PRODUCTION OF
LOW COST FOAM CONCRETE USING
INDIGENOUS MATERIALS

By

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DEDICATED

TO

MY PARENTS, WIFE, DAUGHTER AND SONS

ACKNOWLEDGEMENT

Thanks to The Ever Merciful and Kind All Mighty Allah Who made me able to carry out this research work.

I would like to express my gratitude to everyone who has contributed to this study. Special thanks are extended to :

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ABSTRACT

Foam concrete is regarded by many experts and researchers as an excellent construction material because of its unique properties. However, the use of Foam concrete is limited in general construction, due to its higher production cost, mainly because of the use of costlier imported Foaming Agents (FA). This highlights the need to study manufacturing of low cost Foam concrete, using indigenous FAs like detergents (surfactants).

This research study was designed to produce Foam concrete using locally manufactured detergent, Leopard Surf, as FA, and study its properties and cost comparison to the Foam concrete (control mix) produced using generic FA, Feb Foam.

The research study was conducted into two phases. In first phase, the dosage of FA (Feb Foam), detergent (Leopard Surf), cement content and sand content were varied to achieve optimum mix design. In second phase, using optimum mix design, variations were made in sand content only. For both phases, water to cement ratio of 0.65 was kept constant.

Test results validate that it is feasible to produce Foam concrete using indigenous detergent. The use of such detergent in place of FA resulted in production of low cost Foam concrete having physical and mechanical properties comparable with control mix. Mix design containing surfactant at the rate of 0.4 per cent by weight of cement and having cement and sand in a ratio of 60 and 40 per cent, respectively, was found to satisfy most of the properties (compressive strength, thermal conductivity, dry density, water absorption, drying shrinkage and tensile strength) of Foam concrete as prescribed by ASTM, PCA and ACI.

Comparative cost analysis indicate that optimum mix design, was 42.73 per cent lesser costlier than the corresponding control mix, whereas, both had approximately the same 28-days compressive strength, tensile strength, water absorption, drying shrinkage, and thermal conductivity.

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Chapter 1

INTRODUCTION

1.1 GENERAL BACKGROUND

Building insulation has its roots in the ancient time (Berntsson and Chandra 2003). It has been carried out by employing various traditional methods, such as, by putting mud, laying of sun burnt bricks, and by placing burnt clay tiles, etc. These methods have been employed for insulation of roofs, floors and wall cavities of buildings. Such methods of building insulation have been a source of additional dead loads, resulting in over designed uneconomical structures.

Foam concrete also known as Aerated concrete and Cellular concrete was first produced in Sweden in 1930 (Holt and Raivio 2004). It was originally designed for use as building blocks, but subsequently due to its various attractive properties, its use expanded. Perhaps the most useful property of Foam concrete is its excellent thermal insulation. It has been used for insulation against heat and sound in roof, floor, and as interspace filling between brickwork. Strictly speaking, the term 'concrete' is inappropriate because no coarse aggregate is present in Foam concrete (Neville 2000).

Foam concrete is a low density (generally ranging from 19 lb/ft^3 to 100 lb/ft^3) hardened Portland cement paste or mortar containing large number of intentionally introduced small air bubbles, called entrained air. Entrainment of air for production of Foam concrete is achieved either by mixing a suitable Foaming agent (FA) with water in mixer, producing foam and then feeding cement-sand slurry into the foam, alternatively, pre-formed foam (made in a special generator) is introduced into the mixer together with cement, water and with or without sand (Neville 2000). In either case the foam cells must have 'walls' which remain stable during mixing, transporting (which may include pumping) and placing the fresh concrete. The cells, or bubbles, are discrete and range in size between 0.1 and 1.0 mm (0.004 and 0.04 in.) (Neville 2000). The FA is usually some form of hydrolyzed protein, resin soap, or cationic and

anionic surfactant (Kosmatka et al. 2005). Another way of air entrainment is by the way of introduction of gas which is achieved usually by the use of finely divided aluminum powder, at a rate of about 0.2 per cent by weight of cement. The reaction of the powder with a hydroxide of calcium or alkalis from the cement liberates bubbles of hydrogen as shown in the chemical equation below.

$$2AL + 3Ca(OH)_2 + 6H_2O \rightarrow 3CaO.\ Al_2O_3.\ 6H_2O + 3H_2 \ \text{(gas)}$$

The bubbles expand the cement paste or the mortar, which must have such consistency as to prevent their escape. Such a concrete is also known as Gas concrete. Air entrainment can also be achieved by using detergent (surfactant) in cement-sand slurry as air-entraining agent.

