is achieved when 4 % is used and the greatest 3-day strength is achieved for 2 % use. In fact the 1- and 3-day strengths of the 25 % perlite mixture is comparable to the respective strengths of the 100 % OPC mixture. The strength of the specimens at later ages however, particularly beyond 28 days, seem to decrease, even to below that of the non-activated case. Therefore, the use of this activator may be considered only in cases where an increase in early-strength is desired. The effect of the activating chemical on durability must also be kept in mind and be known prior to use, of course, as with all chemical activators mentioned here.

- $CaCl_2$ is observed to be the only activator that increases the strength of the perlite-incorporating mixtures, at all ages. For the 25 % perlite mixtures, the 1-, 3-, and 7-day strengths of the mixtures to which 2 % $CaCl_2$ has been added are comparable to the respective strengths of the 100 % OPC mixture and the strengths at and beyond 28 days exceed those of the pure OPC mixture. Increasing the amount of activator to above 2 % diminishes its beneficial effects. For the 50 % perlite mixtures, the strength increasing benefit of $CaCl_2$ is not observed as clearly as in the lower perlite case. In fact, the use of 2 % of this chemical is only beneficial (compared to the non-activated mixture) to the later-age strength of the mixtures. At beyond 28 days, these mixtures surpassed the pure OPC mixture strengths as well. This is probably the case because $CaCl_2$ works on the Portland cement rather than the perlite and as the Portland cement contents decreases from 75 % to 50 %, the beneficial effect of the chemical reduces. However, as hydration continues, perlite being a good pozzolan, reacts with hydration products to give the mixture good ultimate strength. 2% appears to be the ideal amount to use, for the 50 % perlite mixtures as well. Based on these results, the use of this chemical can be justified to achieve high early and/or ultimate strength, keeping in mind the risk of rebar corrosion if used in reinforced concrete.

- The influence of HCl on strength is similar to that of $CaCl_2$ except that the early and ultimate strengths achieved are lower. In fact, the 1-day strengths of these mixtures are lower than the non-activated mixture strength at the same age. It could be said that HCl is a good later-age activator, achieving a 20 % or higher strength than the pure OPC mixture, and even then, it is less effective than $CaCl_2$. Thus, its use would only be justified for cases where early-strength is not required and if studies showed that it is less harmful to the durability of the structure than $CaCl_2$. Again, 2 % addition seems to work best when this chemical is used.

- As per the results of overall tests, with the exception of NaOH, chemicals may be grouped into 2 according to the general strength gaining tendencies, as; Na containing and Cl containing chemicals.

- Changing the addition percentage of activators doesn't affect the flexural strength for the mixtures considerably.

- In terms of flexural strength gaining efficiency , Na_2SO_4 is followed by Na_2SiO_3 and $CaCl_2$.

- Thermal curing of Na_2SO_4 containing mixtures results in a considerable increase in flexural strength at early ages. Thermal curing does not affect the flexural strength of Na_2SiO_3 and HCl containing mixtures considerably.

❖ For all chemical activator types, as the curing temperature increased from room temperature to 55 ^oC to 85 ^oC, the early strength of the specimens generally increased, with a few exceptions. Similarly, for a chosen curing temperature, as time in the oven increased from 3 hours to 10 hours, the 1-day strength increased for all activators, and the 3-day strength for most. This increase was generally more remarkable for the 85 ^oC curing temperature, probably because hydration reactions were greatly accelerated. However, this beneficial effect diminished with progressing age and the 28-day and later strengths of the thermally activated specimens were lower than those of the specimens cured at room temperature.

❖ Based on these results, it could be said that high-temperature thermal activation is justified mainly when very-high-early strength values are required. In other cases, lower temperature activation or even room or ambient temperature curing should be preferred. Also, potential future problems, such as delayed ettringite formation, which can be caused by high-temperature curing should not be ignored. The ultimate strength of pure OPC mixtures is only achieved at very late ages by the thermally activated mixtures containing $CaCl_2$ or HCl.

❖ It appears possible to use perlite at cement-replacement percentages even higher than 50 %. The attempt to thermally and chemically activate an 80 % perlite mixture gave about 11 MPa at 28 days and 14 MPa at 56 days, which indicates that it may have an ultimate strength greater than 15 MPa. This may suffice for certain applications.

❖ Judging from the ultimate strength values for mixtures containing 50 % ground-perlite being greater than 50 MPa, the replacement of 50-75 % of portland cement while still maintaining sufficient strength appears possible and can make for a considerably cheaper concrete with a lower environmental impact.

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- All thermal curing trials with $CaCl_2$, Na_2SO_4 , Na_2SiO_3 and HCl increase the early compressive strengths considerably whereas equal or less compressive strengths to non-activated 50 % perlite-containing mixtures, are obtained at 28 days.

- Increasing perlite content up to 80 %, results in an ultimate compressive strength decrease to one-third and an initial compressive strength decrease to half, which means an efficiency decrease from 2,46 to 1,22 with age change.

CHAPTER 6

RECOMMENDATIONS

The initial objective of our study was to compare the expansions of ASTM C 1293 concrete test and other mortar bar methods, regarding the high alkali content of perlite. Due to the previously explained setbacks, the required comparison could not be made. However, the suppressive effect of perlite use in concrete was proven one more time. In future studies, after required laboratory conditions are provided, this comparison should be made to be sure of the behaviour of perlite addition on alkali-silica expansions. As regarding the activation attempts of perlite-containing mixtures, it was clearly shown that perlite is a pozzolan that can be used as an additive in concrete at high replacement levels especially with chloride containing chemicals. It is possible to obtain superior compressive strengths by thermal curing but, moderate temperatures and long cuing time should be preferred. In light of our study, the topics below may be useful to investigate.

Observed decrease in alkali-silica expansions at low perlite addition should be deeply investigated to be sure about probable pessimum behaviour of perlite. Durability concerns of chemically activated mortars should be investigated.

Higher percentages of perlite addition, under different curing conditions should be examined and feasibility of cement replacement by perlite vs. thermal curing should be studied.

Hydration process of chemically and thermally activated mortars should be studied. Especially early strength gaining of Na_2SO_4 containing mixtures should be investigated.

Activation of perlite by addition of more than one chemical should be tried.

Blended cements of perlite together with other pozzolanic materials should be studied and activation of these blended cements should also be investigated.

REFERENCES

1. Monteiro P.J.M., Mehta P.K. , *Concrete; Microstructure, Properties and Materials*, McGraw-Hill, U.S., 2006.

2. Hendrik G.V.O., U.S. Geological Survey Mineral Commodity Summaries, *Minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2008-cemen.pdf*, accessed on 08.11.2009.

3. Türkiye Hazır Beton Birliği, *www.thbb.org/files/file/2007.pdf*, accessed on 08.11.2009.

4. Erdoğan T.Y., *Beton (Revised 2nd Edition),* METU Press, Ankara, 2007 (in Turkish).

5. Lea F.M., *The Chemistry of Cement and Concrete (Revised Edition of Lea and Desch),* Butler and Tanner Ltd., Great Britain, 1956.

6. Choate W.T. *Energy and Emission Reduction Opportunities For The Cement Industry*, U.S. Department of Energy,Columbia, 2003.

7. Vanderley M.J, *On The Sustainability of The Concrete,* Extended version of the paper commissioned by the UNEP Journal-Industry and Environment, University of Sao Paulo, Brazil, 2003.

8. Erdoğdu K., *CE 7005 Cement Replacement Materials Lecture Notes,* METU, Ankara, 2008.

9. ASTM C 125-06a *Standard Terminology Related to Concrete and Concrete Aggregates,* ASTM International, West Conshohocken, 2006

10. ACI Committee 232, *Proposed Report: Use of Natural Pozzolans in Concrete*, 232.1R-1994.

11. Erdoğdu K., Tokyay M., Türker P.- *Traslar ve Traslı Çimentolar ;* TÇMB/ AR-GE / Y99-2 7.Baskı, Dumat, Ankara, 2007 (in Turkish).

12 inspectAPedia.com, http://www.inspect-ny.com/**,** *www.inspect-ny.com/interiors/perlite.jpg***,** accessed on 08.11.2009.

13. Özgür T., *Perlit ve Öteki Volkanik CamlarınTerminolojisi,* , I.Ulusal Perlit Kongresi, MTA, Ankara, 1977.

14. Karaman M.E, Kibici Y., *Temel Jeoloji Prensipleri* , Devran Matbaacılık, Ankara, 1999, (in Turkish).

15. Taşkın C., *Perlitin Tanımı ve Oluşumu ile Kökeni Hakkında Genel Bilgi ve Türkiye Perlit Zuhurları*, I.Ulusal Perlit Kongresi, MTA, Ankara, 1977.

16. DPT- *8. Beş Yıllık Kalkınma Planı, Madencilik Özel İhtisas Komisyonu Raporu, Endüstriyel Hammadeler Alt Komisyonu, Yapı Malzemeleri 3. Çalışma Grubu Raporu*, Ankara, 2001(in Turkish).

17. U.S *Geological Survey,*
http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf,
Wallace P.Bolen, accessed on 08.12.2009

18. USGS-Perlite, United States Geological Survey Minerals Yearbook - Perlite, 2007, accessed on 08.11.2009. http://*minerals.usgs.gov/minerals/pubs/commodity/perlite/c/myb1-2007-perli.pdf.*

19. DPT-*9. Beş Yıllık Kalkınma Planı, Madencilik Özel İhtisas Komisyonu Raporu,*Ankara, 2007 (in Turkish).

20. Erdem T.K., Investigation On The Pozzolanic Property Of Perlite For Use In producing Blended Cements, PhD. Thesis, METU, Ankara, 2005.

