THE RESISTANCE OF CONCRETE
TO HIGH TEMPERATURES
AND REFRACTORY CONCRETES

by

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ABSTRACT

The properties of concrete interrelated with the resistance to fire and high temperatures are investigated for the preparation as well as the experimental evaluation of refractory concretes with correlation to the theoretical basis. Plain and special concretes prepared with shamotte, silica powder and crushed firebrick are exposed to high temperatures and their compressive strengths are determined after cooling. The cost analysis of the samples is included to investigate the economic aspects and the possibilities of industrial application.

CHAPTER 1

INTRODUCTION

Concrete, as one of the major construction materials has many properties which determine the efficiency and standard of behavior of the structural elements designed for the intended functions.

The properties of concrete related to elevated temperatures become important in certain fields of application and during certain phases of common constructions. Most concrete is subjected to high temperatures within the range of variation of weather conditions. The important exceptions are construction fires, which as a threatening possibility need close consideration, jet air blast and some applications in industry where concrete is a primary or secondary material in chimney, furnace and reactor units (1). Other cases of exposure to high temperatures are radiation, contact of hot coils and by use of solid propellants and oxygen lance for cutting through concrete (2).

Concrete is incombustible and has some heat-resistant properties but its loss of strength at elevated temperatures (due to shrinkage and expansion by heat and dehydration of $Ca(OH)_2$, thermal incompatibility of aggregate and cement, and other disintegrating factors) is one of the problems in structures. Consequently the study and preparation of special heat-resistant concrete is a major objective.

In studying and testing the properties of concrete at high temperatures, interpretation of definitions and meaning of related terms is essential. Fire resistance is defined by ASTM Tentative Definitions of Terms relating to Fire Tests of Building Construction and Materials (E176-64T) as follows:

> The property of material or assembly to withstand fire or to give protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a structural function or both (3:292).

The British standard Definition for Fire Resistance is applicable only to structural elements, instead of the material which forms it. In connection with concrete, the term implies only the relative comparison of different concretes used in structural units for giving good fire resistant properties (4:569).

The fire reistance of structural elements is measured by the length of time they continue to perform their functions and retain their structural integrity, when exposed to fire. The primary objectives of work in this field has been to classify fire resistance of walls, columns, ceilings and partitions for fire-ratings. To achieve this, primary consideration has been given to design tests to provide the necessary theoretical and experimental background and to reproduce the actual behavior of structures under field stress, strain, buckling, and heat transmission conditions.

It is as long as 1923 that the effects of construction fires were last discussed at an A.C.I. meeting (5). A study by Portland Cement Assn. indicated the influence of type of aggregate (3:293). Determinations of weight loss, linear expansion and dynamic modulus of elasticity were made in connection with an investigation of the fire resistance of concrete conducted at the Portland Cement Association Research and Development Laboratories in 1957 (1).

Menzel's extensive study on concrete slabs (2) covered the effects of bond between aggregate and cement paste, spalling and shattering, fusion, change of shape and cracking. Tests have been conducted to investigate the effect of high temperatures on the compressive strength of concrete. Lea and Stradling studied the resistance to fire and the development of fire-resistant concrete (6). Cubes heated to 200°C were tested for compressive strength after cooling. A rapid strength loss increasing to a reduction of 40% at 650°C was observed. Lea, in the second set of experiments observed a strength loss of 50% at 550°C and 80% at 690°C.

Grun and Beckman's tests on mortar blocks made with Portland cement and quartz sand indicated a strength reduction of 18% at 300°C and 42% at 500°C (6).

More recently the Japanese Building Research Institute tested compressive strength after heating to 450°C and 600°C, measuring 50% and 72% reduction in strength respectively (6).

Such a study by Malhotra (6) lead to denote the effects of Water-Cement ratio, the aggregate cement ratio, presence of design stress, and reduction in residual strength. Peter Smith worked on compressive strength, modulus of elasticity, spalling, cracking, volume change and other properties of concrete and steel (5).

Carlson's report (8) on the effect of moisture, the size of specimen, conditions of restraint, Benjamins report (8) on fire resistance of reinforced concrete, Troxell's discussion on prestressed concrete (9) are noted studies.

Nekrassov's (10), Petzold and Rohm's (11), and Branister's studies (12) on behavior of cement and aggregate when exposed to elevated temperatures and on types of special heat resistant concrete made with portland and aluminious cement, slag, fire brick and light aggregates compromise the studies specially carried out in Russia, in the related subjects and tests.

The object of the thesis work is to study the properties of concrete which affect its performance as a structural or protective unit when exposed to fires or high temperatures. The effects of cements, aggregates, mix characteristics and time-temperature relationships are investigated for the analysis of change in properties such as compressive strength, modulus of elasticity, dilatometric and thermo-gravimetric relations. The theoretical basis is correlated with the preparation and experimental evaluation of refractory concretes.

Plain concrete and special refractory concrete samples prepared with shamotte, silica powder and crushed fire brick are exposed to high temperatures attained according to a specific time-temperature relationship, and their compressive strengths are tested after cooling. The index values based on cost-strength ratio of plain concrete are determined to compare the strength losses and costs for the investigation of the economic and industrial aspects as well as the structural requirements.

CHAPTER II

THEORY

The evaluation of the resistance to high temperature requires the consideration of every property of concrete other than that of the concrete's resistance to freezing and thawing. These factors include the type and quality of ingredients, mix design, volume and weight change, extent of curing and drying, aggregate-cement compatibility, carbonation, porosity, wetting and drying and modulus of elasticity (2). Consequently, to avoid the complexity, classifications of concrete related to weight, natural or manufactured aggregates, types of hydraulic cement, degree of exposure are considered.

The fire resistance of concrete structures is determined by the following main and general factors (4, 13).

1) The capacity of the concrete to withstand heat and action of water without loosing strength and without cracking or spalling.
2) The conductivity of concrete to heat
3) Heat capacity of the concrete
4) Type and size of aggregate
5) Cement content

A. EFFECT OF CEMENTS:

The basic physical and chemical transformations of cement matrix which is exposed to high temperatures are results of:

1) Dehydration reactions and the consequent volume and weight changes during the process of thermal expansion.

2) Chemical changes in compounds and reactions which are usually irreversible.

Hydrated portland cement which is formed from the tricalcium silicate and beta-dicalcium components of the cement can be idealized as the gel and a mixture of infinite number of hydrates in which water molecules are held by bonds. These bonds have different strengths which vary in infinitesimal steps (14, 15). Some $Ca(OH)_2$ crystals and anhydrous residues of the cement are the remaining components of the paste.

Portland cement when heated, undergoes both expansion and shrinkage, the limit and rate of which may vary. The expansion is thermal while the opposing contraction is due to shrinkage of the paste, as water is driven off in different stages of dehydration. As illustrated by Czernin and others (14, 3, 5) capillary or free water is lost up to 100°C (212°F) by evaporation. Then water which is combined with hydration products is dehydrated at higher temperatures up to 800°C. At 250-350°C, the hydration products containing allumi-num and iron loose their water while between 400-700°C siliceous products are dehydrated of crystal water (15, 16).

The expansion and contraction of concrete follows a general pattern as shown in the experiments reported by Philleo (2, 1). His general conclusions were that weight loss due to loss of water was complete at 800°F and above this temperature coefficient of expansion increased since expansion was no longer inhibited by drying shrinkage up to 1000°F, the rate being about 40×10^{-6} per degree Fahrenheit in temperatures between 500 to 750°F. Lea and Desch conclude that the actual temperature at which the maximum expansion is reached varies with the size of specimen and the conditions of heating, being as high as 300°C for air dry specimens. The contraction from the originaldimension has been reported to amount ultimately to 0.5% or more (4). The mechanisms of the dehydrations and the related reactions lead to cracking and thus to a major drop in strength and integrity of the concrete.

The change in compounds of the hydraulic cement is the second subject of consideration and analysis in the investigation of heat resistance. When the cement paste is heated to 400-450°C (4), the dehydration of $Ca(OH)_2$ takes place which can be observed by the relevant weight loss and shrinkage. At about 1000°F (5, 2) calcium hydroxide is decomposed leaving CaO. If this CaO combines with water by wetting after cooling or through moisture in the air, it rehydrates to calcium hydroxide. The accompanying volume change and a shrinkage of the mass amounting to 2% are the main causes of cracks and loss of strength following decomposition of $Ca(OH)_2$ to CaO, calcination, subsequent rehydration or carbonation. If the temperature is further increased up to 1450°C, the hydration products will form ceramic bonds and the mass will get tougher and more resistant but this phenomena has no practical application due to excessive decrease in volume (16).

Most of the dehydration reactions in the cement paste are irreversible. When a paste is exposed to a certain temperature, it will keep the characteristics attained after cooling until there is exposure to a greater temperature. Therefore selection of cement remains as one of the few alternatives for obtaining a better fire resistant paste. In the related considerations, the amount of calcium hydroxide present becomes the dominant factor and this leads to a preference of portland blast-furnace cement and aluminous cement. The blast-furnace cement in addition to having a low proportion of free calcium hydroxide, is also significant for the combination of free lime with granulated slag at high temperatures. In aluminous cement, even though a drop in strength is observed after the loss of chemically combined water, this decrease in strength does not lead to breakdown of the structures. As explained by Chernin (14), when the temperature is further increased, the hydraulic bonding is replaced by ceramic bonding. The resistance increases if well-burnt crushed clay or fire clay or corrundum is used as aggregate enabling use up to 1600°C (2912°F) in furnaces and kilns.

B. EFFECT OF AGGREGATES:

Type of aggregate used has a definite influence on the heat resistance of concrete due to effects on physical and chemical properties. Thermal diffusivity, conductivity and coefficient of expansion are dependent also on the various types of aggregates. The concrete when exposed to high temperatures is subject to action of two opposing forces since the cement paste after the point of maximum expansion tends to contract due to dehydration while the aggregates expand. These counteracting thermal processes produce large strains.

Aggregates may themselves disrupt due to physical and chemical actions during the period of heating. These include disintegration due to expulsion of free or combined water which is explosive and accompanied by volume change as well as changes in crystal form of minerals present, like decarbonation of lime stones and changes of phase in silica.

There are many classification of aggregates depending on their behavior during heating. In both British and American practice (8:33) classification is made as:

a) Type I (All aggregates having less than 30% free silica)

b) Type II (Includes the balance of aggregates with a reduced fire endurance value)

The Natural Board of Fire Underwriters (8:25) classifies as follows:

Group 1: Blast furnace slag, limestone, calcareous gravel, trap rock, burnt clay or shale, cinders containing not more than 25% of combustible material and not more than 5% of volatile material.