Fig. 1.1. Equipment set for production of Foam concrete (Litebuilt 2005)

Fig. 1.2. Casting of Foam concrete in panels (Litebuilt 2005)

The unique properties of Foam concrete such as low density, thermal insulation, acoustical insulation, better fire resistance than normal concrete, and excellent resistance to freeze and thaw, are exploited in many engineering applications (Neville and Brooks 1987). The demand of Foam concrete in many applications of modern construction is increasing owing to the advantage that lower density results in a significant benefit in terms of load-bearing elements of smaller cross sections and a corresponding reduction in the size of the foundation.

Fig. 1.3. Casting of Foam concrete for roof insulation

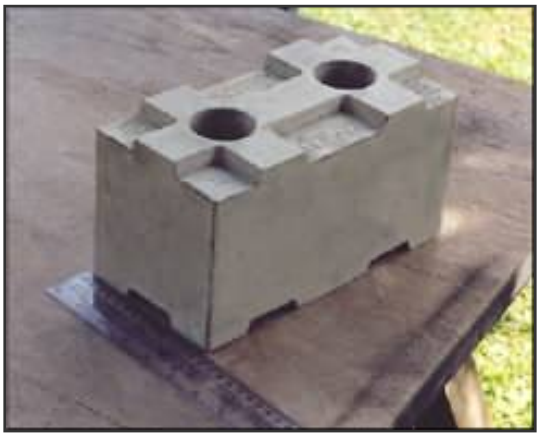

Fig. 1.4. Pre-cast Foam concrete masonry block

Foam concrete offers many advantages when used in general as well as special construction works:

- It is one of the few materials available having good mechanical strength combined with lightweight and low thermal conductivity. It can be produced in a wide range of densities and properties which can vary to suit particular requirements (Alex, L. 2001).
- Like ordinary concrete, it can easily be molded to any desired shape or size. Its surface texture makes it an excellent sound absorbent and provides a good mechanical bond for stucco and plaster.
- It has the ease of working, e.g. pre-cast Foam concrete members can be cut with hand-saw and chisel. In-situ Foam concrete offers an ease of creating simple structures, especially for small buildings.
- Foam concrete is environment friendly, such as having less construction site waste and using one fifth of the amount of resources as compared to conventional concrete (Holt and Raivio 2004).

1.2 PROBLEM STATEMENT

The main requirement in the manufacturing of Foam concrete is the proper air-entrainment of the mortar mix. This can be achieved by using commercially available FA in the mix. However, due to the higher cost of these FA, the cost of Foam concrete is escalated, which restricts its use in general construction. This problem can be overcome by using locally produced detergent in place of the expensive FA as air entraining agent with considerably lower manufacturing cost.

In manufacturing low cost Foam concrete, it is required to evaluate the possibility of using the detergent in place of FA, and if so, how the variation in its dosage will affect the properties of Foam concrete in fresh and hardened state. This research study is aimed to evaluate manufacturing of low cost Foam concrete using detergent as air-entraining agent. Its economical production with requisite material properties can replace ineffective traditional methods of insulation in developing countries.

The usage of Foam concrete in general construction work is limited in Pakistan. Other than being expensive, there is lack of information, local experience and user friendly design and construction guidelines available to promote the use for this material. This research study will result as a reference document for the users to make their design mixes according to their requirements based on the local materials.

1.3 OBJECTIVES

The primary objective of this research study is to evaluate the possibility of the production of Foam concrete using locally available detergent as foaming agent.

This research study has following specific objectives:

- To develop economical Foam concrete using indigenous detergent.
- To investigate the influence of the variation in proportion of cement, sand, FA and detergent on various properties of Foam concrete in fresh and hardened states, such as; as-placed density, air-dry density, oven-

dry density, compressive strength, tensile strength, water absorption, drying shrinkage, thermal conductivity, and effect of acid attack.

- To study the relative costs of Foam concrete produced by using detergent with the one produced by using commercially available FA.