21. Meral Ç., *Use Of Perlite As A Pozzolanic Addition in Blended Cement Production*, Ms. Thesis, METU, Ankara, 2004.

22. Meral Ç., Erdem T.K, Tokyay M., Erdoğan T., *Use of Perlite As a Pozzolanic Addition in Producing Blended Cements*, Cement & Concrete Composites 29,13-21, 2007.

23. Bektaş F., Turanlı L., Monteiro P.J.M., *Use of Perlite Powder to Suppress the ASR*, Cement and Concrete Research 35, 2014-2017, 2005.

24. Yu L.H, Ou H., Lee L.L., *Investigation On Pozzolanic Effect Of Perlite Powder In Concrete*, Cement and Concrete Research 33, 73-76, 2003.

25. Katsioti M., Gkanis D., Pipilikaki P., *Study Of The Substitution Of Limestone Filler With Pozzolanic Additives in Mortars*, Construction and Building Materials 23, 1960-1965, 2009.

26. Erdem E., *Effect of Various Additives on The Hydration of Perlite–Gypsium* , Turkish.Journal of Chemistry 21, 209-214, 1997.

27. Ray A., Sriravindrarajah R. , Gverbois J.B, Thomas P.S, Border S., Ray H.N, Haggman J., Joyce P., *Evaluation of Waste Perlite Fines in The Production of Construction Material,* Journal of Thermal Analysis and Calorimetry, Vol.88,1,279-283, 2007.

28. Vessalas K., Ray A.S., Thomas P.S, Ravindrarajah S.R., Joyce P. and Haggman J., *Pitchstone Fines Pozzolanic Activity Assessment As Partial Portland Cement Replace*ments, J.Aust.Ceram.Soc. 44,1,7-12, 2008.

29. Stanton T.E.*, Expansion of Concrete Through Reaction Between Cement and Aggregate*, Proceedings of the American Society of Civil Engineers 66, 10, 1781-1811, 1940

30. Mielenz R.C., *Petrographic Examination of Concrete Aggregate to Determine Potential Alkali Reactivity* , Highway Research Board, Report 18-C, 1958.

31. Swamy R.N, *The Alkali Silica Reaction in Concrete*, Blackie and Son Ltd., NewYork, 2003.

32. ASTM C 227-03, *Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations* (Mortar Bar Method), ASTM International, West Conshohocken, 2003.

33. Thomas M., Fournier B., Folliard K., Ideker J., Shehata M.*, Test Methods for Evaluating Preventive Measures for Controlling Expansion Due to Alkali-Silica Reaction in Concrete*, Cement and Concrete Research 36, 1842-1856, 2006.

34. ASTM C 1293-08a, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali – Silica Reaction,* ASTM International, West Conshohocken, 2008.

35. Oberholster R.E., Davies G., *An Accelerated Method for Testing The Potential Alkali Reactivity of Siliceous Aggregates.* Cement and Concrete Research,16,18,181-189, 1986.

36. ASTM C 1260-07, *Standard Test Method for Potential Alkali Reactivity of Aggregates* (Mortar Bar Method), ASTM International, West Conshohocken, 2007.

37. ASTM C 1567-04, *Standard Test Method for Determining The Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate* (Accelerated Mortar Bar Method). ASTM International, West Conshohocken, 2004.

38. Hudec P.P, Larbi J.A, *Rapid Methods Of Predicting Alkali Reactivity*, Alkali-Aggregate Reaction-8th International Conference, Edited by Okada K, Nishibayashi S., Kawamura M., Kyoto, 1989.

39. Chatterji S., *A Simple Chemical Test Method For Detection of Alkali- Silica Reactivity of Aggregates*, Alkali-Aggregate Reaction- 8th International Conference, Edited by Okada.K, Nishibayashi S., Kawamura M., Kyoto, 1989.

40. Ohtsu M. - Short Term Evaluation of Mortar Bar Test by Acoustic Emision,Alkali-Aggregate Reaction-8th International Conference, Edited by Okada.K, Nishibayashi S., Kawamura M., Kyoto, 1989 .

41. Kobayashi S.-*A Simple Concrete Bar Test With Double Layered Cylindrical Specimens*, Alkali-Aggregate Reaction-8th International Conference, Edited by Okada K, Nishibayashi S., Kawamura M, Kyoto, 1989.

42. Lu D., Fournier B., Grattan-Bellew P.E, *Evaluation of Accelerated Test Methods for Determining Alkali-Silica Reactivity of Concrete Aggregates*, Cement & Concrete Composites 28, 546-554, 2006.

43. Zhongzi X., Yang S., Doyou L., *Main Parameters in the New Test Method For Alkali-Silica Reactivity*, J.Nanjing Univ.Chem.Technol. 20, 2, 1-7, 1998.

44. Thomas M.D.A., Fournier B., Folliard K., Shehata M.H., Ideker J., Rogers C., *Performance Limits for Evaluating Supplementary Cementing Materials Using Accelerated Mortar Bar Test*, ACI Materials Journal, 104, 2, 115-122.2007.

45. Shi C., *Activation of Natural Pozzolans, Fly Ashes and Blast Furnace Slag*, PhD. Thesis, University of Calgary, 1992.

46. Carino N.J, Lew H.S, *Maturity Method; Theory and Application,* Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Reprinted from the Proceedings of the 2001 Structure Congress and Exposition, Washington D.C, ASCE, Peter C. Chang. Editor, 19 p, 2001.

47. Jiang W., *Alkali- Activated Cementitious Materials: Mechanisms, Microstructure and Properties*, PhD. Thesis, The Pennsylvania State University, Pennsylvania, 1997.

48. Bell R.P., *Acid-Base Catalysis*-Oxford University Press, 1941

49. Malolepszy J., Activation of Synthetic Melitite Slags by Alkalis-8th International Congress on the Chemistry of Cement , Rio de Janerio, Brazil,4,104-107, 1986.

50. Krivenko, P.V., *Special Slag Alkaline Cements* (Kiev: Budivelnik Publisher), 19-54, 1992.

51. Moore J.M, Pearson R.G., *Kinetics and Mechanism, A study of Homogeneous Chemical Reactions-Third Edition*, John Willey and Sons Inc., Canada,1981.

52. Roy D.M, *Alkali-Activated Cements Opportunities and Challenges*, Cement and Concrete Research 29, 249-254, 1999

53. Jimenez A.F., Palomo J.G., Puertas F., *Alkali-Activated Slag Mortars-Mechanical Strength Behaviour*-Cement and Concrete Research 29, 1313-1321, 1999.

54. Shi C., Krivenko P.V., Roy D., *Alkali-Activated Cements and Concretes*, Taylor & Francis, Oxon-New York, 2006.

55. Wang S.D., Scrivener K.L, *Hydration Products of Alkali Activated Slag Cement, Cement and Concrete Research* 25, 561-571, 1995.

56. Hrazdira J*., Activation of Slag in Gypsumless Portland Cements*, Istanbul Conference, 1992.

57. Atiş C.D, Bilim C., Ozlem C., Karahan O., *Influence of Activator on the Strength and Drying Shrinkage of Alkali-Activated Slag Mortar*, Construction and Building Material, 23, 1, 548-555, 2009.

58. Bakharev T., Sanjayan J.G, Alkali Activation of Australian Slag Cements, Cement and Concrete Research 29, 1, 113-120, 1999.

59. Krizan D.,Zivanovic B., *Effects of Dosage and Modulus of Waterglass on Early Hydration of Alkali-Slag Cements*, Cement and Concrete Research 32, 1181-1188, 2002.

60. Brough A.R., Atkinson A*., Sodium Silicate Based, Alkali-Activated Slag Mortars .Part 1. Strength, Hydration and Microstructure*, Cement and Concrete Research 32, 865-879, 2002.

61. Lee C.Y., Lee H.K., Lee K.M., *Strength and Microstructural Characteristic of Chemically Activated Fly-Ash Cement Systems*, Cement and Concrete Research , 33, 3, 425-431.

62. Qian J., Shi C., Zhi W., *Activation of Blended Cements Containing Fly Ash*, Cement and Concrete Research 31, 1121-1127, 2001.

63. Fan Y., Yin S., Wen Z., Zhang J., *Activation of Fly Ash and Its Effects on Cement Properties*. Cement and Concrete Research 29, 467-472, 1999.

64. Jimenez A.F., Palomo A., Criado M., *Microstructure Development of Alkali-Activated Fly Ash Cement: A Descriptive Model*. Cement and Concrete Research 35, 1204-1209, 2005.

65. Jimenez A.F., Palomo A, Sobrados I., Sanz J., *The Role Played by the Reactive Alumina Content in the Alkaline Activation of Fly Ash. Microporous and Mesoporous Materials* 91, 111-119, 2006.

66. Bainton J.W., *Addition of Acidulated Pozzolan to Concrete and Concrete Products*, US Patent 3953222, 1976.

67. Allahverdi A., Ghorbani J., *Chemical Activation and Set Acceleration of Lime-Natural Pozzolan Cement*. Ceramics 50,4,193-199, 2006.

68. Alexander K.M: Aust J.Appl.Sci.6, 224, 1955.

69. Johansen V., Influence of Alkalies on the Strength Development, the Effect of Alkalies on the Properties of Concrete (Proceedings of a Symposium Held in London), 81-97, 1976.

70. Jawed I. and Skalny J., The Influence of Alkali Sulphates on the Properties of Cement and Concrete, World Cement, 11, 325-330, 1983.

71. Shi C., Day R.L., *Pozzolanic Reaction in the Presence of Chemical Activators: Part 1. Reaction Kinetics*, Cement and Concrete Research, 30, 1, 51-58, 2000.