Group 2: Granite, quartz, siliceous gravel, sandstone, gneiss, cinders containing more than 25% but not more than 5% of volatile material and other materials.

Natural aggregates are sometime divided into four groups in regard to their effect upon fire-resistance (13) in descending order of their resistance.

1) Calcareous or lime bearing
2) Feldspathic, basalt, diabase
3) Granites and sandstones
4) Siliceous aggregates, such as quartz, chert and flint

Peter Smith generalizes the types according to decreasing order of heat transmission as concretes made with highly siliceous aggregates, sandstones, traprock, limestone, lightweight aggregates (5).

All the general classifications mentioned above are based on the specific properties and behavior of aggregates at high temperatures. Quartz, the main component of sand, gravel and igneous rocks expand steadily up to 573°C. At this temperature a sudden expansion of 0.85% occurs due to transformation of "low" quartz to "high" quartz. This expansion leads to cracking, spalling and disruption (4). Sandstones do not cause excessive spall even though they contain quartz because the natural cementing intergranular material in sandstones shrinks on heating, thus counteracting the expansion of quartz, but loss of strength is the main disadvantage.

Limestones are among the best natural aggregates. Siliceous aggregates are among the worst because they undergo a change from an alpha to a beta phase at about 1100°C (8) which causes large expansion and consequently spalling. Limestones also expand until a temperature of 900°C is reached, and then begin to contract due to liberation of CO_2 and the decomposition. However, this temperature is greater than the spalling temperatures for quartz aggregates.

Certain artificial aggregates, blast-furnace slag aggregate, haydite, broken brick free from quartz and some lightweight aggregates such as clinker, clay, pumice and expanded clay products are superior to natural aggregates in fire-resistance since their heat conductivity is already lower. Their heat capacity on the other hand is less than that of heavier concretes so it is suggested (3) to use light weight aggregates against heating for short duration whereas aggregates with high thermal conductivity and no crystal water should be used against heat exposure of longer duration.

Peter Smith notes the improvement in performance of the aggregate with smaller size with respect to aggregates of larger size (5).

Tests have shown the effect of aggregate size on the strength and resistance of concrete at high temperatures. With a given cement content, the fire-resistance increased with the increase in the proportion of fine to coarse aggregate in the concrete. For a fineness modulus range from 1.0 to 4.5, the finest grading gave a fire-resistance period which was from 10 to 20% greater than with the coarsest grading (13).

The effect of the thermal properties are illustrated in the figure (8:26).

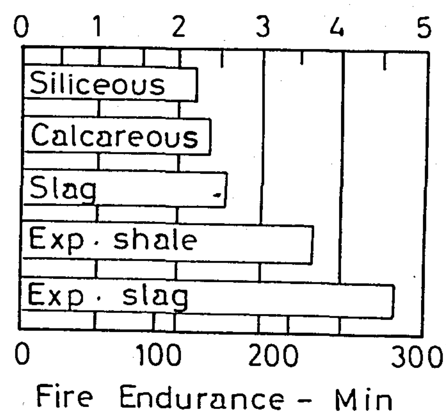

FIGURE 1. FIRE ENDURANCE FOR DIFFERENT AGGREGATES (8:25)

Mathematical analysis of shrinkage stresses in a model of hardened concrete presented by Thomas illustrates the effects of differential volume change due to heat and fire (21). To investigate the internal shrinkage stresses, a model was set up in which the coarse aggregate represented by discs of equal size arranged in a square pattern and the mortar was assumed to be occupying the voids between the discs as shown (21:375) on the top of the following page.

Conway's numerical point matching method was used for stress analysis. Stresses in the are bounded by OA2C were considered. The discs (aggregates) were assumed to be infinitely rigid (E =). Mortar was assumed to be elastic with unit shrinkage and Poisson's ratio of 0.2.

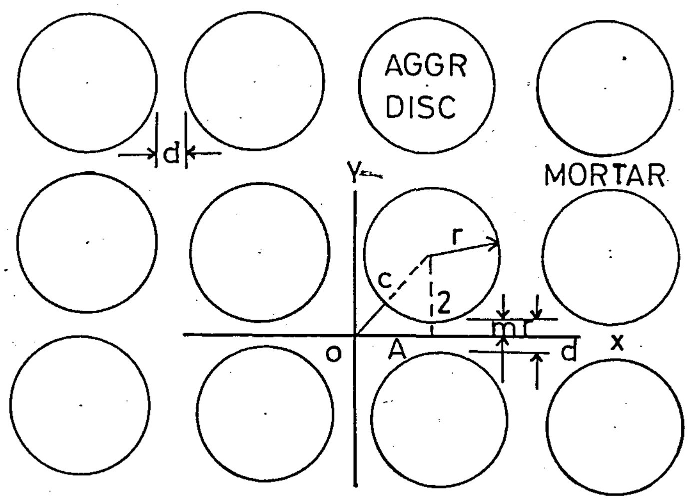

FIGURE 2. TWO DIMENSIONAL MODEL OF CONCRETE SYSTEM (21:375)

To carry out the analysis and to show the magnitude and distribution of stresses at the aggregate interface caused by volume change of mortar, the stress in the mortar is assumed to be constant throughout and equal to:

$$\sigma_1 = \frac{E\,\epsilon}{1-\nu} \tag{1}$$

where is the known free shrinkage strain of the mortar, its modulus of elasticity and its Poisson's ratio. Since the sum of the vertical stresses on the face O to A must be zero,

$$\int_0^A \sigma_2\, y\, dx + \sigma_1\,(1+m)\,r = 0 \tag{2}$$

Then the final stress at each point becomes

$$\sigma_F(x\,y) = \sigma_1 + \sigma_2(x,y)$$

Then σ_2 is determined by assuming a stress function F which must satisfy the plane stress compatibility equation:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)F = 0 \qquad (3)$$

Then

$$\sigma_x = \frac{\partial^2 F}{\partial y^2}$$

$$\sigma_y = \frac{\partial^2 F}{\partial x^2}$$

$$\tau_{xy} = \frac{\partial^2 F}{\partial x \partial y}$$

By expressing the displacements and boundary conditions, the unknowns and the constants were solved by electronic digital computer.

The numerical analysis showed that large tensile stresses exist at the aggregate mortar interface when the distance between aggregate is less than about 0.2 times the aggregate radius as shown :

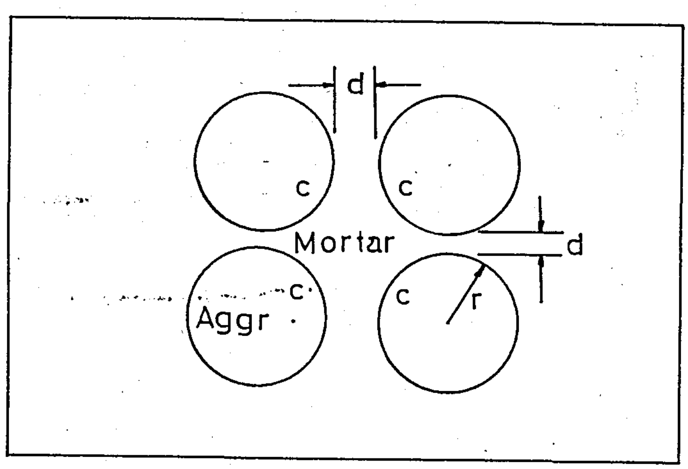

FIGURE 3

Since during exposure to high temperature, the cement paste shrinks after a certain maximum expansion point while the aggregate expands, bond cracks occur with simultaneous mortar cracks. Hsu's analysis also predicts poor fire-resistance performance as the

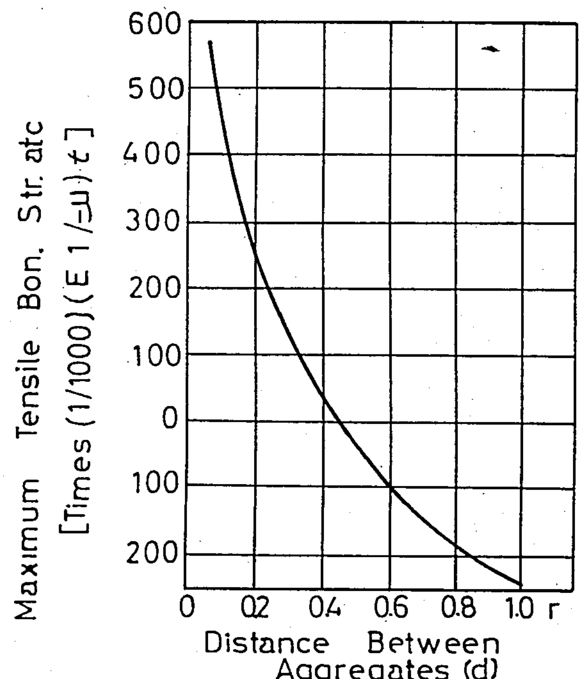

FIGURE 4. VARIATION OF STRESS
WITH DISTANCE BETWEEN AGGREGATE

maximum aggregate size is increased since the increased interface may lead to concentrated shrinkage stresses.

C. CONCRETE MIX:

The effect of the temperature on the reduction in strength during exposure of concrete to high temperature is independent of the water-cement ratio within the normal ranges (6).

The aggregate cement ratio has a significant effect on the strength and fire-resistance of concrete. The strength loss in inversely proportional to the cement quantity, the proportional reduction being smaller for lean mixtures than for rich ones. This may be attributed to the fact that in leaner mixtures, there is less internal stresses developed by expansion of the aggregate, counter-acting the shrinkage of the cement paste. Curing has practically no affect on fire-resistance even though control of the ambient temperature and humidity of the concrete after curing may give better results (ASTM Standards).

D. PHYSICAL PROPERTIES OF CONCRETE AT HIGH TEMPERATURES:

a) Compressive strength:

When concrete is exposed to high temperatures there is a reduction in strength due to:

1. Loss of strength of mortar
2. Incompatibility of aggregate and cement paste
3. Formation of bond and mortar cracks
4. Dehydration of calcium hydrate

The amount of reduction depends on the temperature reached, time-temperature relationships, physical properties of aggregate and cement paste.

Tests have shown that there is little loss of strength up to 300°C. At a temperature about 600°C a serious reduction takes place which is in the order of 25, 50, and 80% after heating siliceous gravel aggregate to 350 , 700 and 1050°C respectively and testing after cooling (5). Grun found that mortars suffered little loss in strength when heated for ten hours at 300°C but at 500°C there was a loss of about half of the original strength (4). Experiments by Lea and Stradling (6) indicated no loss of strength up to 540°C and then a rapid drop in strength amounting to 40% at 650°C (4). In the preliminary tests by the Building Research Station, no significant loss of strength was observed up to a temperature of 300°C (4).