1.4 SCOPE AND LIMITATIONS

This research study is divided into two phases.

In first phase, Foam concrete with following variables is produced.

- Variation in the dosage of FA (Chemical / detergent), ranging from 0.3 per cent to 0.5 per cent by weight of cement.
- Variation in the proportion of fine aggregate.
- Variation in cement content.

During this phase of the study, following parameters are kept constant.

- Type of detergent & FA.
- Water cement ratio
- Gradation of sand.

In this phase, 4-design mixes of non air-entrained mortar are also produced with same variables and constants for comparison of properties with Foam concrete.

In second phase, number of variables is reduced, that is, cement content and the dosage of FA are kept constant and a variation in the proportion of sand is made.

In this study cement refers to Ordinary Portland Cement (OPC). Medium size sand passing No. 30 to No.100 sieves was used. The FA used in control mixes carried the commercial name of ‘Feb Foam’. Locally produced detergent ‘Leopard Surf’ was used as an alternate indigenous FA.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Since its advent in Europe in 1930, Holt and Raivio (2004), Foam concrete is being utilized as lightweight core in sandwich structures and as thermal insulator. These usages of Foam concrete are due to its low density, low thermal conductivity, good creep resistance, and high specific stiffness and strength (Huang, Jong-Shin and Cheng, Chan-Kuen 2003). However, its wider use in structural applications has been inhibited due to lack of technical and engineering unfamiliarity and a perceived difficulty of achieving sufficiently high strength.

It is a relatively new construction material when compared to reinforced or plain normal-weight concrete. The major factor limiting the use of Foam concrete is the lack of information and design guidance regarding the acceptable performance of the material. For commonly used construction materials such as normal-weight concrete, material durability, its use and other mechanical properties are well-researched and documented. Testing standards and performance criteria exists for normal concrete, which enable the designers to specify product performance. In case of foam concrete, the issue is neither very well researched nor do any state of the art standards / specifications exist.

Despite being in the developmental process, Foam concrete has already found an important place in the global construction industry. In addition to its traditional uses, it has been incorporated in more sophisticated works like designs of military and high-security structures (Schenker 2005). Due to its high insulating properties and non-combustibility, the material finds application in refectory linings of boilers and volume fill works such as disused petrol station tanks and sewers to give improved safety conditions (Mix-concrete 2004). Foam concrete when filled in steel hollow

tubes of square and circular sections, significantly improves their bending strength (Hunaiti 1997). The ingredients formulating Foam concrete are shown in Fig. 2.1.