72. Lea F.M., *The Chemistry of Cement and Concrete*, 3rd Edition, Edward Arnold, 1974.

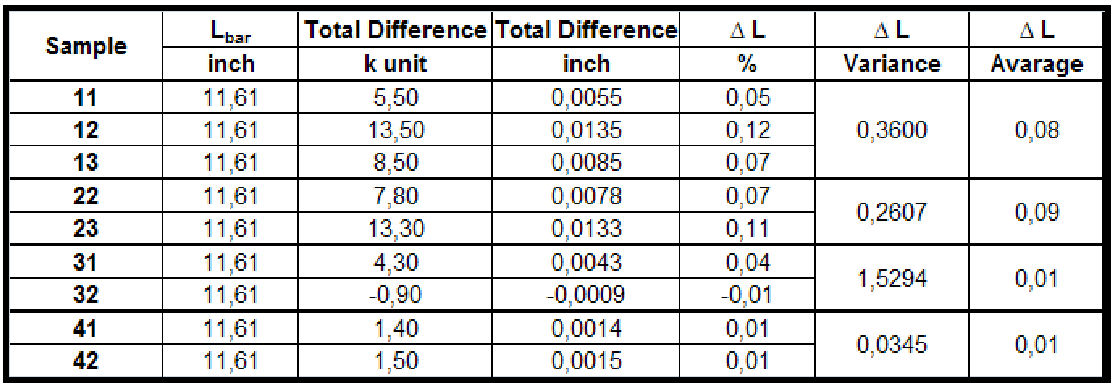
73. Day R.L., *Natural Pozzolans for Building in Latin America*, Proceedings of Project Identification Meeting on Local Building Materials, British Science Council, Nairobi, 1988.

74. Deng Y., Wu X., and Tang M., *High Strength Alkali-Slag Cement*, Journal of Institute of Chemical Technology, 11, 2,1-7, P.R. China,1989 (in Chinese).

75. Talling B., *Effect of Curing Conditions on Alkali-Activated Slags*, 3rd International Conference on the Use of Fly ash, Silica Fume, Slag and Natural Pozzolans in Concrete, ACI SP-114, 2, 1485-1500, Trondheim, 1989.

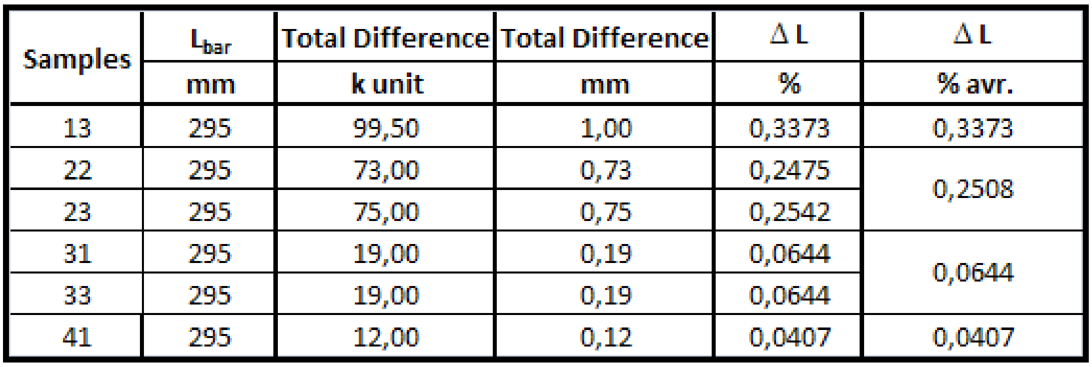
APPENDIX

Table A1. Length Changes of ASTM C 1293 Samples



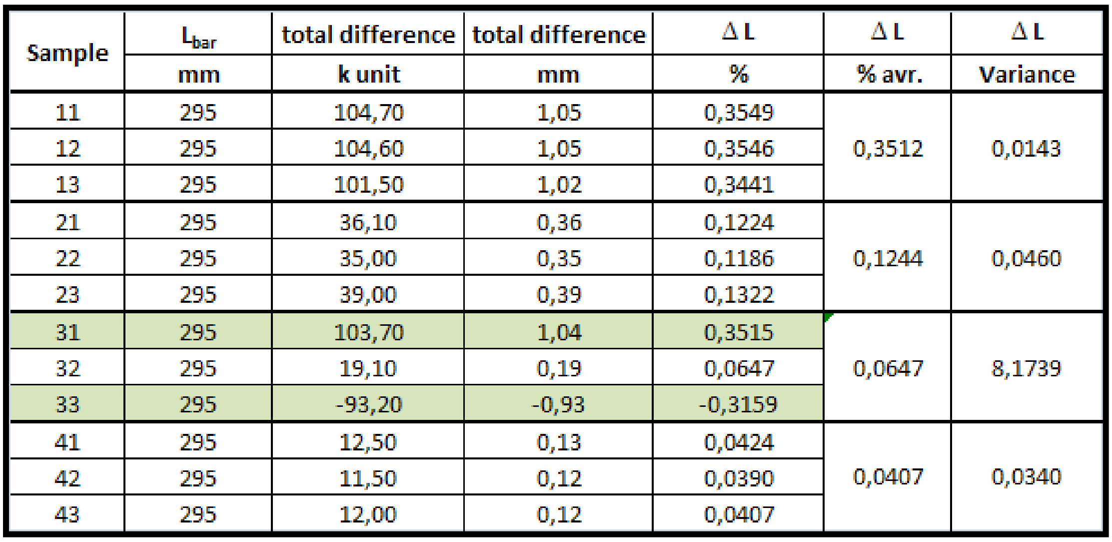
Sample	L_{bar}	Total Difference	Total Difference	Δ L	Δ L	Δ L
	inch	k unit	inch	%	Variance	Avarage
11	11,61	5,50	0,0055	0,05	0,3600	0,08
12	11,61	13,50	0,0135	0,12		
13	11,61	8,50	0,0085	0,07		
22	11,61	7,80	0,0078	0,07	0,2607	0,09
23	11,61	13,30	0,0133	0,11		
31	11,61	4,30	0,0043	0,04	1,5294	0,01
32	11,61	-0,90	-0,0009	-0,01		
41	11,61	1,40	0,0014	0,01	0,0345	0,01
42	11,61	1,50	0,0015	0,01		

Table A2. Length Changes of ASTM C 1567 Samples



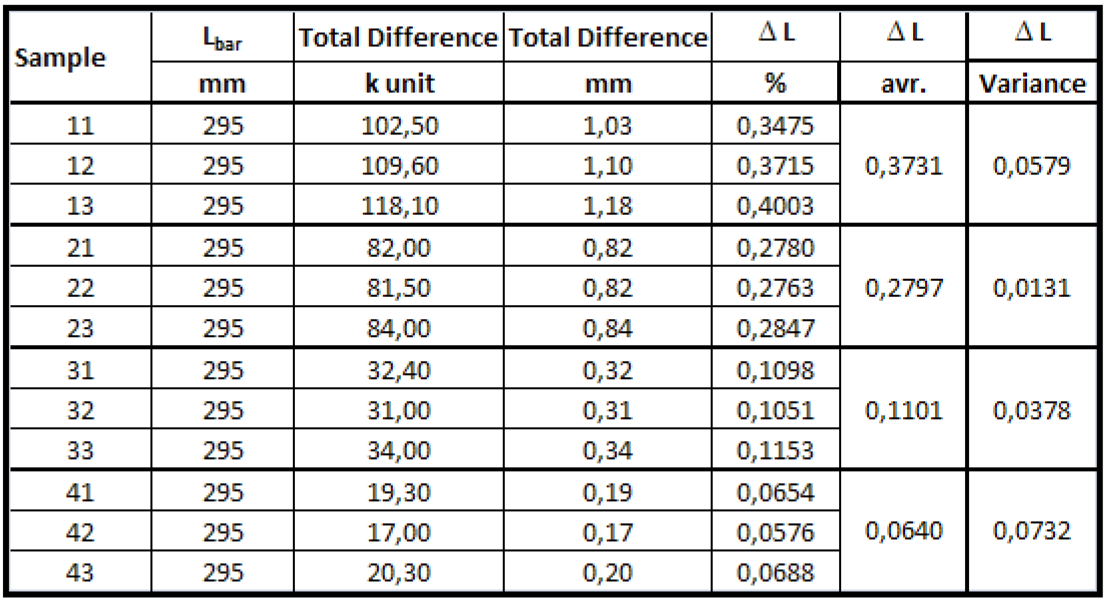
Samples	L_{bar}	Total Difference	Total Difference	Δ L	Δ L
	mm	k unit	mm	%	% avr.
13	295	99,50	1,00	0,3373	0,3373
22	295	73,00	0,73	0,2475	0,2508
23	295	75,00	0,75	0,2542	
31	295	19,00	0,19	0,0644	0,0644
33	295	19,00	0,19	0,0644	
41	295	12,00	0,12	0,0407	0,0407

Table A3. Length Changes of ASTM C 1567-1N Modified Samples



Sample	L_{bar}	total difference	total difference	Δ L	Δ L	Δ L
	mm	k unit	mm	%	% avr.	Variance
11	295	104,70	1,05	0,3549	0,3512	0,0143
12	295	104,60	1,05	0,3546		
13	295	101,50	1,02	0,3441		
21	295	36,10	0,36	0,1224	0,1244	0,0460
22	295	35,00	0,35	0,1186		
23	295	39,00	0,39	0,1322		
31	295	103,70	1,04	0,3515	0,0647	8,1739
32	295	19,10	0,19	0,0647		
33	295	-93,20	-0,93	-0,3159		
41	295	12,50	0,13	0,0424	0,0407	0,0340
42	295	11,50	0,12	0,0390		
43	295	12,00	0,12	0,0407		