Tests reported by Malhotra (6), on the crushing strength of concrete at various temperatures in the hot state took into account the mix proportions, water-cement ratio and the type of the aggregate. The testing conditions were:

1. Concrete specimens heated to a specific temperature and tested in the hot state
2. Specimens heated under a constant stress and tested in the hot state
3. Specimens tested to find the residual strength after cooling.

Malhotra's conclusions were:

1. The water-cement ratio within the normal range does not affect the strength of concrete at high temperatures.
2. The aggregate cement ratio influences the strength, the reduction in lean mixtures being smaller than for rich ones.
3. Concrete under a compressive stress of the order of its design stress has a smaller proportional decrease in strength than if the stress were absent.
4. The residual strength of heated concrete shows further reduction in strength on cooling, being approximately 20% less than the corresponding hot strength in the temperature range 200 to 450°C for 1:4.5 and 1:6 mix concrete.

b) Thermal Expansion:

During heating the shrinkage and expansion of cement paste is not uniform and additive, so the coefficient of expansion varies depending on the properties of aggregate and cement paste as well as

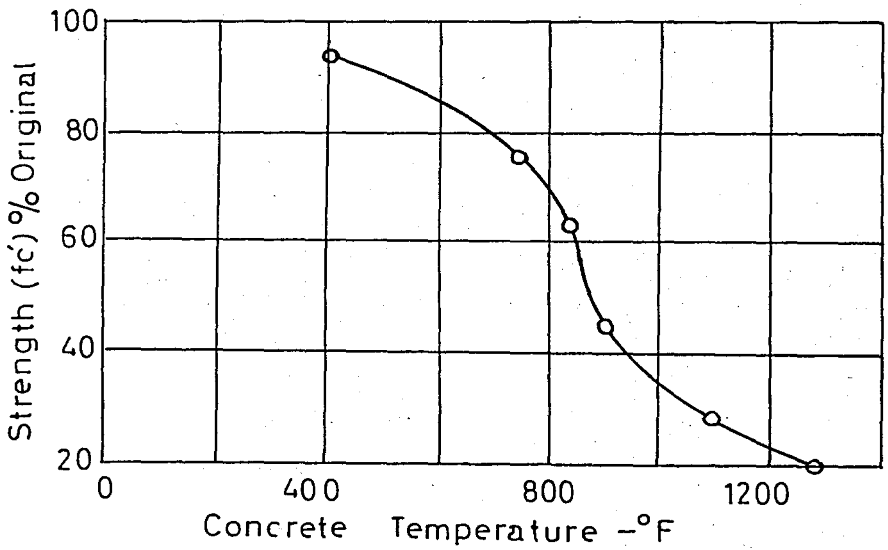

FIGURE 5. EFFECT OF TEMP. ON COMPRESSIVE STRENGTH (8:28)

concrete mix and rate of heating. Tests done by Philleo (1) as represented by the graphs (Fig.6) plotted two linear coefficient of expansion represented by the slope of two straight lines with a short transition section between them. The slope of the first gives the linear coefficient of expansion below about 500°F, and the slope of the second gives the coefficient above 800°F. Coefficient of expansion is not counteracted by shrinkage after drying is nearly complete.

Length change of concrete is also a basis for determining the temperature history of concrete following exposure to heat. Linear expansion is determined by dilatometric tests. Such tests carried out by Harmathy (15) gave the dilatometric curves in which the temperature at which a definite sagging is first observed can be taken as the estimated temperature of previous heating.

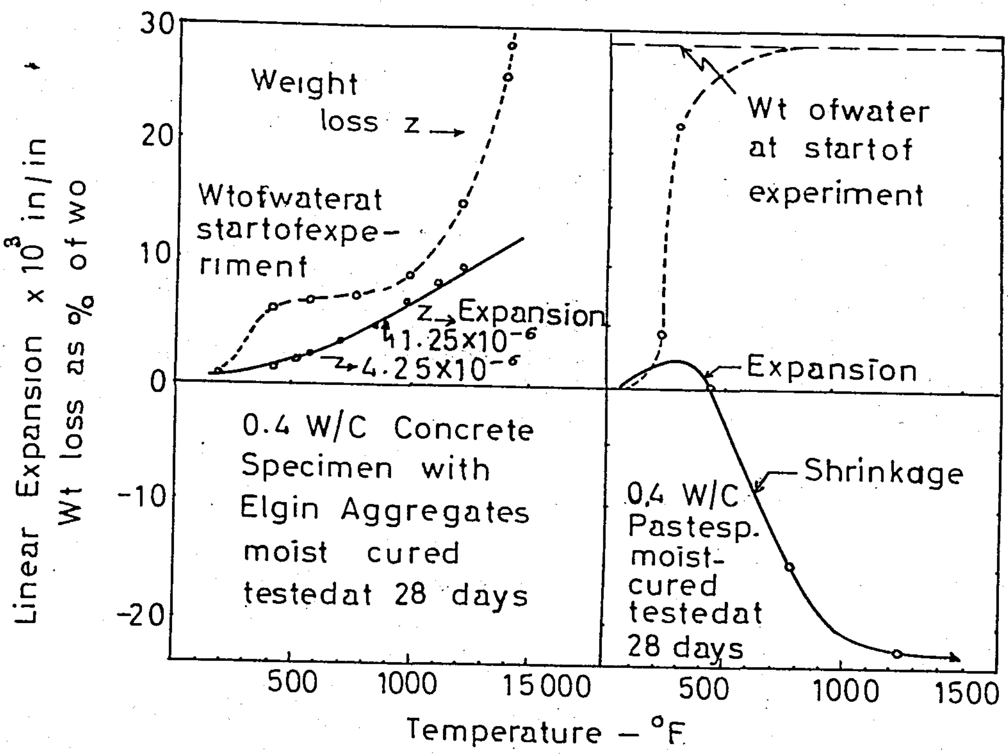

FIGURE 6. EXPANSION AND WEIGHT LOSS OF GRAVEL CONCRETE AND CEMENT PASTE (1:360)

c) Weight Change:

Weight losses in concrete are measured by dehydration and expulsion of water as well as the chemical nature of aggregate, Philleo (1) as well as Harmathy in their experiments showed that decrease in weight caused by loss of water is substantially complete at 800°F. In calcareous aggregate, the expulsion of carbon-dioxide at high temperatures is also a contributing factor.

As can be observed from Figure 8, if concrete is subjected to a temperature around 1500°C for a prolonged period, the weight will be reduced to that of the dry components.

d) Modulus of Elasticity and Poissons ratio:

In the experiments carried out by Philleo (1), the modulus of elasticity suffered serious reductions in the order of 25% at 400 F

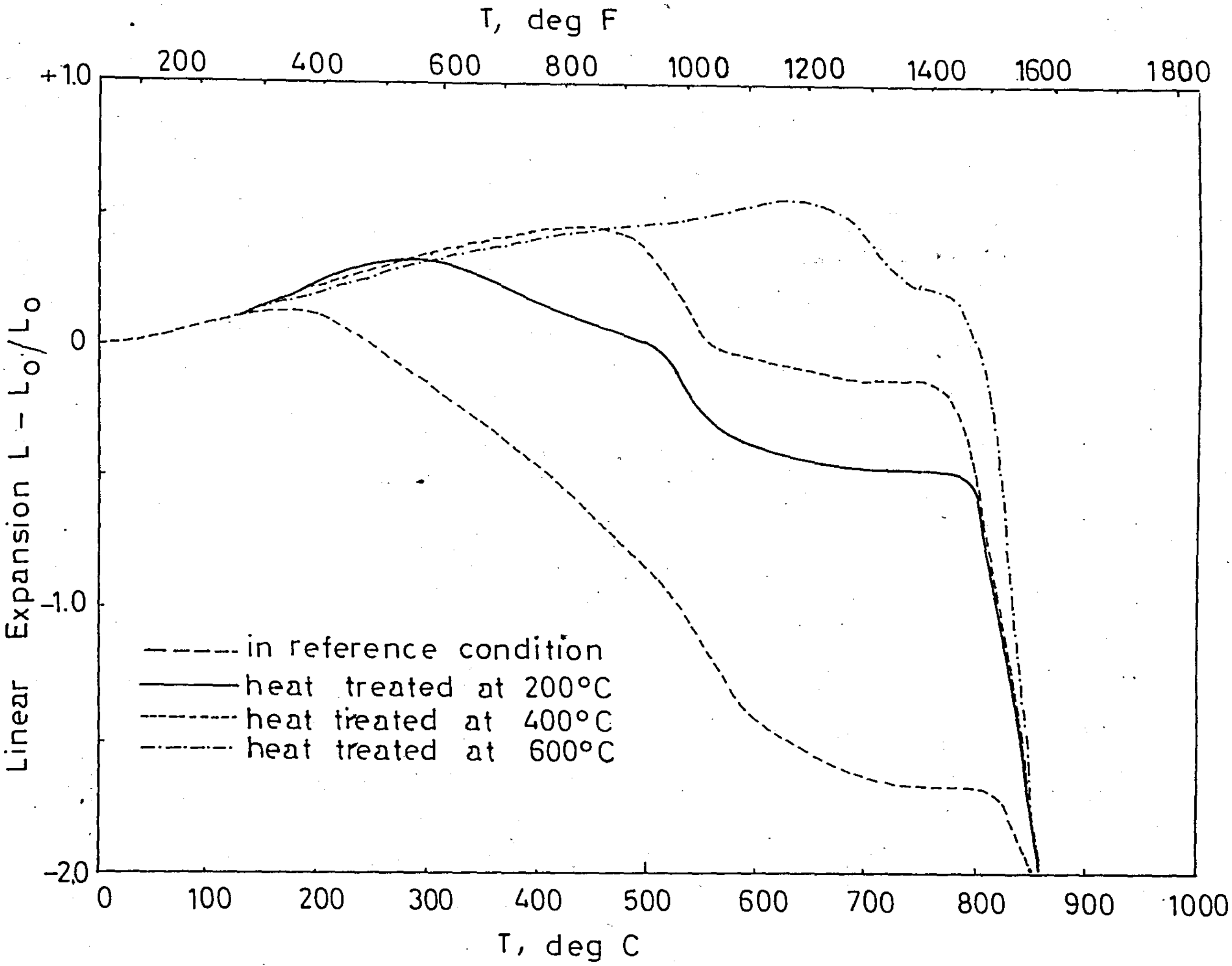

FIGURE 7. DILATOMETRIC CURVE (15:963)

50% at 800°F, 70% at 1400°F, with calcareous gravel aggregates. After dehydration, specimens had the same low modulus of elasticity, independent of age or curing conditions, but the effect of water-cement ratio was observed. The lower the water-cement ratio the higher the modulus of elasticity was after dehydration.