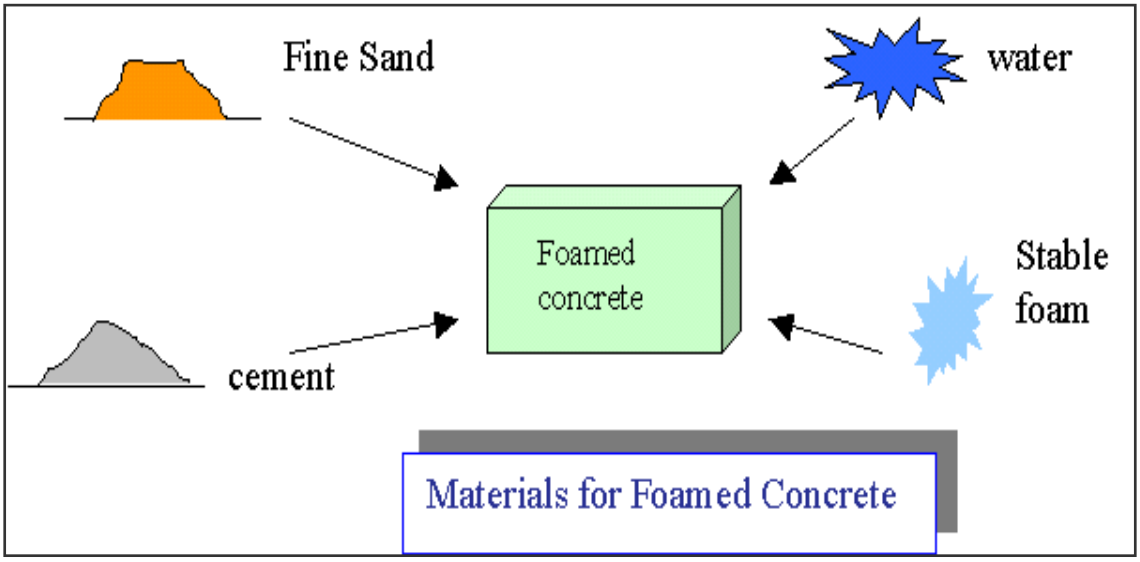

Fig. 2.1. Pictorial view of materials required for Foam concrete

2.2 AIR-ENTRAINING DETERGENTS (SURFACTANTS)

Surfactants, also known as wetting agents, lower the surface tension of a liquid, allowing easier spreading by enabling water to hold air when agitated. The term surfactant is a compression of "Surface active agents". Surfactants are usually organic compounds that contain both hydrophobic (water repelling) and hydrophilic (water attracting) groups, and are thus semi-soluble in both organic and aqueous solvents. Surfactants are used in aqueous cleaners to provide detergency, emulsification and wetting action. The four major classifications of surfactants are: anionic, cationic, nonionic, and amphoteric (Swarup et al. 1993). Since surfactants form the basic components of some of the FA and that of detergents, therefore, in this research study the practicality of air-entrainment of Foam concrete using locally manufactured detergent (surfactant) in place of the commercially available FA has been evaluated.

The chemical formula of a typical air-entraining surfactant which consists of a

non-polar hydrocarbon chain with an anionic polar group is shown in Fig. 2.2 (Mehta 2006). The mechanism by which air is entrained and stabilized when a surfactant is added to the cement-water system is described by Lea (1971), "At the air-water interface the polar groups are oriented towards the water phase lowering the surface tension, promoting bubble formation and counteracting the tendency for the dispersed bubbles to coalesce. At the solid-water interface where directive forces exist in the cement surface, the polar groups become bound to the solid with the non-polar groups oriented towards the water, making the cement surface hydrophobic so that air can displace water and remain attached to the solid particles as bubbles".

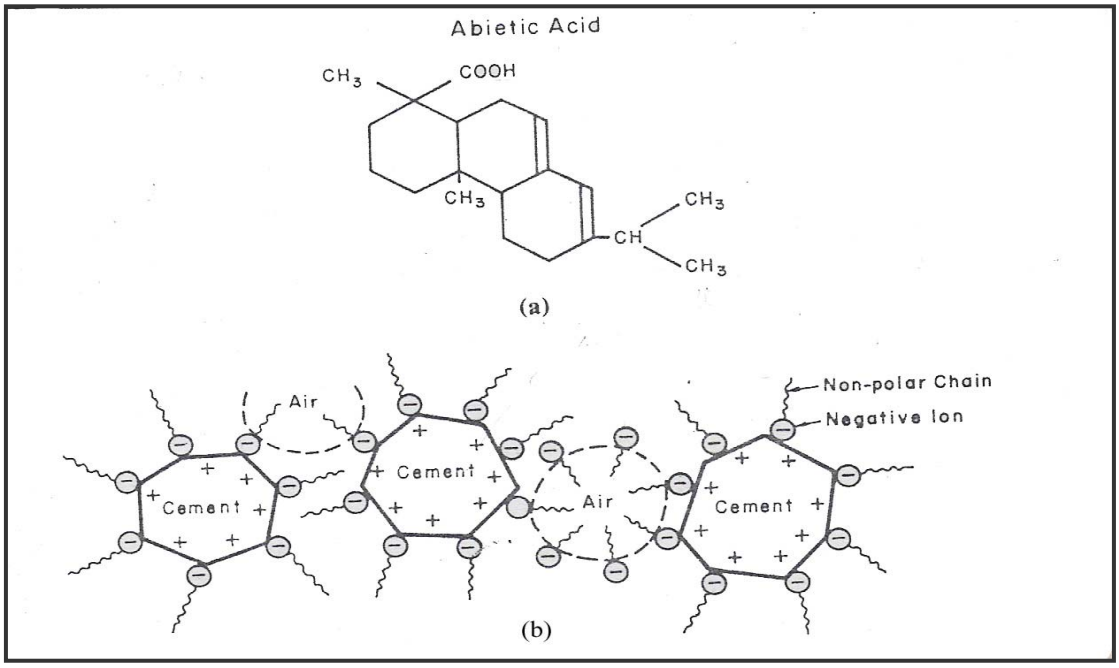

Fig. 2.2. (a) Formula of air-entraining surfactant (Mehta 2006)
(b) Mechanism of air-entrainment