Table A4. Length Changes of ASTM C 1567-2N Modified Samples



Sample	L_{bar}	Total Difference	Total Difference	Δ L	Δ L	Δ L
	mm	k unit	mm	%	avr.	Variance
11	295	102,50	1,03	0,3475	0,3731	0,0579
12	295	109,60	1,10	0,3715		
13	295	118,10	1,18	0,4003		
21	295	82,00	0,82	0,2780	0,2797	0,0131
22	295	81,50	0,82	0,2763		
23	295	84,00	0,84	0,2847		
31	295	32,40	0,32	0,1098	0,1101	0,0378
32	295	31,00	0,31	0,1051		
33	295	34,00	0,34	0,1153		
41	295	19,30	0,19	0,0654	0,0640	0,0732
42	295	17,00	0,17	0,0576		
43	295	20,30	0,20	0,0688		

Table A5. Length Measurements of ASTM C 1293 Concrete Samples

1st Reading			2nd Reading			3rd Reading			4th Reading			Explanations
Sample	**Small Gauge**	**Big Gauge**	**Sample**	**Small Gauge**	**Big Gauge**	**Sample**	**Small Gauge**	**Big Gauge**	**Sample**	**Small Gauge**	**Big Gauge**	
11	1,80	0,50	**11**	1,50	15,50	**11**	1,50	17,00	**11**	1,50	15,00	With pin
12	1,10	11,50	**12**	1,00	3,00	**12**	0,90	1,30	**12**	0,50	19,00	With pin
13	18,00	8,50	**13**	17,50	0,00	**13**	17,00	16,20	**13**	17,50	0,00	With pin
13			**13**			**13**	15,50	19,00	**13**			Without Pin
21	17,30	16,90	**21**	15,50	18,50	**21**	15,50	18,00	**21**	15,50	15,50	Without Pin
22	1,00	7,30	**22**	1,00	5,50	**22**	0,90	1,40	**22**	0,50	19,50	With pin
23	6,50	16,80	**23**	6,00	6,50	**23**	6,00	7,50	**23**	6,00	3,00	With pin
31	17,80	3,80	**31**	17,50	19,00	**31**	17,50	19,50	**31**	17,50	19,50	With pin
32	1,50	16,70	**32**	1,50	14,50	**32**	1,50	15,90	**32**	1,50	17,50	With pin
33	0,00	6,80	**33**	0,00	3,00	**33**	0,00	3,00	**33**			With pin
33			**33**			**33**	18,00	6,00	**33**	19,50	3,50	Without pin
41	13,20	15,20	**41**	13,20	14,00	**41**	13,20	14,20	**41**	13,50	14,00	Without pin
42	12,30	16,00	**42**	12,50	16,00	**42**	12,50	15,50	**42**	12,50	14,50	Without pin
43	17,50	1,50	**43**	15,50	2,30	**43**	15,50	2,80	**43**	15,50	1,50	Without pin
Reference Bar	7,00	4,00	**Reference Bar**	7,00	4,00	**Reference Bar**	7,00	5,00	**Reference Bar**	7,00	6,00	With pin
EMPTY	16,50	0,00	**EMPTY**	16,50	0,00	**EMPTY**	16,50	0,00	**EMPTY**	16,50	0,00	

TABLE A6. Length Measurements of ASTM C 1567 Mortar Samples

Sample	1st Reading		2nd Reading		3rd Reading		4th Reading		5th Reading	
	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge
13	18,80	17,50	18,50	5,50	18,50	36,00	17,50	46,00	16,90	18,00
22	0,50	1,00	0,00	40,00	0,00	26,00	19,50	49,00	19,00	28,00
23	1,20	35,00	1,00	23,50	1,00	9,00	0,20	34,00	0,00	10,00
31	17,00	22,00	16,50	11,00	16,50	7,50	16,50	7,00	16,50	3,00
33	17,00	24,00	16,50	11,50	16,50	10,00	16,50	9,00	16,50	5,00
41	6,00	22,00	6,00	13,50	6,00	12,50	6,00	11,50	6,00	10,00
Empty	7,50	41,00	7,50	41,00	7,50	36,50	7,50	42,00	7,50	36,00
Referance Bar	17,50	2,00	17,50	2,00	17,50	1,50	17,00	3,10	17,50	2,00

TABLE A7. Length Measurements of ASTM C 1567 - 1N Modified Mortar Samples

Sample	1st Reading		2nd Reading		3rd Reading		4th Reading		5th Reading	
	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge
11	2,9	34,8	2,3	14,3	2	40,8	1,5	23,8	1	2
12	2,3	19,5	1,8	36,3	1,3	15,2	1	45,5	0,5	26,5
13	4	39,2	4,3	14,8	3,8	38	3,5	26,2	3	5
21	18,6	31,2	17	4	17	0	17	48	16,5	38,5
22	3	46,5	2,9	40,2	2,8	35,5	2,8	38,8	2,5	26
23	17	10,1	18,5	25,2	18,3	22,8	18,2	14	18	6
31	1,8	30	1,8	31	19	0	19	48,8	18,8	37,5
32	3,5	23,5	3,6	27	3,5	27	3,5	24	3,2	14
33	19	4	19	2,5	1,8	32	1,5	29,8	1,5	20
41	1,5	24,5	1,5	23,2	1,5	23	1,5	23	1,3	18
42	2,5	36,1	2,5	25	2,5	24,8	2,5	25	2,5	21,5
43	16,5	35	16,5	33	16,5	34,5	16,5	32,5	16,5	29
Referance Bar	17,5	33,1	17,6	34,8	17,5	35	17,5	35	17,5	22
Empty	7,5	16,1	7,5	18,5	7,5	17,5	7,5	19	7,5	21

TABLE A8. Length Measurements or ASTM C 1567- 2N Modified Mortar Samples

Sample	1st Reading		2nd Reading		3rd Reading		4th Reading		5th Reading		6th Reading	
	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge	Small Gauge	Big Gauge
11	4,50	23,00	4,20	10,10	3,50	34,00	3,10	8,00	3,00	44,00	2,50	20,50
12	1,70	33,20	1,30	19,00	0,90	40,00	0,10	13,10	0,00	49,00	19,00	23,60
13	3,00	44,60	2,80	29,50	2,00	2,50	1,50	24,00	1,20	11,00	0,00	26,50
21	0,30	18,50	0,00	4,50	19,80	34,80	19,30	18,50	19,20	9,50	18,00	36,50
22	19,50	28,00	19,20	16,00	19,00	0,50	18,50	29,50	18,50	20,00	17-18	46,50
23	18,00	0,50	17,50	40,50	17,30	20,00	16,00	48,80	16,00	37,50	16,00	16,50
31	19,00	2,00	18,90	42,50	18,90	40,00	18,50	35,50	18,80	33,00	18,00	19,60
32	1,00	41,00	0,80	32,00	0,50	28,80	0,50	25,50	0,50	22,30	0,00	10,00
33	19,00	46,50	18,90	38,80	18,80	35,00	18,50	32,20	18,50	28,00	18,00	12,50
41	18,50	35,50	18,50	26,00	18,40	24,80	18,30	21,20	18,50	24,50	18,00	16,20
42	18,00	48,50	17,80	40,00	17,80	39,00	17,80	37,00	17,80	38,50	17,00	31,50
43	18,00	46,50	17,80	41,00	17,80	37,00	17,50	34,80	17,50	36,50	17,00	26,20
Empty	7,50	19,50	7,50	17,50	7,50	35,00	7,50	21,00	7,50	18,00	7,50	21,00
Referance Bar	17,50	35,00	17,50	35,00	17,50	19,00	17,50	33,50	17,50	35,00	17,50	33,50

TABLE A9. FLEXURAL STRENGTHS OF 25 % PERLITE AND 2% ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
CONTROL	a	1,00	5,50	7,60	8,30	9,70	0,97	5,50	7,00	8,25	9,55	0,05	0,11	0,09	0,01	0,02	1,00	0,90	5,50	5,50	7,60	6,40	8,30	8,20	9,70	9,40
	b	1,00	5,50	6,40	8,20	9,40																				
	c	0,90	5,50																							
11	a	2,50	5,00	6,70	7,70	9,90	2,27	4,63	6,50	7,55	9,85	0,09	0,08	0,03	0,02	0,01	2,50	2,00	5,00	4,10	6,70	6,30	7,70	7,40	9,90	9,80
	b	2,30	4,80	6,30	7,40	9,80																				
	c	2,00	4,10																							
12	a	2,43	3,90	4,80	7,10	6,80	2,36	3,70	4,70	6,95	7,05	0,05	0,06	0,02	0,02	0,04	2,46	2,20	3,90	3,40	4,80	4,60	7,10	6,80	7,30	6,80
	b	2,46	3,40	4,60	6,80	7,30																				
	c	2,20	3,80																							
13	a	1,90	4,40	7,00	8,00	9,40	2,13	4,63	6,85	7,95	9,45	0,08	0,06	0,02	0,01	0,01	2,30	1,90	5,00	4,40	7,00	6,70	8,00	7,90	9,50	9,40
	b	2,30	4,50	6,70	7,90	9,50																				
	c	2,20	5,00																							
14	a	3,00	4,80	6,70	8,30	9,70	3,00	5,43	6,90	7,65	9,80	0,03	0,11	0,03	0,08	0,01	3,10	2,90	6,20	4,80	7,10	6,70	8,30	7,00	9,90	9,70
	b	3,10	5,30	7,10	7,00	9,90																				
	c	2,90	6,20																							
15	a	2,70	4,70	5,40	6,80	8,80	2,83	5,03	5,40	7,00	8,85	0,03	0,05	0,00	0,03	0,01	2,90	2,70	5,30	4,70	5,40	5,40	7,20	6,80	8,90	8,80
	b	2,90	5,30	5,40	7,20	8,90																				
	c	2,90	5,10																							
16	a	1,20	4,40	5,60	7,80	9,40	1,70	4,53	5,85	7,90	9,60	0,21	0,03	0,04	0,01	0,02	2,00	1,20	4,70	4,40	6,10	5,60	8,00	7,80	9,80	9,40
	b	1,90	4,50	6,10	8,00	9,80																				
	c	2,00	4,70																							