There was also a tendency for Poisson's ratio to decrease during exposure to high temperatures even though the results were erratic due to sensitivity to errors in determining the resonant frequencies (1).

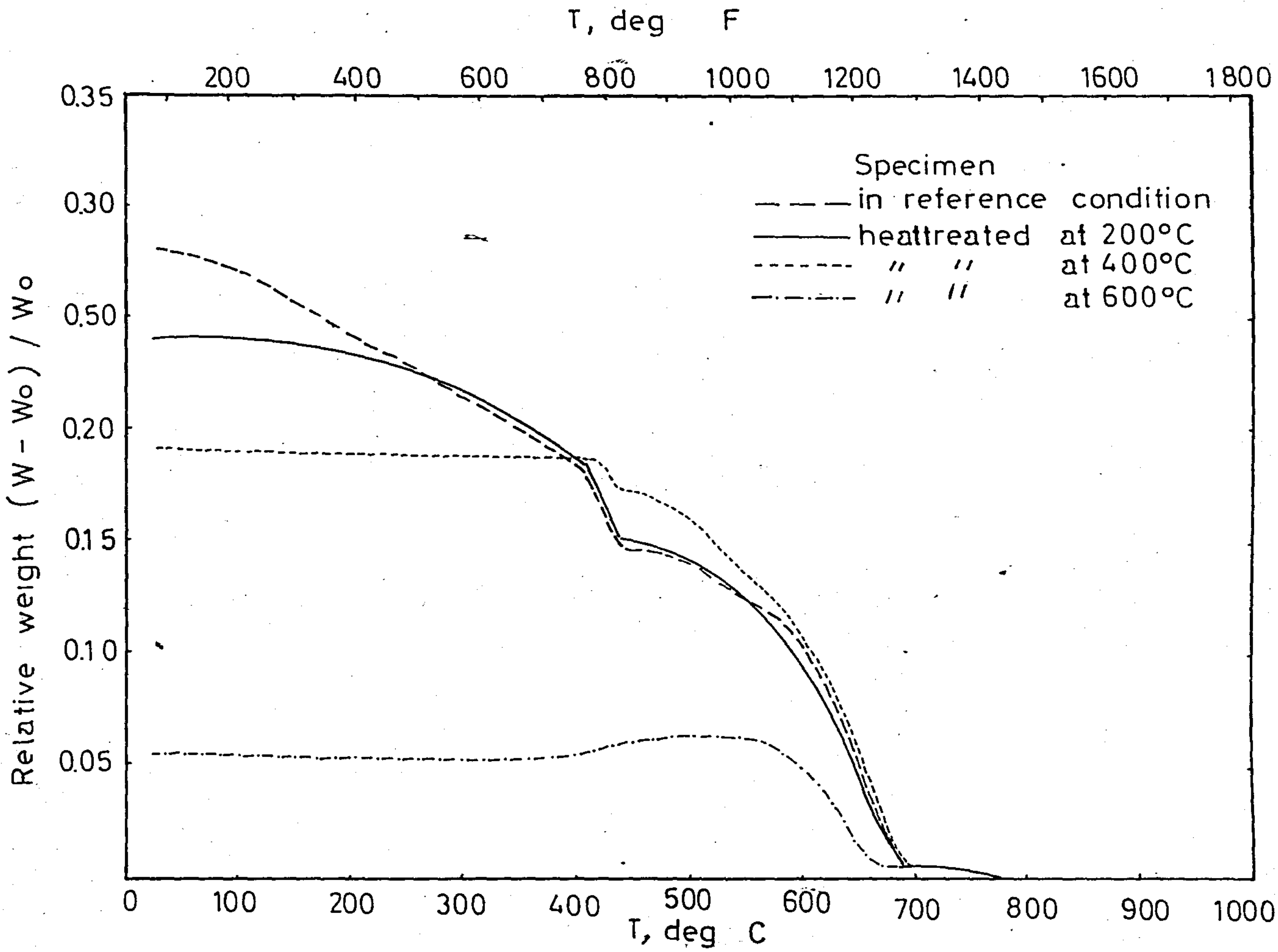

FIGURE 8. THERMOGRAVIMETRIC CURVE (15:962)

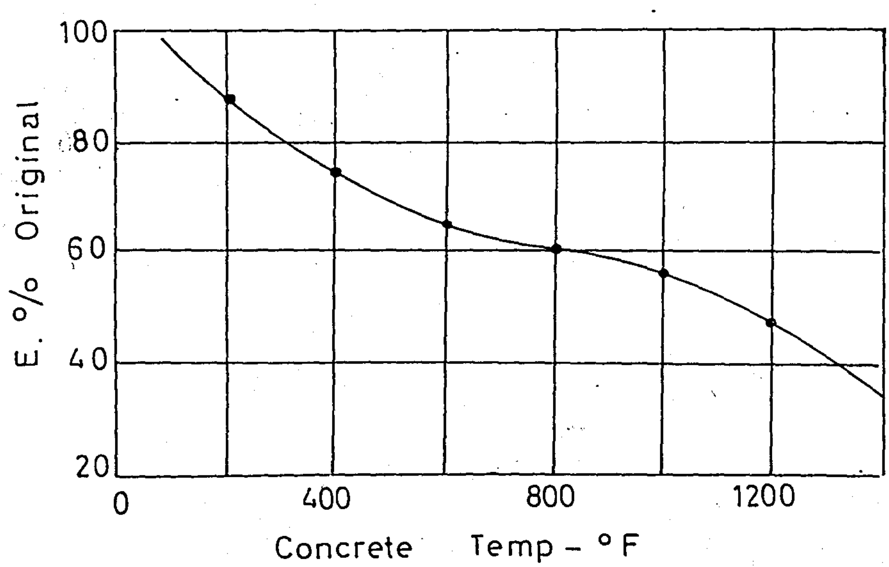

FIGURE 9. EFFECT OF TEMP. ON MODULUS OF ELASTICITY (8:28)

E.. REFRACTORY CONCRETES:

Suitable selection of the ingredients and mix proportion enables the preparation of concrete which can continue to perform satisfactorily up to a temperate of 1200°C.

Heat resistant concrete can be made by using portland, blast-furnace and aluminous cements. Lack of calcium hydroxide in the aluminous cements and the ceramic bonding make it the most sutiable cement, and when fire-clay is used as the aggregate a refractory material resisting temperatures up to 1600°C (2912°F) is formed,(14). If portland cement is used the disintegration caused by the action of $Ca(OH)_2$ can be compensated by use of fine-grained ceramic stabilizers (11).

The most intensive studies in this field were done in Russia (16). They worked on ways of prevention of shrinkage and CaO formation as well as the effects of using heat resistant aggregates. Fine-grained aggregates from quartz counteract shrinkage by their expansion during heating. Slag, shamotte grains and volcanic rocks are used as the aggregates. The Russian literature on this subject notes that resistance to a temperature of 1200°C can be attained by proper control of the factors above. They also suggest the use of fine-grained quartz, powdered brick and slag, crushed brick and basalt at lower temperatures, provided that cement content is above 250 kg/m^3, and the percentage of the fine-powder additive to the cement content is between 30 and 100%.

Control of the aggregate-cement ratio, the maximum size of the aggregate and other mix and curing conditions are additional factors to be considered in the design and preparation of refractory concrete.

F. TEMPERATURE HISTORY:

The temperature attained during exposure to fire in a construction can be determined approximately by observation of physical properties, color, length and weight changes. Irreversible reactions that take place in the cement paste are the basis for dilatometric and thermo-gravimetric tests which are used in relating the irreversible length and weight variations in the study of temperature history.

According to Smith some temperature markers are (5):

1) Color change (If aggregates are not igneous, concrete undergoes permanant color change on heating. Color is normal below 450°F. From 550°F to 1100°F, pink changes to red. Between 1100°F and 1650°F, color changes to grey.

2) Quartz pop-out: 1070°F

3) Spalling over steel to expose one-quarter of the bar: 1650°F

4) White powder of decomposed cement hydration products: 1650°F

5) Surface crazing: approximately 550°F

6) Deeper cracking: approximately 1000°F

7) Fusion temperatures of material.

G. FIRE RESISTANCE OF REINFORCED AND PRESTRESSED CONCRETE:

In reinforced concrete thermal factors discussed for the plain concrete such as type of aggregate, moisture effect as well as the structural factors like concrete stress level, temperature effect on concrete strength and concrete mix types determine the resistance to fire. Cover of reinforcement and geometry of section along with the lateral strains are other effective factors.

Physically, since the coefficient of expansion of steel is larger than that of concrete, the excessive expansion breaks the bond between concrete and steel.

An analysis of stresses around circular inclusions due to Thermal Gradients with particular reference to reinforced concrete is given by J. Dundurs and Zienkiewicz (17). The magnitude and distribution of stresses around a reinforcing bar is studied.

When large thermal gradients exist, the presence of steel will induce tensile stresses, since flow of heat is disturbed by inclusion (steel) with different thermal and elastic properties than those of the surrounding matrix (concrete). In the analysis a long circular bar embedded in surrounding elastic material subjected to a uniform temperature gradient transverse to the axis of the bar, is taken.

Temperature distribution is determined by satisfying the steady heat condition equation:

$$\nabla^2 T = 0 \tag{4}$$

in each region and by observing the continuity of temperature and heat flow:

$$T_1 = T_2$$

$$k_1 \frac{\partial T_1}{\partial r} = k_2 \frac{\partial T_2}{\partial r} \tag{5}$$

The present solution is represented through the Airy Stress function ϕ.

$$\sigma_{rr} = \frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi}{\partial \theta^2}$$

$$\sigma_{r\theta} = -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \phi}{\partial \theta}\right) \tag{6}$$

$$\sigma_{\theta\theta} = \frac{\partial^2 \phi}{\partial r^2}$$

Equation of compatibility:

$$\nabla^4 \phi = 0 \qquad (7)$$

and the conditions of (a) continuous radial and tangential tractions on the interface, (b) vanishing stresses at infinity and (c) single valued displacement are used to find the corresponding stresses.