TABLE A10. FLEXURAL STRENGTHS OF 25 % PERLITE AND 4 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
22	a	2,60	3,90	5,50	6,40	8,00	2,50	3,90	5,30	6,40	8,00	0,03	0,00	0,04	0,00	0,00	2,60	2,40	3,90	3,90	5,50	5,10	6,40	6,40	8,00	8,00
	b	2,40	3,90	5,10	6,40	8,00																				
	c	2,50	3,90																							
23	a	2,10	4,30	5,00	6,40	8,10	2,10	4,10	4,95	6,60	7,95	0,00	0,03	0,01	0,03	0,02	2,10	2,10	4,30	4,00	5,00	4,90	6,80	6,40	8,10	7,80
	b	2,10	4,00	4,90	6,80	7,80																				
	c	2,10	4,00																							
24	a	2,90	4,90	6,70	8,00	9,60	3,33	5,10	6,30	7,80	9,90	0,10	0,03	0,06	0,03	0,03	3,70	2,90	5,30	4,90	6,70	5,90	8,00	7,60	10,20	9,60
	b	3,70	5,10	5,90	7,60	10,20																				
	c	3,40	5,30																							
25	a	2,50	3,20	3,90	6,30	8,20	2,27	3,17	4,00	5,95	8,20	0,09	0,01	0,03	0,06	0,00	2,50	2,00	3,20	3,10	4,10	3,90	6,30	5,60	8,20	8,20
	b	2,30	3,20	4,10	5,60	8,20																				
	c	2,00	3,10																							
26	a	1,50	3,20	5,40	7,10	8,80	1,67	3,50	5,05	7,45	8,95	0,10	0,07	0,07	0,05	0,02	1,90	1,50	3,80	3,20	5,40	4,70	7,80	7,10	9,10	8,80
	b	1,90	3,80	4,70	7,80	9,10																				
	c	1,60	3,50																							

TABLE A11. FLEXURAL STRENGTHS OF 25 % PERLITE AND 6% ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
32	a	2,30	3,10	4,30	2,70	2,50	2,43	3,07	4,10	2,75	2,75	0,05	0,17	0,05	0,02	0,09	2,60	2,30	3,70	2,40	4,30	3,90	2,80	2,70	3,00	2,50
	b	2,60	3,70	3,90	2,80	3,00																				
	c	2,40	2,40																							
33	a	2,40	3,60	5,30	5,20	7,30	2,33	3,80	4,90	5,45	6,95	0,07	0,04	0,08	0,05	0,05	2,50	2,10	4,00	3,60	5,30	4,50	5,70	5,20	7,30	6,60
	b	2,10	3,80	4,50	5,70	6,60																				
	c	2,50	4,00																							
34	a	2,80	5,50	6,80	8,50	11,40	2,70	5,43	6,95	8,80	11,05	0,05	0,01	0,02	0,03	0,03	2,80	2,50	5,50	5,40	7,10	6,80	9,10	8,50	11,40	10,70
	b	2,80	5,40	7,10	9,10	10,70																				
	c	2,50	5,40																							
35	a	2,10	3,70	4,40	7,40	8,60	2,13	3,27	4,35	7,45	8,15	0,06	0,09	0,01	0,01	0,06	2,30	2,00	3,70	3,00	4,40	4,30	7,50	7,40	8,60	7,70
	b	2,00	3,00	4,30	7,50	7,70																				
	c	2,30	3,10																							
36	a	1,40	2,60	4,10	6,00	6,80	1,30	2,57	4,05	6,60	7,10	0,11	0,05	0,01	0,09	0,04	1,40	1,10	2,70	2,40	4,10	4,00	7,20	6,00	7,40	6,80
	b	1,40	2,40	4,00	7,20	7,40																				
	c	1,10	2,70																							

TABLE A12. FLEXURAL STRENGTHS OF 50 % PERLITE AND 2 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
41	a	2,10	1,10	1,60	7,90	9,40	2,07	1,03	1,45	7,80	9,00	0,02	0,05	0,10	0,01	0,04	2,10	2,00	1,10	1,00	1,60	1,30	7,90	7,70	9,40	8,60
	b	2,00	1,00	1,30	7,70	8,60																				
	c	2,10	1,00																							
43	a	1,40	1,10	1,10	7,40	7,70	1,37	1,00	1,10	7,30	7,70	0,03	0,08	0,00	0,01	0,00	1,40	1,30	1,10	0,90	1,10	1,10	7,40	7,20	7,70	7,70
	b	1,40	0,90	1,10	7,20	7,70																				
	c	1,30	1,00																							
44	a	2,30	1,10	1,30	8,10	9,00	2,23	1,07	1,40	8,35	8,30	0,02	0,04	0,07	0,03	0,08	2,30	2,20	1,10	1,00	1,50	1,30	8,60	8,10	9,00	7,60
	b	2,20	1,00	1,50	8,60	7,60																				
	c	2,20	1,10																							
45	a	2,00	0,80	1,00	6,50	7,70	1,87	0,80	1,00	6,25	6,65	0,07	0,00	0,00	0,04	0,16	2,00	1,70	0,80	0,80	1,00	1,00	6,50	6,00	7,70	5,60
	b	1,90	0,80	1,00	6,00	5,60																				
	c	1,70	0,80																							
46	a	1,50	0,70	1,00	6,60	8,30	1,33	0,70	1,10	6,90	7,85	0,13	0,00	0,09	0,04	0,06	1,50	1,10	0,70	0,70	1,20	1,00	7,20	6,60	8,30	7,40
	b	1,10	0,70	1,20	7,20	7,40																				
	c	1,40	0,70																							

TABLE A13. FLEXURAL STRENGTHS OF 50 % PERLITE AND 4 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
53	a	1,70	0,80	0,80	6,80	5,60	1,57	0,77	0,85	6,55	5,60	0,06	0,06	0,06	0,04	0,00	1,70	1,50	0,80	0,70	0,90	0,80	6,80	6,30	5,60	5,60
	b	1,50	0,80	0,90	6,30	5,60																				
	c	1,50	0,70																							
54	a	0,60	1,10	1,80	8,40	6,90	0,60	1,07	1,80	8,75	6,85	0,00	0,04	0,00	0,04	0,01	0,60	0,60	1,10	1,00	1,80	1,80	9,10	8,40	6,90	6,80
	b	0,60	1,00	1,80	9,10	6,80																				
	c	0,60	1,10																							
55	a	0,40	0,60	0,70	4,60	5,60	0,40	0,57	0,70	5,15	6,15	0,00	0,08	0,00	0,11	0,09	0,40	0,40	0,60	0,50	0,70	0,70	5,70	4,60	6,70	5,60
	b	0,40	0,50	0,70	5,70	6,70																				
	c	0,40	0,60																							
56	a	0,20	0,70	0,80	6,10	5,40	0,27	0,63	0,80	6,05	6,15	0,18	0,07	0,00	0,01	0,12	0,30	0,20	0,70	0,60	0,80	0,80	6,10	6,00	6,90	5,40
	b	0,30	0,60	0,80	6,00	6,90																				
	c	0,30	0,60																							

TABLE A14. FLEXURAL STRENGTHS OF 50 % PERLITE AND 6 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
63	a	0,30	0,70	0,80	6,30	4,20	0,40	0,67	0,90	5,90	4,30	0,20	0,07	0,11	0,07	0,02	0,50	0,30	0,70	0,60	1,00	0,80	6,30	5,50	4,40	4,20
	b	0,40	0,70	1,00	5,50	4,40																				
	c	0,50	0,60																							
64	a	0,60	1,00	1,50	9,30	6,90	0,60	0,97	1,65	8,85	6,85	0,00	0,05	0,09	0,05	0,01	0,60	0,60	1,00	0,90	1,80	1,50	9,30	8,40	6,90	6,80
	b	0,60	1,00	1,80	8,40	6,80																				
	c	0,60	0,90																							
65	a	0,40	0,60	0,70	5,50	5,50	0,43	0,60	0,70	5,05	5,75	0,11	0,00	0,00	0,09	0,04	0,50	0,40	0,60	0,60	0,70	0,70	5,50	4,60	6,00	5,50
	b	0,40	0,60	0,70	4,60	6,00																				
	c	0,50	0,60																							
66	a	0,40	0,50	0,70	6,00	5,00	0,33	0,50	0,70	5,65	6,00	0,14	0,00	0,00	0,06	0,17	0,40	0,30	0,50	0,50	0,70	0,70	6,00	5,30	7,00	5,00
	b	0,30	0,50	0,70	5,30	7,00																				
	c	0,30	0,50																							

TABLE A 15. FLEXURAL STRENGTH OF THERMALLY CURED MORTARS (1)

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T1-1	a	0,60	3,00	4,40	6,20	5,40	0,60	3,20	3,95	6,25	4,25	0,00	0,07	0,63	0,71	0,75	0,60	0,60	3,50	3,00	4,40	3,50	6,30	6,20	6,00	5,40
	b	0,60	3,50	3,50	6,30	6,00																				
	c	0,60	3,10																							
T1-2	a	3,50	4,60	5,40	7,50	5,50	3,90	4,90	5,25	7,25	0,20	0,08	0,06	0,03	0,03	0,04	4,20	3,50	5,30	4,60	5,40	5,10	7,50	7,00	5,50	5,10
	b	4,20	5,30	5,10	7,00	5,10																				
	c	4,00	4,80																							
T1-3	a	2,20	3,10	4,20	6,50	6,90	2,27	3,10	4,30	7,10	0,40	0,02	0,05	0,02	0,08	0,06	2,30	2,20	3,30	2,90	4,40	4,20	7,70	6,50	6,90	6,10
	b	2,30	3,30	4,40	7,70	6,10																				
	c	2,30	2,90																							
T1-4	a	2,30	2,80	4,50	7,00	6,60	2,40	2,93	4,30	6,95	0,80	0,03	0,06	0,05	0,01	0,14	2,50	2,30	3,20	2,80	4,50	4,10	7,00	6,90	6,60	5,00
	b	2,50	3,20	4,10	6,90	5,00																				
	c	2,40	2,80																							

TABLE A 16. FLEXURAL STRENGTH OF THERMALLY CURED MORTARS (2)

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T2-1	a	2,80	3,70	4,90	7,70	3,80	2,80	3,70	5,20	7,55	0,80	0,03	0,04	0,06	0,02	0,17	2,90	2,70	3,90	3,50	5,50	4,90	7,70	7,40	5,40	3,80
	b	2,90	3,50	5,50	7,40	5,40																				
	c	2,70	3,90																							
T2-2	a	6,40	7,40	6,80	8,10	4,90	6,17	6,53	6,95	7,45	0,30	0,07	0,10	0,02	0,09	0,07	6,50	5,60	7,40	5,90	7,10	6,80	8,10	6,80	4,90	4,30
	b	5,60	5,90	7,10	6,80	4,30																				
	c	6,50	6,30																							
T2-3	a	2,80	3,70	5,80	8,20	5,80	2,83	4,50	5,65	8,60	0,65	0,04	0,13	0,03	0,05	0,13	3,00	2,70	5,10	3,70	5,80	5,50	9,00	8,20	5,80	4,50
	b	2,70	5,10	5,50	9,00	4,50																				
	c	3,00	4,70																							
T2-4	a	2,90	3,40	5,10	7,50	4,60	2,80	3,63	5,25	8,00	0,35	0,03	0,05	0,03	0,06	0,08	2,90	2,70	3,80	3,40	5,40	5,10	8,50	7,50	4,60	3,90
	b	2,70	3,80	5,40	8,50	3,90																				
	c	2,80	3,70																							

TABLE A 17. FLEXURAL STRENGTH OF THERMALLY CURED MORTARS (3)

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T 3-1	a	2,30	3,40	5,40	6,70	5,00	2,30	3,53	5,35	7,30	0,15	0,04	0,10	0,01	0,08	0,03	2,40	2,20	4,00	3,20	5,40	5,30	7,90	6,70	5,30	5,00
	b	2,40	3,20	5,30	7,90	5,30																				
	c	2,20	4,00																							
T 3-2	a	3,60	3,50	4,70	6,10	3,80	3,53	4,30	4,60	6,15	0,25	0,05	0,16	0,02	0,01	0,07	3,70	3,30	5,20	3,50	4,70	4,50	6,20	6,10	3,80	3,30
	b	3,30	5,20	4,50	6,20	3,30																				
	c	3,70	4,20																							
T 3-3	a	2,10	3,30	4,10	5,20	5,20	2,17	3,60	4,50	5,40	0,45	0,08	0,06	0,09	0,04	0,09	2,40	2,00	3,80	3,30	4,90	4,10	5,60	5,20	5,20	4,30
	b	2,40	3,70	4,90	5,60	4,30																				
	c	2,00	3,80																							
T 3-4	a	2,10	3,70	3,60	8,20	5,30	2,37	3,07	4,25	7,50	0,50	0,09	0,16	0,15	0,09	0,10	2,60	2,10	3,70	2,50	4,90	3,60	8,20	6,80	5,30	4,30
	b	2,60	3,00	4,90	6,80	4,30																				
	c	2,40	2,50																							

TABLE A 18. FLEXURAL STRENGTH OF THERMALLY CURED MORTARS (4)

SAMPLE	SPECIMENS	FLEXURAL STRENGTHS (MPa)					AVERAGE FLEXURAL STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T4-1	a	1,10	2,50	3,60	5,20	5,20	1,17	2,40	3,50	5,05	0,05	0,04	0,03	0,03	0,03	0,01	1,20	1,10	2,50	2,30	3,60	3,40	5,20	4,90	5,30	5,20
	b	1,20	2,40	3,40	4,90	5,30																				
	c	1,20	2,30																							
T4-2	a	3,30	4,40	5,10	6,70	6,70	3,43	4,40	5,15	6,45	0,25	0,04	0,02	0,01	0,04	0,04	3,60	3,30	4,50	4,30	5,20	5,10	6,70	6,20	6,70	6,20
	b	3,60	4,30	5,20	6,20	6,20																				
	c	3,40	4,50																							
T4-3	a	2,20	2,20	3,90	3,90	6,80	1,60	2,43	3,65	5,40	1,20	0,44	0,07	0,07	0,28	0,21	2,20	0,60	2,60	2,20	3,90	3,40	6,90	3,90	6,80	4,40
	b	2,00	2,60	3,40	6,90	4,40																				
	c	0,60	2,50																							
T4-4	a	2,20	2,80	4,40	5,80	6,00	2,20	2,73	4,30	5,90	0,05	0,07	0,03	0,02	0,02	0,01	2,40	2,00	2,80	2,60	4,40	4,20	6,00	5,80	6,10	6,00
	b	2,40	2,60	4,20	6,00	6,10																				
	c	2,00	2,80																							
T5	a	2,30	2,20	2,60	3,30	3,00	2,27	2,33	2,55	3,65	0,25	0,06	0,04	0,02	0,10	0,08	2,40	2,10	2,40	2,20	2,60	2,50	4,00	3,30	3,50	3,00
	b	2,10	2,40	2,50	4,00	3,50																				
	c	2,40	2,40																							

TABLE A19. COMPRESSIVE STRENGTHS OF 25 % PERLITE AND 2 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
CONTROL	a	14,20	25,90	36,60	46,70	54,20	13,43	24,50	34,53	44,93	51,81	0,06	0,05	0,14	0,04	0,04	14,50	12,20	26,00	22,70	41,00	28,70	47,00	43,00	54,20	49,30
		14,10	26,00	41,00	47,00	52,82																				
	b	14,50	24,10	28,70	43,00	49,30																				
		12,80	22,70	31,80	43,00	50,92																				
	c	12,80	23,80																							
		12,20	24,50																							
11	a	10,10	22,60	31,90	42,30	57,20	8,77	23,12	31,70	42,88	55,00	0,12	0,06	0,02	0,03	0,03	10,30	7,50	25,20	21,50	32,60	30,80	44,30	41,30	57,20	52,70
		10,30	21,50	32,60	44,30	54,60																				
	b	8,60	23,00	31,50	41,30	52,70																				
		8,50	21,70	30,80	43,60	55,50																				
	c	7,50	25,20																							
		7,60	24,70																							
12	a	7,30	12,70	15,70	23,70	28,30	7,42	12,60	14,55	24,20	29,38	0,06	0,01	0,08	0,01	0,02	8,00	6,70	12,70	12,40	15,80	13,20	24,60	23,70	30,20	28,30
		7,50	12,60	15,80	24,20	29,20																				
	b	8,00	12,40	13,50	24,60	29,80																				
		7,90	12,50	13,20	24,30	30,20																				
	c	6,70	12,70																							
		7,10	12,70																							
13	a	5,70	17,10	26,10	41,10	47,90	6,47	19,65	28,18	41,73	47,18	0,10	0,11	0,07	0,02	0,02	7,20	5,60	22,00	16,50	30,70	26,10	42,90	41,10	48,00	46,10
		5,60	16,50	26,10	41,60	46,70																				
	b	6,50	20,10	30,70	42,90	46,10																				
		6,80	20,40	29,80	41,30	48,00																				
	c	7,00	22,00																							
		7,20	21,80																							
14	a	13,30	23,90	31,40	40,10	49,10	12,63	25,23	31,80	39,30	47,60	0,03	0,04	0,02	0,02	0,02	13,30	12,10	26,30	23,60	32,80	31,10	40,10	37,90	49,10	46,90
		12,90	23,60	31,10	39,90	47,10																				
	b	12,10	26,20	31,90	37,90	46,90																				
		12,40	25,50	32,80	39,30	47,30																				
	c	12,60	25,90																							
		12,50	26,30																							
15	a	11,30	28,80	37,60	56,90	55,70	12,27	29,73	35,98	57,10	58,63	0,06	0,02	0,03	0,01	0,05	13,10	11,20	30,60	28,80	37,60	34,80	58,20	56,10	62,10	55,70
		11,20	29,10	36,40	57,20	62,10																				
	b	12,50	30,60	34,80	56,10	58,10																				
		12,50	29,70	35,10	58,20																					
	c	13,10	29,80																							
		13,00	30,40																							
16	a	5,10	23,30	32,00	52,50	50,50	5,80	24,55	33,55	52,90	55,83	0,12	0,05	0,07	0,01	0,07	6,40	4,70	26,60	22,90	36,90	31,10	53,80	52,00	59,80	50,50
		4,70	22,90	31,10	53,30	59,80																				
	b	5,90	25,70	34,20	53,80	57,20																				
		6,30	24,70	36,90	52,00																					
	c	6,40	24,10																							
		6,40	26,60																							