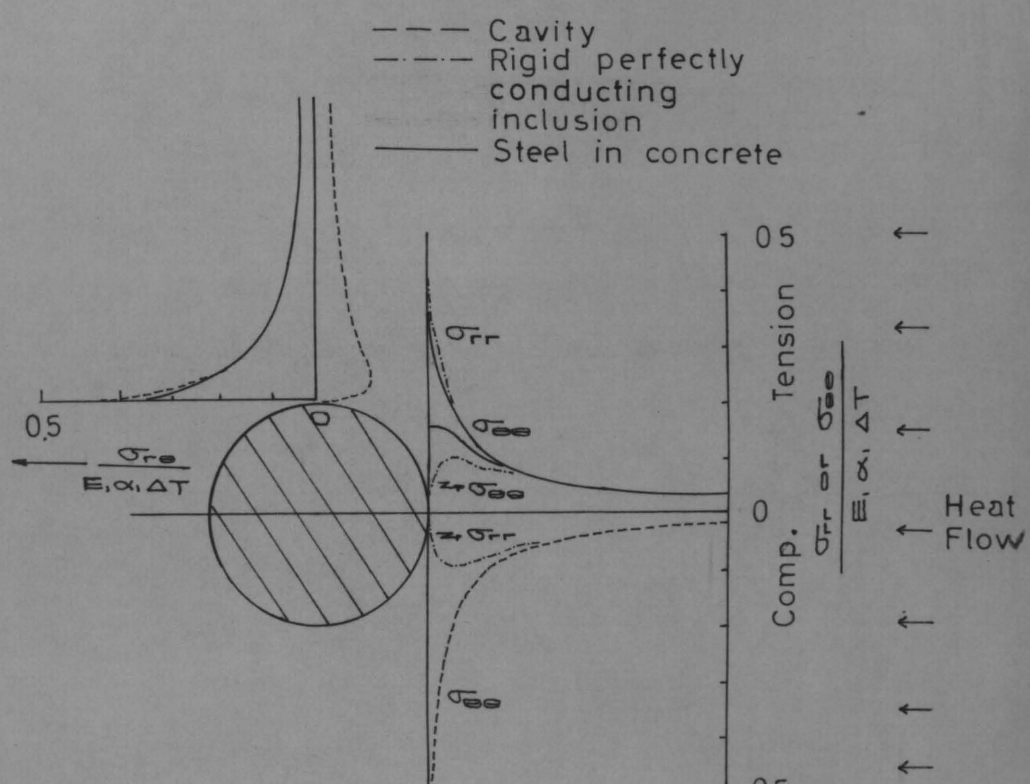

FIGURE 10. STRESSES AROUND THE INCLUSION (21:1533)

In addition, the presence of discontinuties due to the aggregates may increase the stress around the reinforcement, causing local failure (17).

Prestressed concrete is affected by all the factors discussed previously for plain and reinforced concrete.in addition to loss of prestress in the steel by annealing and creep. Spalling can be severe due to low permeability and greater rigidity of the higher quality concrete used.

CHAPTER III.

EXPERIMENTAL ANALYSIS

The purpose of the experiments is to determine the compressive strength of plain and refractory concretes prepared with shamotte, silica powder and crushed fire brick after exposing them to elevated temperatures.

The existence of various fields requiring the application of refractory concretes in Turkey as discussed previously produces the needs for fire-resistance testing. The present thesis work is intended to supplement the relevant studies since this is the first investigation in Turkey (to the author's knowledge) of heat resistance of refractory concretes at temperatures as high as 850°C.

A. MATERIALS

1.) Aggregates:

The aggregates used for preparation of plain concrete were local siliceous sand with a specific gravity of 2.63, crushed limestone with a specific gravity of 2.72 and gravel (rounded quartz) whose specific gravity is equal to 2.66 (Appendix, Part A).

2). Cement:

Concrete was prepared with Type I portland cement manufactured by Akçimento A.Ş. (Büyükçekmece, Istanbul).

3) Special Aggregates and Additives:

a) Crushed Firebrick:

Firebricks produced by Aslan Tuğla Sanayi for lining of electrical furnaces with model designation 233 were crushed and used as the special heat-resistant aggregate.

b) Shamotte:

Shamotte which is a clay heat, treated at 1300-1350°C with a composition of $Al_2O_3 + SiO_2$, was provided from Gorbon-Işıl Seramik Endüstrisi. It is considered a good refractory since its Al_2O_3 content is equal to 35%

c) Silica Powder:

Silica powder, which is 100% pure in its natural state may contain 1%-5% of Fe_2O_3, Fe_2O and Fe_3O_4. The silica powder that was provided from Gorbon-Işıl Seramik Endüstrisi, which had an Al_2O_3 content of 5% and 2% of iron oxide, was originally brought from Kütahya.

B. MIX PROPORTIONS, MIXING, CURING AND PREPARATION FOR TESTING

There were three groups of mortar specimens to be tested for resistance to high temperatures (Appendix, Part B).

I. O (Plain) Group

1. Gravel + Sand + Cement
2. Crushed limestone + Sand + Cement
3. Crushed firebrick + Sand + Cement

II. A (Shamotte) Group

1A. Gravel + Shamotte + Cement
2A. Crushed limestone + Shamotte + Cement
3A. Crushed Firebrick + Shamotte + Cement

III. B (Silica) Group

1B. Gravel + Silica Powder + Cement
2B. Crushed Limestone + Silica Powder + Cement
3B. Crushed Firebrick + Silica Powder + Cement

The following values were selected for proportioning of the mix:

Cement	:	325 Kg/m^3
W/c	:	0.70
Additive	:	200 Kg/m^3
Slump	:	80% flow (ASTM Designation : C 230 - 55T)
d max.	:	3/8"
Grading	:	Fuller Curve

After determination of specific gravity for each material, volume and weight of the constituent components of concrete were calculated and their gradations were controlled.

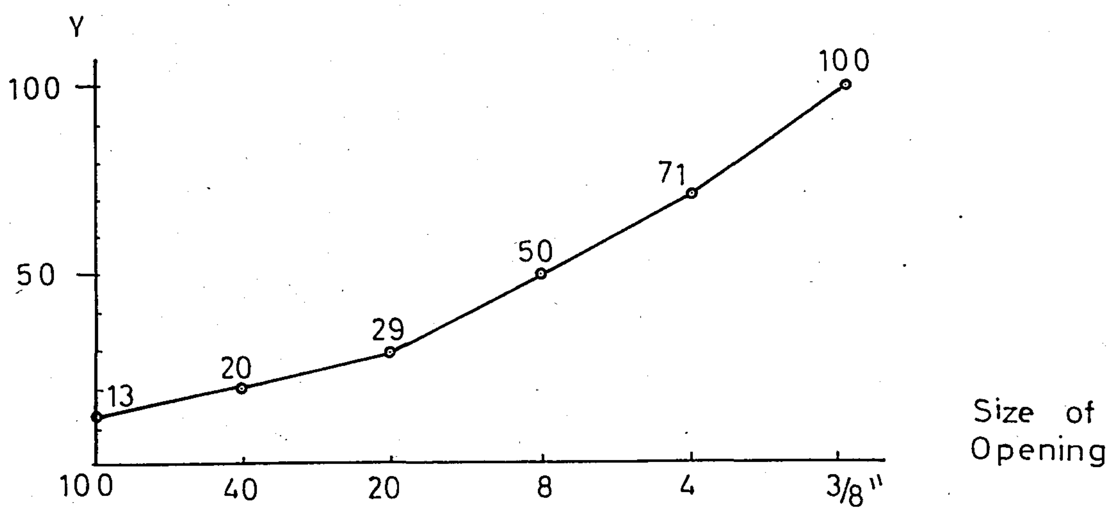

FIGURE 11. GRADATION CURVE OF THE MIX

The Mortar was mixed in an electrical two speed mixer for five minutes and poured into 2" x 4" cylindrical steel molds. Compaction was done by placing the concrete in three layers and rodding each layer 25 times with a tamping rod.

Molds were removed twenty-four hours after pouring and the samples were placed in water for seven day curing period. After a week, they were removed from water and kept in the laboratory for 21 days until they attained their testing age of 4 weeks.

C. APPARATUS

The following instruments were employed for the preparation and testing of samples:

(1) Pychnometer

(2) Vacuum Pump

Horse Power: 1/3

Model : 5Kh35KG113E

General Electric Co.

(3) Sieve

3/8" No : 8, 20, 40, 100

Newark Wire Cloth Co.

Central Scientific Co.

(4) Sieve Machine

Cenco-Meinzer Sieve shaker

50/60 cycles

Central Scientific Co.

(5) Vibrator

Model CT-164

12 Amperes, 50 Cycles

Soiltest Inc.

(6) Flow Indicator

Soiltest CT20

(7) 2 Speed Mixer

Model 212, 12 gt

Reynolds Electric Co.

(8) 2" x 4" cylindrical steel mol ds

(9) Sulphur-capping apparatus

(10) Electric Oven

Model sW-17TA

Temperature Range 40-200°C

Blue M Electric Co.

(11) Balance of Oil gm Sensitivity

(12) Electric Furnace

Type FR207

Maximum Temperature °F	:	1850
Maximum power KW	:	16
Furnace Voltage	:	73

Hoskins Manufacturing Co:

(13) Universal Testing Machine

Model : Riehle, screwtype, mechanical, maximum loading capacity of 70,000 lbs.

D. TESTING PROCEDURE:

The specimens which were water cured for seven days and air cured for 21 days were separated into two groups for determination of the compressive strength at normal temperatures as well as after heating to 850°C.

Two specimens from each group were put into an electric furnace at a temperature of 120°C for 1-1/2 hours. After this exposure, the samples were put into the main electric furnace and heated to a temperature of 850°C following the time-temperature rating as given in Figure 12. Then the specimens were allowed to cool to normal temperature within 3 hours.

All the specimens were capped with the sulphur capping compound and tested for their compressive strength in a Universal Testing Machine.