TABLE A20. COMPRESSIVE STRENGTHS OF 25 % PERLITE AND 4 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
22	a	4,70	7,50	9,53	16,80	23,20	4,62	7,05	10,12	16,68	22,83	0,02	0,14	0,04	0,01	0,02	4,70	4,50	7,90	5,00	10,78	9,53	16,80	16,40	23,20	22,30
		4,60	7,00	10,78	16,40	23,00																				
	b	4,70	5,00	10,15	16,80	22,30																				
		4,70	7,40	10,00	16,70																					
	c	4,50	7,50																							
		4,50	7,90																							
23	a	7,10	19,70	24,70	26,70	38,40	6,87	18,45	23,88	32,55	39,20	0,05	0,05	0,03	0,11	0,02	7,50	6,40	19,70	16,70	24,70	22,90	36,20	26,70	40,00	38,40
		6,70	18,90	22,90	36,20	40,00																				
	b	7,50	16,70	24,10	33,40	39,20																				
		6,90	18,10	23,80	33,90																					
	c	6,40	18,80																							
		6,60	18,50																							
24	a	12,00	24,00	28,20	34,90	46,70	13,20	22,43	27,80	35,78	45,93	0,07	0,05	0,04	0,03	0,01	14,90	12,00	24,00	20,70	29,30	26,00	37,50	34,50	46,70	45,40
		12,30	22,90	29,30	34,50	45,70																				
	b	14,90	20,70	27,70	36,20	45,40																				
		13,70	21,00	26,00	37,50																					
	c	13,20	22,60																							
		13,10	23,40																							
25	a	9,40	18,00	24,80	38,90	51,90	8,72	17,23	25,50	40,48	51,85	0,05	0,06	0,06	0,03	0,01	9,40	8,30	18,30	15,60	27,60	23,40	42,50	38,90	52,70	51,00
		8,40	17,60	23,40	39,90	52,70																				
	b	8,30	17,80	26,20	40,60	51,80																				
		8,60	18,30	27,60	42,50	51,00																				
	c	9,10	16,10																							
		8,50	15,60																							
26	a	6,30	18,40	30,00	47,70	60,40	6,90	18,62	30,60	48,45	60,83	0,08	0,05	0,05	0,04	0,04	7,70	6,30	20,20	17,40	32,80	29,00	51,90	46,50	64,00	58,10
		6,70	17,40	32,80	51,90	64,00																				
	b	6,40	19,60	29,00	47,70	58,10																				
		6,80	20,20	30,60	46,50																					
	c	7,50	17,90																							
		7,70	18,20																							
32	a	4,30	5,60	8,00	13,30	17,80	4,30	5,70	7,28	13,95	19,13	0,02	0,11	0,14	0,05	0,05	4,40	4,10	6,20	4,40	8,10	5,50	14,90	13,20	20,00	17,80
		4,30	4,40	5,50	14,90	20,00																				
	b	4,10	6,00	8,10	14,40	19,60																				
		4,40	6,20	7,50	13,20																					
	c	4,30	6,20																							
		4,40	5,80																							

TABLE A21. COMPRESSIVE STRENGTHS OF 25 % PERLITE AND 6 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
33	a	8,90	16,60	24,70	31,90	44,50	8,42	16,75	23,05	32,70	44,77	0,15	0,06	0,05	0,03	0,04	9,70	6,60	18,50	15,70	24,70	21,70	33,80	31,70	47,00	42,80
		8,90	16,10	23,80	31,70	47,00																				
	b	6,60	15,70	22,00	33,40	42,80																				
		6,80	15,90	21,70	33,80																					
	c	9,70	18,50																							
		9,60	17,70																							
34	a	11,80	21,10	29,90	37,40	47,90	11,65	22,48	29,25	37,30	49,00	0,04	0,04	0,02	0,02	0,02	12,40	10,90	23,50	21,10	29,90	28,10	38,40	36,40	50,30	47,90
		11,80	21,60	29,40	37,00	50,30																				
	b	11,50	22,60	28,10	36,40	48,80																				
		12,40	23,10	29,60	38,40																					
	c	11,50	23,00																							
		10,90	23,50																							
35	a	6,70	17,10	23,10	40,60	50,20	6,78	14,92	23,30	43,38	50,90	0,01	0,07	0,01	0,05	0,02	6,90	6,70	17,10	13,80	23,80	23,10	45,80	40,60	52,10	50,20
		6,90	14,90	23,80	42,50	52,10																				
	b	6,90	14,60	23,10	45,80	50,40																				
		6,70	14,00	23,20	44,60																					
	c	6,80	13,80																							
		6,70	15,10																							
36	a	4,21	13,60	22,50	48,10	50,40	4,03	13,08	22,63	44,88	49,30	0,04	0,02	0,01	0,06	0,02	4,21	3,75	13,60	12,70	23,10	22,30	48,10	41,80	50,40	48,40
		3,75	13,10	22,30	43,20	49,10																				
	b	4,10	12,70	23,10	41,80	48,40																				
		4,10	12,90	22,60	46,40																					
	c	4,10	13,30																							
		3,90	12,90																							

TABLE A22. COMPRESSIVE STRENGTHS OF 50 % PERLITE AND 2 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
41	a	6,80	15,40	17,50	29,70	39,30	6,62	15,58	18,68	30,45	38,90	0,03	0,01	0,07	0,02	0,02	6,90	6,40	15,80	15,40	20,30	17,40	31,30	29,70	39,40	38,00
		6,90	15,80	17,40	29,80	39,40																				
	b	6,40	15,40	19,50	31,30	38,00																				
		6,60	15,80	20,30	31,00																					
	c	6,40	15,50																							
		6,60	15,60																							
43	a	4,70	14,50	15,50	32,20	37,70	4,52	13,80	16,58	31,53	37,97	0,03	0,04	0,04	0,02	0,02	4,70	4,30	14,50	12,60	17,30	15,50	32,20	30,50	38,80	37,40
		4,50	14,10	16,30	32,10	38,80																				
	b	4,60	13,70	17,20	30,50	37,40																				
		4,60	13,90	17,30	31,30																					
	c	4,40	12,60																							
		4,30	14,00																							
44	a	7,10	15,90	19,10	31,90	40,30	7,08	15,88	19,90	31,83	39,10	0,04	0,03	0,03	0,02	0,02	7,40	6,50	16,60	15,20	20,60	19,10	32,30	30,90	40,30	38,50
		7,20	16,30	19,40	30,90	38,50																				
	b	6,50	15,60	20,60	32,20	38,50																				
		7,20	15,20	20,50	32,30																					
	c	7,10	16,60																							
		7,40	15,70																							
45	a	5,90	12,90	19,20	33,60	43,40	5,90	12,75	18,38	33,15	43,07	0,01	0,03	0,03	0,04	0,01	6,00	5,80	13,10	12,30	19,20	17,70	35,00	31,60	43,40	42,50
		6,00	13,10	18,60	35,00	42,50																				
	b	5,90	13,00	17,70	32,40	43,30																				
		5,90	12,30	18,00	31,60																					
	c	5,80	12,90																							
		5,90	12,30																							
46	a	4,30	11,80	17,60	33,40	42,20	4,28	11,60	18,40	34,05	43,37	0,02	0,03	0,04	0,02	0,02	4,40	4,20	12,00	11,00	19,40	17,60	34,90	33,40	44,60	42,20
		4,30	11,90	18,40	34,10	43,30																				
	b	4,30	11,00	18,20	34,90	44,60																				
		4,20	11,30	19,40	33,80																					
	c	4,40	12,00																							
		4,20	11,60																							

TABLE A23. COMPRESSIVE STRENGTHS OF 50 % PERLITE AND 4 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
53	a	5,60	11,70	13,60	25,10	34,90	5,50	11,95	14,08	25,18	33,53	0,05	0,02	0,02	0,02	0,03	6,00	5,20	12,30	11,70	14,30	13,60	25,80	24,70	34,90	32,50
		5,50	12,30	14,30	25,10	32,50																				
	b	5,30	11,70	14,30	25,80	33,20																				
		5,40	12,00	14,10	24,70																					
	c	5,20	12,00																							
		6,00	12,00																							
54	a	10,20	15,60	22,30	34,30	42,30	9,72	15,02	22,43	35,08	42,60	0,03	0,03	0,01	0,04	0,02	10,20	9,20	15,60	14,30	22,80	22,10	37,30	33,20	43,80	41,70
		9,50	14,70	22,80	35,50	43,80																				
	b	9,80	15,30	22,10	37,30	41,70																				
		9,80	14,60	22,50	33,20																					
	c	9,80	15,60																							
		9,20	14,30																							
55	a	5,70	8,60	13,00	27,10	39,10	5,42	8,65	13,08	28,55	38,97	0,03	0,03	0,01	0,03	0,01	5,70	5,20	8,90	8,10	13,40	12,90	29,60	27,10	39,60	38,20
		5,40	8,60	13,00	28,90	38,20																				
	b	5,30	8,80	13,40	29,60	39,60																				
		5,40	8,10	12,90	28,60																					
	c	5,50	8,90																							
		5,20	8,90																							
56	a	3,70	9,50	13,00	31,00	21,90	3,62	9,20	12,95	29,65	34,43	0,03	0,03	0,05	0,04	0,26	3,70	3,40	9,50	8,80	13,60	11,80	31,00	27,90	41,10	21,90
		3,40	9,40	11,80	29,90	40,30																				
	b	3,70	9,10	13,40	29,80	41,10																				
		3,60	9,50	13,60	27,90																					
	c	3,70	8,80																							
		3,60	8,90																							