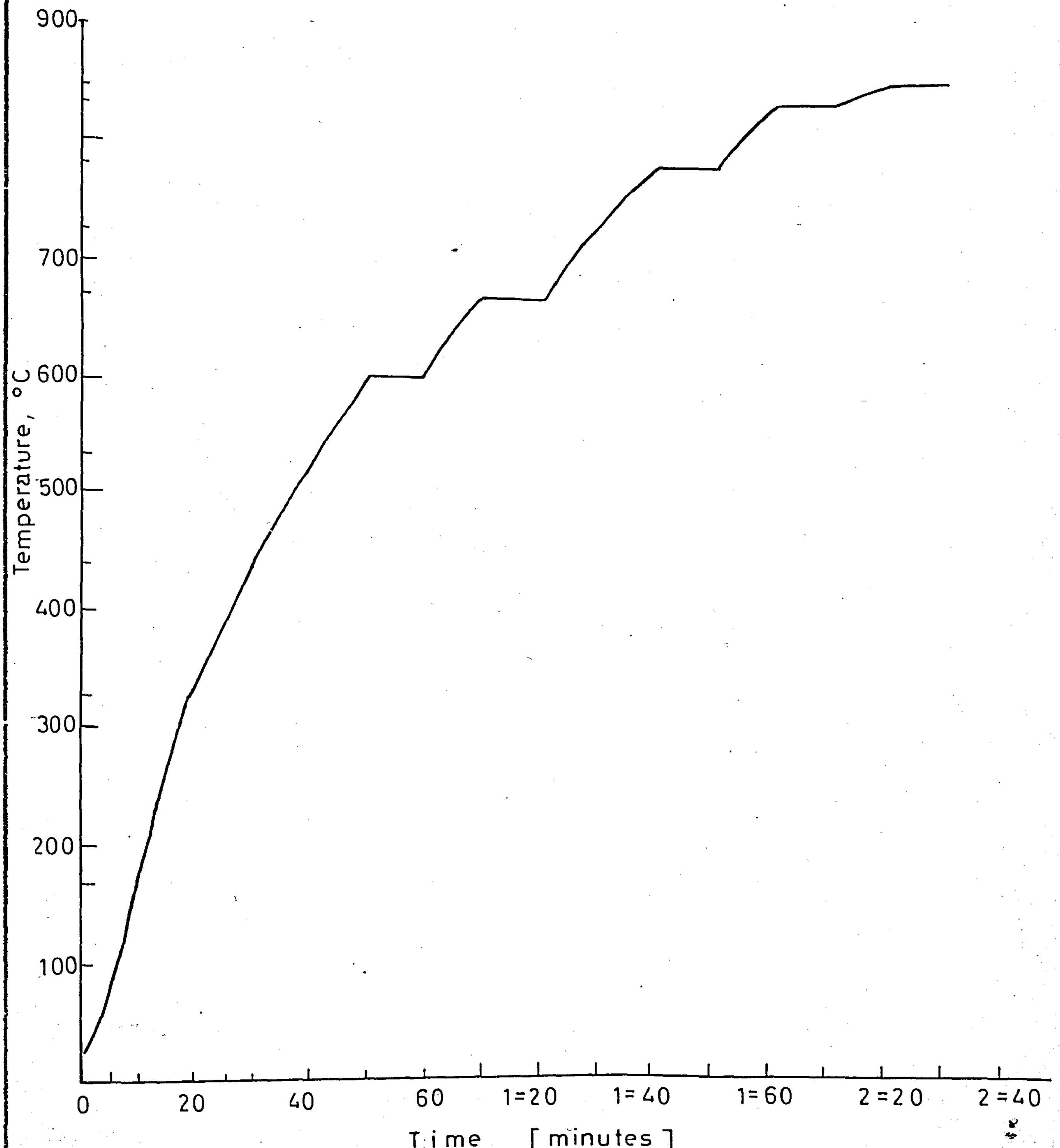

FIGURE 12. TIME-TEMPERATURE RATING OF THE FURNACE

CHAPTER IV

RESULTS

* The data obtained from compression test of specimens are tabulated below:

Test No	Group	Compressive Strength at Normal Temperature lbs/in^2	Compressive Strength After Heating to 850°C and Tested After cooling lbs/in^2
1	01	2050	436
2	01	2220	382
3	02	2730	955
4	02	2340	795
5	03	2370	875
6	03	2150	795
7	03	2280	925
8	A1	2780	735
9	A1	2660	620
10	A2	2430	1575
11	A2	2220	1765
12	A3	2175	1240
13	A3	2060	1560
14	A3	2100	1330
15	B1	2100	710
16	B1	2000	880
17	B2	2310	1300
18	B2	2330	1400
19	B3	1750	1425
20	B3	1530	1195
21	B3	1895	1250

TABLE 1. COMPRESSION TEST DATA

* The average values of compressive strength and the corresponding reduction in strength due to heating are given in the following table.

No	Groups	Compressive strength at normal temperature lbs/in^2	Compressive strength when tested after heating to 850° C and allowing to cool lbs/in^2	% loss of strength (As % reduction of original strength)
1	01	2135	409	74.0
2	02	2535	875	65.5
3	03	2266	865	61.8
4	A1	2720	678	71.5
5	A2	2325	1670	28.0
6	A3	2110	1377	34.6
7	B1	2050	795	61.3
8	B2	2320	1350	41.7
9	B3	1725	1290	25.0

TABLE 2. COMPRESSIVE STRENGTH AND PERCENT REDUCTION DUE TO HEATING

Type of Concrete		Compressive Strength Ratio before heating	Compressive Strength Ration after heating	Index Value
01	Gravel + Sand + Cement	1.00	1.00	1.00
02	Crushed limestone + Sand + Cement	1.16	2.14	0.75
03	Crushed Firebrick + Sand + Cement	1.06	2.11	6.70
A1	Gravel + Shamotte + Cement	1.27	1.65	2.37
A2	Crushed limestone + Shamotte + Cement	1.08	4.08	0.94
A3	Crushed Firebrick + Shamotte + Cement	0.99	3.35	6.20
B1	Gravel + Silica Powder + Cement	0.96	1.95	1.86
B2	Crushed Limestone + Silica Powder + Cement	1.08	3.30	1.24
B3	Crushed Firebrick + Silica Powder + Cement	0.81	3.15	5.63

TABLE 3 COMPARISON OF COMPRESSIVE STRENGTH AND INDEX VALUES

(Compressive strength and cost-strength ratio of plain 01 concrete is taken as the base)

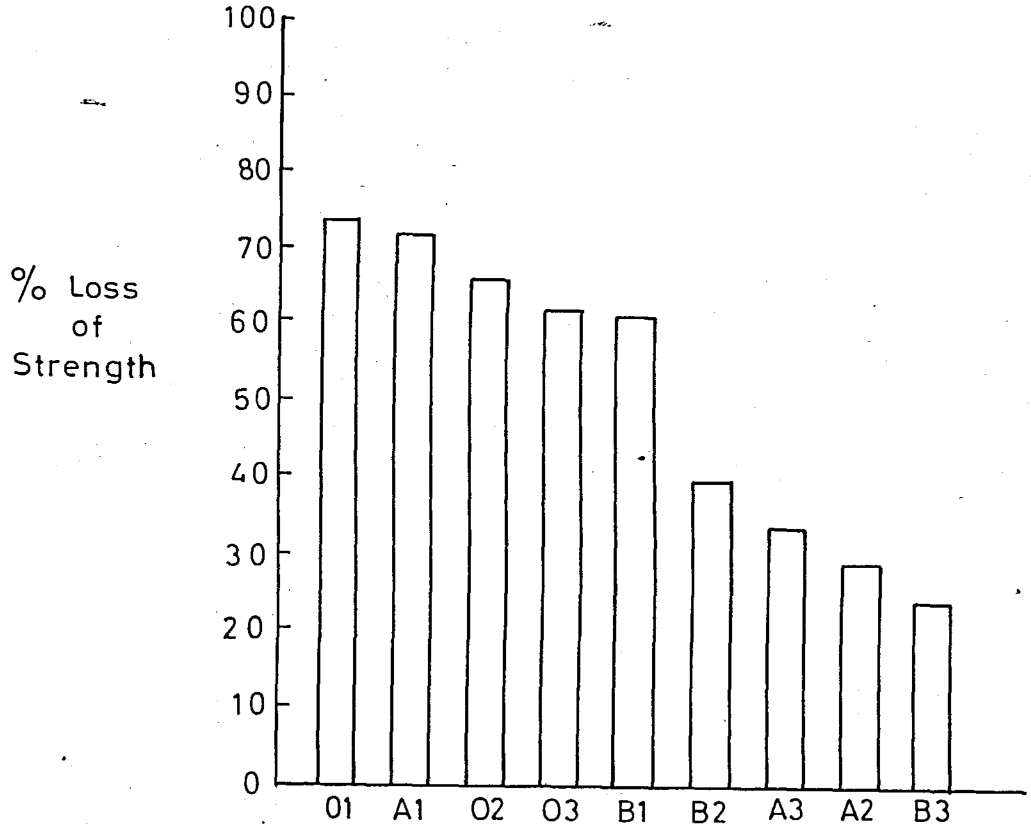

FIGURE 13. PERCENT LOSS OF STRENGTH

CHAPTER V

DISCUSSION OF RESULTS

The results obtained by testing the specimens of the plain, shamotte and silica powder group of concretes are given in the previous chapter with the explicit numerical correlations and charts.

In the preparation of the samples, the only variable factor was the type and amount of the aggregates and the special additives. Consequently, the effects of type of cements, water-cement ratio, aggregate size and the aggregate cement ratio, the humidity and curing conditions were not within the scope of the experiments and the objects.

Another major consideration is the fact that the experimental techniques were not applied according to the procedures given by A.S.T.M. E119, which specifies a certain time temperature relationship, size of specimens, methods of heating and conditions of loading and restraining. The experiments were carried out for the investigation of exposure to high temperatures, thus deviating from the standard fire testing methods. This fact is important in the analogy and comparison of the data and results of the present work with other similar studies in this field.

Under the view of the previous discussion, the results are in proper correlation with the theoretical basis discussed in Chapter II. The reduction in compressive strength of the plain concrete group is highest, reaching 74% of original strength for 01 group (gravel + sand + cement). The behavior of crushed limestone is superior to that of gravel, as expressed by the results since 02 group of plain concrete (crushed limestone + sand + cement) suffers a strength loss which is less than that of A1 group which contains shamotte. The addition of silica powder to gravel cannot produce a considerable improvement in compressive strength level either.

The use of crushed fire-brick or limestone as the aggregate with the additives, shamotte and silica powder gave better results, within the order of 25% - 40% loss of original strength. B3 group (crushed fire-brick + silica powder + cement) suffered the minimum loss of strength, 25% whereas A2 group (crushed limestone + shamotte + cement) had the highest compressive strength equaling to 1670 psi after being heated at 850 C.