TABLE A24. COMPRESSIVE STRENGTHS OF 50 % PERLITE AND 4 % ACTIVATOR CONTAINING SAMPLES

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					AVERAGE COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
63	a	6,10	11,10	13,70	25,00	32,00	5,87	10,28	14,60	26,45	31,33	0,04	0,10	0,06	0,13	0,03	6,10	5,40	11,40	8,90	15,50	13,70	32,20	23,80	32,00	30,00
		5,90	11,20	13,80	23,80	30,00																				
	b	6,00	8,90	15,50	24,80	32,00																				
		5,40	9,90	15,40	32,20																					
	c	5,80	11,40																							
		6,00	9,20																							
64	a	8,40	11,70	20,90	33,10	43,40	8,47	13,35	21,35	32,23	42,97	0,02	0,07	0,03	0,05	0,02	8,70	8,10	14,30	11,70	22,20	20,80	34,10	29,70	44,00	41,50
		8,10	14,10	22,20	34,10	41,50																				
	b	8,70	12,90	20,80	32,00	44,00																				
		8,60	13,00	21,50	29,70																					
	c	8,40	14,10																							
		8,60	14,30																							
65	a	5,10	9,10	12,60	29,50	39,50	5,20	8,88	12,95	29,45	39,10	0,04	0,03	0,02	0,00	0,58	5,50	4,90	9,20	8,40	13,40	12,60	29,50	29,30	39,50	38,70
		4,90	9,20	13,40	29,50	38,70																				
	b	5,30	8,80	12,70	29,50																					
		5,00	8,80	13,10	29,30																					
	c	5,40	9,00																							
		5,50	8,40																							
66	a	3,30	7,30	10,90	24,50	36,40	3,43	7,37	10,80	23,10	35,87	0,02	0,04	0,03	0,08	0,01	3,50	3,30	7,90	7,10	11,10	10,30	24,90	20,30	36,40	35,50
		3,40	7,10	10,30	24,90	35,70																				
	b	3,50	7,20	10,90	20,30	35,50																				
		3,50	7,20	11,10	22,70																					
	c	3,50	7,50																							
		3,40	7,90																							

TABLE A 25. COMPRESSIVE STRENGTH OF THERMALLY CURED MORTARS (1)

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T 1-1	a	10,60	13,90	18,70	30,60	40,50	0,06	0,04	0,03	0,04	0,03	10,90	9,10	14,10	12,32	18,80	17,50	30,60	27,40	42,60	39,80
		10,40	13,80	18,80	29,20	42,60															
	b	10,90	14,10	17,60	29,00	39,80															
		9,60	13,10	17,50	27,40																
	c	9,10	12,32																		
		10,10	13,60																		
T 1-2	a	14,10	16,70	25,20	35,90	29,38	0,17	0,11	0,07	0,04	1,00	21,00	13,20	21,00	16,10	27,00	22,50	35,90	32,40	29,38	0,00
		13,20	16,70	27,00	32,40	0,00															
	b	17,70	20,80	22,50	33,70																
		17,90	21,00	23,90	32,80																
	c	21,00	17,40																		
		20,70	16,10																		
T 1-3	a	6,60	13,90	18,30	29,50	47,18	0,07	0,08	0,07	0,01	1,00	7,60	6,40	14,40	11,80	21,80	18,30	29,70	28,68	47,18	0,00
		6,90	14,40	20,00	29,70	0,00															
	b	6,40	11,80	21,80	28,68																
		6,60	12,00	21,50	29,70																
	c	7,60	12,00																		
		7,60	12,20																		
T 1-4	a	8,10	12,50	17,60	33,70	47,60	0,07	0,05	0,03	0,05	1,00	9,50	8,10	12,90	11,00	18,80	17,60	34,20	30,40	47,60	0,00
		8,30	11,80	18,80	33,80	0,00															
	b	9,50	12,70	18,10	30,40																
		9,20	12,90	18,60	34,20																
	c	9,50	11,00																		
		9,50	11,80																		

TABLE A 26. COMPRESSIVE STRENGTH OF THERMALLY CURED MORTARS (2)

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T 2-1	a	9,10	12,90	15,80	27,50	58,63	0,07	0,08	0,04	0,01	1,00	10,00	8,30	13,20	10,70	16,20	14,80	28,10	27,10	58,63	0,00
		10,00	13,10	16,20	27,10	0,00															
	b	9,50	13,20	14,80	27,50																
		10,00	13,00	14,80	28,10																
	c	8,40	11,50																		
		8,30	10,70																		
T 2-2	a	18,90	19,40	19,60	24,80	55,83	0,02	0,04	0,08	0,00	1,00	19,10	17,70	19,40	17,40	21,20	17,10	25,10	24,80	55,83	0,00
		18,20	19,40	21,00	24,80	0,00															
	b	19,10	18,20	21,20	25,10																
		18,50	18,20	17,10	24,90																
	c	18,50	18,10																		
		17,70	17,40																		
T 2-3	a	8,20	12,30	20,00	33,70	22,83	0,11	0,08	0,02	0,03	1,00	11,20	8,20	15,30	12,30	20,00	18,90	33,70	31,00	22,83	0,00
		8,70	12,60	19,40	31,00	0,00															
	b	11,20	14,60	19,70	33,70																
		9,60	14,20	18,90	32,20																
	c	10,80	15,30																		
		10,60	14,10																		
T 2-4	a	9,40	9,40	17,60	26,20	39,20	0,08	0,13	0,13	0,07	1,00	10,90	8,60	13,20	9,20	18,50	13,40	31,10	26,20	39,20	0,00
		9,50	10,00	18,50	26,20	0,00															
	b	8,60	11,10	13,40	29,20																
		10,90	9,20	14,40	31,10																
	c	10,00	11,70																		
		10,40	13,20																		

TABLE A 27. COMPRESSIVE STRENGTH OF THERMALLY CURED MORTARS (3)

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T 3-1	a	6,90	13,50	19,00	39,10	45,93	0,03	0,04	0,02	0,11	1,00	7,50	6,90	14,50	12,80	19,10	18,10	40,30	31,80	45,93	0,00
		7,30	13,30	19,10	40,30	0,00															
	b	7,50	12,80	18,50	31,80																
		7,50	14,00	18,10	31,90																
	c	7,10	13,80																		
		7,00	14,50																		
T 3-2	a	14,10	14,00	15,10	24,00	51,85	0,07	0,04	0,05	0,03	1,00	14,10	12,00	15,90	14,00	17,40	15,10	24,00	22,20	51,85	0,00
		13,90	14,10	17,40	22,40	0,00															
	b	12,40	15,90	15,90	22,20																
		12,00	15,20	16,40	23,00																
	c	12,20	15,00																		
		12,00	14,60																		
T 3-3	a	5,30	12,00	15,50	33,20	60,83	0,07	0,07	0,02	0,03	1,00	6,30	5,30	13,90	11,50	16,20	15,50	33,20	30,60	60,83	0,00
		5,30	11,50	15,60	30,60	0,00															
	b	6,20	13,60	16,20	32,80																
		6,30	13,40	15,70	32,50																
	c	5,60	13,40																		
		5,60	13,90																		
T 3-4	a	7,80	14,10	16,50	31,40	19,13	0,06	0,05	0,05	0,06	1,00	8,80	7,50	14,40	12,40	18,10	16,00	31,40	27,30	19,13	0,00
		7,50	14,40	16,00	30,60	0,00															
	b	8,80	13,70	18,00	27,70																
		8,70	13,40	18,10	27,30																
	c	7,80	12,70																		
		7,60	12,40																		

TABLE A 28. COMPRESSIVE STRENGTH OF THERMALLY CURED MORTARS (4)

SAMPLE	SPECIMENS	COMPRESSIVE STRENGTHS (MPa)					VARIANCE					1-d		3-d		7-d		28-d		56-d	
		1-d	3-d	7-d	28-d	56-d	1-d	3-d	7-d	28-d	56-d	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
T 4-1	a	4,50	8,10	13,00	16,80	44,77	0,11	0,06	0,22	0,10	1,00	4,70	3,40	9,00	7,70	13,00	7,10	21,60	16,80	44,77	0,00
		4,70	9,00	12,80	21,30	0,00															
	b	4,40	8,00	7,10	18,40																
		4,70	8,90	10,00	21,60																
	c	3,80	7,70																		
		3,40	8,40																		
T 4-2	a	15,30	18,70	23,80	35,10	49,00	0,08	0,07	0,04	0,06	1,00	16,90	13,50	20,60	17,00	23,80	21,20	36,10	31,00	49,00	0,00
		14,10	19,90	23,00	31,00	0,00															
	b	15,30	20,60	22,00	36,10																
		16,90	18,40	21,20	32,70																
	c	13,70	17,00																		
		13,50	17,40																		
T 4-3	a	3,30	9,40	18,00	35,20	50,90	0,14	0,05	0,09	0,04	1,00	3,40	2,40	10,70	9,40	18,00	14,60	35,20	32,10	50,90	0,00
		3,10	9,80	17,30	32,10	0,00															
	b	2,40	10,60	14,70	34,70																
		2,40	10,70	14,60																	
	c	3,40	10,60																		
		3,10	9,80																		
T 4-4	a	6,50	11,80	20,70	31,10	49,30	0,12	0,05	0,08	0,03	1,00	8,90	6,50	13,00	11,00	20,70	16,70	33,40	31,10	49,30	0,00
		6,60	11,70	19,10	31,20	0,00															
	b	8,40	11,60	17,60	33,40																
		8,60	11,00	16,70																	
	c	8,60	13,00																		
		8,90	12,40																		
T5	a	6,90	5,70	7,20	11,70	38,90	0,04	0,08	0,03	0,01	1,00	7,00	6,20	7,20	5,70	7,20	6,70	11,90	11,60	38,90	0,00
		6,30	6,00	6,90	11,90	0,00															
	b	6,60	7,20	6,70	11,60																
		6,20	6,90	6,70																	
	c	7,00	6,80																		
		6,60	6,80																		