ECONOMY

The costs of different types of the concretes tested were analysed to judge the feasibility of industrial application. Table (3) includes the index values (cost-strength ratios with respect to plain concrete) calculated in Appendix, Part (E). The index values indicate that except for the groups in which crushed fire-brick is used as the aggregate (O3, A3, B3), the cost strength ratio has a general tendency to justify the use of the specific refractory concretes. Furthermore the economic considerations sometimes may be of secondary significance due to the possibility that the amount of concrete to be used for special heat resistance can be limited and the strength considerations can precede the economic requirements.

CHAPTER VI

CONCLUSION

Test results indicate that refractory concretes, prepared with special aggregates and additives by consideration of mix proportions and the related theoretical basis, can be expected to show a satisfactory fire resistance as well as structural performance related to strength characteristics. The use of crushed fire-brick, silica powder and shamotte as well as other light weight aggregates and ceramic stabilizers bring additional fields of application for concrete in cases of exposure to high temperatures in chimneys, furnaces, reactors, radiation units and blast areas.

The reduction in compressive strength, which is of primary concern for structural stability and integrity, can be controlled in refactory concretes, thus enabling the designed level of performance of concrete as a structural element, refractory or protective units in cases of exposure to fire and high temperatures.

CHAPTER VII

SUGGESTIONS

The results of the theoretical and experimental investigations of this thesis work is specifically related to the crushing strength of concrete, even though all the aspects of properties of concrete related to heat resistance are included within the scope of the theoretical part. Therefore, as an extension of the present work further analysis of cement and aggregate behavior, possibilities of selection of the natural aggregates for preparation of refractory concretes, and tests for modulus of elasticity, stress-strain relationships, strain at failure and volume changes related to fire resistance of refractory concretes under field conditions and design stresses would contribute to this field of research.

APPENDIX

DATA FOR DETERMINATION OF SPECIFIC GRAVITY

	Shamotte	Silica Powder	Sand	Crushed Limestone	Gravel
Bottle Number	3	4	3	4	3
Wtbottle + water + soil, W1(q)	413.55	401.00	437.05	420.15	423.80
Temperature T in C	31	30	28	30	30
Wtbottle + water, W2 in gm	356.18	340.70	356.40	340.70	356.26
Evaporating dish No.	4-S	4-si	K.7	CL	G
Wt dish + dry soil (gm)	228.35	230.90	264.10	261.75	219.40
Wt dish, in (gm)	134.60	133.70	134.75	136.90	111.60
Wt. soil, Ws, in (gm)	93.75	92.20	129.35	124.85	107.80
Specific Gravity of H_2O at T1, Gt	0.99	0.99	0.99	0.99	0.99
Sp. Gr. of solid, Gs	2.54	2.88	2.63	2.72	2.66

$Gs = GtWs/(Ws-W1+W2)$

A. DETERMINATION OF SPECIFIC GRAVITY

1) Shamotte

Gs = GtWs/(Ws-W1+W2)

Gs = (0.99) (93.75)/(93.75-413.55+356.18)

= 92.50/36.38

= 2.54

2) Silica Powder

Gs = GtWs/(Ws-W1±W2)

= (0.99) (92.20)/(92.20-401.00+340.70)

= 91.50/31.90

= 2.88

3) Sand

Gs = (0.99) (120.35)/(129.35-437.05+356.40)

= 128.0/48.70

= 2.63

4) Crushed Limestone

Gs = GtWs/(Ws=W1+W2)

= (0.99) (124.85)/(124.85-420.15+340.70)

= 123.50/45.40

= 2.72

5) Gravel

Gs = GtWs/(Ws=W1+W2)

= (0.99) (107.80)/(107.80-423.80+356.26)

= 106.8/40.26

= 2.66

DETERMINATION OF APPARENT SPECIFIC GRAVITY
(SATURATED, SURFACE DRY) OF CRUSHED BRICK

* W = 2820 gm

* Saturation

$s\% = (3160-2760)/2760$

$= 400/2760$

$= 14.5\%$

* Water = 14.5% x 2820

= 410 gm

* Wt = 2820 + 410

= 3230 gm

* Ga = Apparent Specific gravity

* Saturated Surface dry

$Ga = Wt/V$

$w = (17.8 + 17.8 + 17.8 + 17.8 + 17.75)/5$

$= 17.8$

$L = (38.5 + 36.7 + 36.6 + 36.6 + 36.6)/5$

$= 36.6$

$t = (2.4 + 2.5 + 2.5 + 2.55 + 2.65 + 2.75 + 2.8)/7$

$= 2.59$

$t_1 = (2 + 2 + 2.1 + 2.2 + 2.35)/5$

$= 2.15$

$Vtr = (2.35 \times 1.6 \times 17.5)/2$

$= 33\ cm^3$

$V = (17.8)\ (36.6)\ (2.59 + 2.15)/2$

$= 1540\ cm^3$

$$Vt = 1540 + 33$$
$$= 1573 \text{ cm}^3$$
$$Ga = 3230/1573$$
$$= 2.05$$

B. MIX PROPORTIONS

O-1 Mix:

Sand + Gravel + Cement

$$Wc/Gc + Ww + Wqr/Gqr + Ws/Gs = 1000L$$
$$325/3.15 + 227 + (Vs + Vqr) = 1000L$$
$$Vs + Vqr = 1000 - (103 + 227)$$
$$= 1000 - 330$$
$$= 670L$$

*Vq	= 400L
Vs	= 270L
Vc	= 103L
Vw	= 227L
Vt	= 1000L

*Wc	= 325 Kg/m^3
Ww	= 227 "
Wq	= 1065 "
Ws	= 710 "

For 2L:

*Wc	= 650 gm
Ww	= 454 gm
Wq	= 2130 gm
Ws	= 1420 gm
Wt	= 4654 gm

*Wq + Ws = 3,550 gm

Pan-100	%13 x 3,550	=	462 gm sand
100- 40	% 7 x 3,550	=	249 gm sand
40- 20	% 9 x 3,550	=	320 gm sand
20- 8	%21 x 3,550	=	745 gm 389s + 356gr
8- 4	%21 x 3,550	=	745 gm gravel
4-3/8	%29 x 3,550	=	1030 gm gravel
			3551 gm

0-2 Mix:

* Sand + Crushed Limestone + Cement

Wc/Gc + Ww/Gw + Ws/Gs + Wcrlim/Gcrlim = 1000L

325/3.15 + 227 + Vs + Vcrlim = 1000L

(Vs + Vcrlim) = 1000- (103 + 227)

= 670L

Vcrlim = 400L

Vs = 270L

*Vq = 103L

Vw = 227L

Vcrl = 400L

Vs = 270L

*Wc = 325 Kg/m^3

Ww = 227 "

Ws = 710 "

Wcrl + 1090 "

For 2 L

*Wc = 650 gm

Ww = 454 gm

Ws = 1420 gm

Wcrl = 2180 gm

4704 gm

Ws + Wcrlim = 3600 gm

Pan-100	%13 x 3600	=	468 sand
100- 40	% 7 x 3600	=	252 sand
40- 20	% 9 x 3600	=	324 sand
20- 8	%21 x 3600	=	755 3765 + 379 crlim
8- 4	%21 x 3600	=	755 cr limestone
4-3/8	%29 x 3600	=	1046 cr limestone
			3600 gm

0-3 Mix:

* Sand + Crushed Firebrick + Cement

Wc/Gc + Ww/Gw + Ws/Gs + Wcrfib/Gcrfib = 1000L

325/3.15 + 227 + Vs + V crbr = 1000L

103 + 227 + Vs + Vcrbr = 1000L

Vs + Vcrbr = 1000- (330)

Vcrbr = 670L

Vcrbr = 400 L

Vs = 270 L

*Vc = 103L

Vw = 227L

Vcrbr = 400L

Vs = 270L

Vt = 1000L

*Wc	= 325 Kg/m³		For 2L		
Ww	= 227	"	*Wc	=	650 gm
Wcrbr	= 829	"	Ww	=	454 gm
Ws	= 710	"	Wcrbr	=	1645 gm
			Ws	=	1420 gm
			Wt	=	4164 gm

Ws + Wcrbr = 3060 gm

Pan-100	%13 x 3060	= 398	sand
100- 40	% 7 x 3060	= 214	sand
40- 20	% 9 x 3060	= 275	sand
20- 8	%21 x 3060	= 643	533s + 110crbr
8- 4	%21 x 3060	= 643	crushed brick
4-3/8	%29 x 3060	= 887	crushed brick
		3060	

A-1 Mix:

Gravel + Shamotte + Cement

Wc/Gc + Ww?Gw + Wgr/Ggr + Wsh/Gsh = 1000L

325/3.15 + 227 + Wgr/2.66 + 200/2.54= 1000L

103 + 227 + Wgr/2.66 = 1000-78.8

Vgr = 1000- (330 + 78.8)

Vgr = 591.2L

*Vc = 103L

Vw = 227L

Vgr = 591.2L

Vsh = 78.8L

Vt = 1000.0L

			For 2L		
*Wc	= 325 Kg/m^3		*Wc	=	650 gm
Ww	= 227	"	Ww	=	454 gm
Wgr	= 1575	"	Wgr	=	3150 gm
Wsh	= 200	"	Wsh	=	400 gm
					4654 gm

Wgr + Wsh = 3550

Pan-100	%13 x 3550	=	462 400gm sh + 62 gr
100- 40	% 7 x 3550	=	249 gravel
40- 20	% 9 x 3550	=	320 gravel
20- 8	%21 x 3550	=	745 gravel
8- 4	%21 x 3550	=	745 gravel
4-3/8"	%29 x 3550	=	1030 gravel
			3551

A-2 Mix:

Crushed Limestone + Shamotte + Cement

Wc/Gc + Ww/Gw + Wcrlim/Gcrlum + Wsh/ Gsh = 1000L

325/3.15 + 227 + Wcrlim/2.72 + 200/2.59 = 1000L

Vcrlim = 1000- (103 + 227 + 78.8)

Vgr = 591.2

*Vc = 103L

Vw = 227L

Vcrl = 591.2L

Vsh = 78.8L

1000.0L

			For 2L	
*Wc	= 325 Kg/m^3		*Wc	= 650 gm
Ww	= 227 "		Ww	= 454 gm
Wcrl	= 1602 "		Wcrl	=3204 gm
Wsh	= 200 "		Wsh	= 400 gm
				4708 gm

Wcrlim + Wsh = 3604 gm

Pan-100	% 13 x 3604	= 468 400sh + 68 crlim
100- 40	% 7 x 3604	= 253 crlim
40- 20	% 9 x 3604	= 325 crlim
20- 8	% 21 x 3604	= 756 crlim
8- 4	% 21 x 3604	= 756 crlim
4-3/8"	% 29 x 3604	= 1046
		3604

A-3 Mix:

Crushed Firebrick + Shamotte + Cement

Wc/Gc + Ww/Gw + Wcrfib/Gcrfib + Wsh/Gsh = 1000L

325/3.15 + 227 + V crb + 200/254 = 1000L

Vcrb = 1000- (103 + 227 + 78.8)

Vcrb = 591.2L

*Vc = 103L

Vw = 227L

Vcrb = 591.2L

Vsh = 78.8L

Vt = 1000.0L

		For 2L	
*Wc	= 325 Kg/m^3	*Wc	= 650 gm
Ww	= 227 "	Ww	= 454 gm
Wsh	= 200 "	Wsh	= 400 gm
Wcrb	= 1215 "	Wcrb	=2430 gm
			3934 gm

Wsh + Wcrbr = 2830

Pan-100	% 13 x 2830	= 367	367sh + 45 crbr
100- 40	% 7 x 2830	= 198	33sh + 165 crbr
40- 20	% 9 x 2830	= 255	cr brick
20- 8	% 21 x 2830	= 595	cr brick
8- 4	% 21 x 2830	= 595	cr brick
4-3/8"	% 29 x 2830	= 820	cr brick
		2830	

B-1 Mix:

Gravel + Silica Powder + Cement

$Wc/Gc + Ww/Gw + Wgr/Ggr + Wsi/Gsi = 1000L$

$325/3.15 + 227 + Vgr + 200/2.88 = 1000L$

$Vgr = 1000- (103 + 227 + 69.5)$

$Vgr = 600.5$

*Vc	= 103L			
Vw	= 227L			
Vsi	= 69.5L			
Vgr	= 600.5L			
Vt	= 1000.0L		For 2 L	
*Wc	= 325 Kg/m^3		*Wc	= 650 gm
Ww	= 227 "		Ww	= 454 gm
Wsi	= 200 "		Wsi	= 400 gm
Wgr	= 1600 "		Wgr	= 3200 gm
			Wt	= 4704 gm

Wsi + Wgr = 3600 gm

Pan-100	% 13 x 3600	= 468	400si + 68 gr
100- 40	% 7 x 3600	= 252	gravel
40- 20	% 9 x 3600	= 324	gravel
20- 8	% 21 x 3600	= 755	gravel
8- 4	% 21 x 3600	= 755	gravel
4-3/8"	% 29 x 3600	= 1046	gravel
		3600	

B-2 Mix:

Crushed Limestone + Silica Powder + Cement

Wc/Gc + Ww/Gw + Wcrlim/Gcrlim + Wsi/Gsi = 1000L

325/3.15 + 227 + Wcrlim/2.72 + 200/2.88 = 1000L

Vcrlim = 1000- (103 + 227 + 69.5)

Vcrlim = 600.5L

*Vc = 103L

Vw = 227L

Vcrl = 600.5L

Vsi = 69.5L

Vt = 1000.0L

*Wc = 326 Kg/m³		*Wc	= 650 gm
Ww = 227 "		Ww	= 454 gm
Wcrl = 1635 "		Wcrl	= 3270 gm
Wsi = 200 "		Wsi	= 400 gm
		Wt	= 4774 gm

Wcrlim + Wsi = 3670

Pan-100	% 13 x 3670	= 476	400si + 76crlim
100-40	% 7 x 3670	= 257 cr lim	
40- 20	% 9 x 3670	= 330 cr lim	
20- 8	% 21 x 3670	= 772 cr lim	
8- 4	% 21 x 3670	= 772 cr lim	
4-3/8"	% 29 x 3670	= 1063 cr lim	
		3670	

B-3 Mix:

Crushed Firebrick ± Silica + Cement

Wc/Gc + Ww/Gw + Wcrbr/Gcrbr + Wsi/Gsi = 1000L

325/3.15 + 227 + Wcrbr/Gcrbr + 200/2.88 = 1000L

Vcrbr = 1000- (103 + 227 + 69.5)

Vcrbr = 600.5L

*Vc = 103L				
Vw = 227L				
Vcrbr = 600.5L				
Vsi = 69.5L				
Vt = 1000.0L		For 2 L		
* Wc = 325 Kg/m^3		*Wc	= 650 gm	
Ww = 227 "		Ww	= 454 gm	
Wcrbr = 1240 "		Wcrbr	= 2480 gm	
Wsi = 200 "		Wsi	= 400 gm	
		Wt	= 3984	

Wcrbr + Wsi = 2880 gm

Pan-100	% 13 x 2880	= 374	374si
100- 40	% 7 x 2880	= 202	+ 176 crbr
40- 20	% 9 x 2880	= 250	cr brick
20- 8	% 21 x 2880	= 605	cr brick
8- 4	% 21 x 2880	= 605	cr brick
4-3/8"	% 29 x 2880	= 835	cr brick
		2880	

C. TIME-TEMPERATURE RATING OF THE ELECTRIC FURNACE

Minutes	°C
0	20
5	70
10	165
15	200
20	325
25	385
30	440
35	485
40	530
45	565
50	600
55	635
60	668
65	698
70	725
75	755
80	780
85	805
90	830
95	855
100	878
105	900
110	920
115	938

D. COST ANALYSIS OF CONCRETE

(The prices are taken from The Bill of Materials, published by the Ministry of Public Works, and the current market prices.)

Cost of Workmanship:

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1.	Skilled worker	Hr	2.00	5.00	10.00
2.	Worker (for preparing the mix)	Hr	9.00		
3.	Worker (for carrying the concrete)	Hr	2.00		
4.	Worker (for placing the concrete and compaction)	Hr	5.00		
	Worker		16.00	2.50	40.00
	Total TL				50.00

01 Mix: Sand + Gravel + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Sand	M^3	0.27	12.50	3.38
3	Gravel	"	0.40	12.00	4.80
4	Water	"	0.227	1.00	0.23
	Materials				73.41
	Workmanship				50.00
	Materials + Workmanship				123.41
	Contractor Profit				31.00
	Total Cost/m^3				154.41

02 Mix: Sand + Crushed Limestone + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Sand	M^3	0.27	12.50	3.38
3	Crushed Limestone	M^3	0.40	12.00	4.80
4	Water	M^3	0.227	1.00	0.23
	Material Cost				73.41
	Workmanship				50.00
	Material + Workmanship				123.41
	Contractor Profit				31.00
	Total Cost				154.41

03 Mix: Sand + Crushed Firebrick + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Sand	M^3	0.27	12.50	3.38
3	Crushed Firebrick	M^3	820	2.35	1100.00
4	Water	M^3	0.227	1.00	0.23
	Materials				1168.61
	Workmanship				50.00
	Material + Workmanship				1218.61
	Contractor Profit				304.00
	Total Cost/m^3				1522.61

A1 Mix: Gravel + Shamotte + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Gravel	M^3	0.59	12.0	7.10
3	Shamotte	Kg	2.00	1.0	200.00
4	Water	M^3	0.227	1.0	0.23
	Materials				271.33
	Workmanship				50.00
	Material + Workmanship				321.33
	Contractor Profit				80.50
	Total Cost/m^3				401.83

A2 Mix: Crushed Limestone + Shamotte + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Crushed Limestone	M^3	0.59	12.0	7.10
3	Shamotte	Kg	200	1.0	200.00
4	Water	M^3	0.227	1.0	0.23
	Materials				272.33
	Workmanship				50.00
	Material + Workmanship				322.33
	Contractor Profit				80.50
	Total Cost/m^3				402.83

A3 Mix: Crushed Firebrick + Shamotte + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Crushed Firebrick	Kg	1215	1.35	1610.00
3	Shamotte	Kg	200	1.00	200.00
4	Water	M^3	0.227	1.00	0.23
	Materials				1875.23
	Workmanship				50.00
	Material + Workmanship				1925.23
	Contractor Profit				482.00
	Total Cost/m^3				2407.23

B1 Mix: Gravel + Silica Powder + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Gravel	M^3	0.6	12.0	7.20
3	Silica Powder	Kg	200	1.10	220.00
4	Water	M^3	0.227	1.00	0.23
	Materials				292.43
	Workmanship				50.00
	Material + workmanship				342.43
	Contractor Profit				85.75
	Total Cost/m^3				428.18

B2 Mix: Crushed Limestone + Silica Powder + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Crushed Limestone	M^3	0.60	12.0	7.20
3	Silica Powder	Kg	200	1.10	220.00
4	Water	M^3	0.227	1.00	0.23
	Materials				292.43
	Workmanship				50.00
	Material + Workmanship				342.43
	Contractor Profit				85.75
	Total Cost/m^3				428.18

B3 Mix: Crushed Firebrick + Silica + Cement

No	Type	Unit	Quantity	Unit Price TL	Cost TL
1	Cement	Kg	325	0.2	65.00
2	Crushed Firebrick	Kg	1240	1.35	1675.00
3	Silica Powder	Kg	200	1.10	220.00
4	Water	M^3	0.227	1.00	0.23
	Materials				1960.23
	Workmanship				50.00
	Material + Workmanship				2010.23
	Contractor Profit				500.00
	Total Cost/m^3				2510.23

E. CALCULATION OF INDEX VALUES

$$In = \frac{Cn / Co}{Sn / So} = \frac{So / Co}{Sn / Cn}$$

where

In = Index of concrete

Sn = Percent of original strength of concrete retained after heating.

Cn = Cost of concrete.

So = Percent of original strength of plain concrete (gravel + sand + cement) retained after heating.

Co = Cost of plain concrete.

(1) 02 concrete (Crushed Limestone + Sand + Cement)

$$In = \frac{So/Co}{S / C} = \frac{26/154.4}{34.5/154.4} = 0.75$$

(2) 03 Concrete (Crushed firebrick + Sand + Cement)

$$In = \frac{So/Co}{S / C} = \frac{26/154.4}{38.2/1522} = 6.70$$

(3) A1 Concrete (Gravel + Shamotte + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{28.5/401.83} = 2.37$$

(4) A2 Concrete (Crushed Limestone + Shamotte + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{72/402.83} = 0.94$$

(5) A3 Concrete (Crushed Firebrick + Shamotte + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{65.4/2407.83} = 6.20$$

(6) B1 Concrete (Gravel + Silica Powder + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{38.7/428.18} = 1.86$$

(7) B2 Concrete (Crushed Limestone + Silica Powder + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{58.3/428.18} = 1.24$$

(8) B3 Concrete (Crushed Firebrick + Silica Powder + Cement)

$$In = \frac{So/Co}{S/C} = \frac{26/154.4}{75/2510.23} = 5.63$$

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