2.3 PROPERTIES OF FOAM CONCRETE

2.3.1 Density

Generally the density of Foam concrete made with cement and foam only ranges from 19 - 38 lb/ft^3, whereas, the density of Foam concrete containing cement, foam and sand, ranges from 38 - 100 lb/ft^3 (Litebuilt 2005). The air-dry density of Foam concrete is considerably lower than its as-placed density. As an approximation the air-dry density is 5 lb/ft^3 (80 kg/m^3) less than the as-placed density. The lowest value of the density is oven-dry density which is of interest in determination of thermal conductivity of Foam concrete (Neville 2000). The as-placed density should always be correlated with the oven-dry density to ensure construction control (ACI SP-2 1999).

2.3.2 Compressive Strength

As in other lightweight concretes, compressive strength varies in proportion to density (Neville and Brooks 1987). Strength of Foam concrete can be expressed as a function of the void content taken as the sum of induced voids and the volume of evaporable water. Thus, the strength of moist-cured Foam concrete is governed by the total volume of voids in the concrete; that is, the strength is influenced both by water/cement ratio of the mix and by the volume of the induced voids (Hoff 1972). Other factors affecting the compressive strength of Foam concrete include age, moisture content, the physical and chemical characteristics of component materials and mix proportions (Litebuilt 2005). Compressive strength can be significantly improved through moist curing for in-situ form and high pressure steam curing for pre-cast form. Generally, compressive strength of Foam concrete ranges between 200 psi to 1450 psi (ASTM C 869 - 91).

2.3.3 Thermal Insulation

Thermal insulation is one of the salient characteristics of Foam concrete. Due to its cellular structure it offers a very low transmission of heat. By comparison, the

thermal conductivity of Foam concrete is 10 times smaller than that of normal concrete (Neville and Brooks 1987).

The high insulation property of Foam concrete gains importance as energy cost is saved by reducing both heating and air conditioning requirement. It is to be noted that the thermal conductivity increases linearly with the moisture content, "when this is 20 per cent, the conductivity is typically almost double that when the moisture content is zero" (Neville and Brooks 1987).

2.3.4 Acoustic Insulation

Foam concrete has a high sound absorption capacity. In general, dense weight concrete tends to deflect sound, whereas, Foam concrete absorbs sound (Litebuilt 2005). Thus it is often used as an insulating layer on structural concrete slabs to restrict noise transmission from floor to floor in multiple levels residential or office buildings. Foam concrete can have a sound insulation of up to 7 dB (decibels) greater than other solid building materials at the same weight per surface area (Holt and Raivio 2004).

2.3.5 Drying Shrinkage

Foam concrete exhibits higher shrinkage as compare to normal concrete. It ranges from $700x10^{-6}$ for Foam concrete with an oven-dry density of 1600 kg/m^3 to $3000x10^{-6}$ with an oven-dry density of 400 kg/m^3 (Neville 2000). Generally, the drying shrinkage of Foam concrete can be as much as 0.5 per cent (ACI SP-2 1999). Long-term drying shrinkage of Foam concrete can be improved to well under 0.1 per cent through autoclave curing (Gibbons and Wolverhampton 1972).

2.3.6 Tensile Strength

Depending on the curing method, the tensile strength of Foam concrete can be up to 0.25 of its compressive strength with a strain of around 0.1 per cent at the time of rupture (Litebuilt 2005).

2.3.7 Shear Strength

Foam concrete has a shear strength varying between 6 to 10 per cent of its compressive strength (Litebuilt 2005).

2.3.8 Water Absorption

Foam concrete has high water absorption property; however, the rate of water penetration through Foam concrete is low, making it less susceptible to frost (Neville and Brooks 1987). Its coefficient of permeability varies from 10^{-6} to 10^{-10} m/s (Neville 2000).

2.3.9 Fire Resistance

Foam concrete is extremely fire resistant and is thus well suited to fire rated application. The fire resistance is higher than ordinary concrete (Neville and Brooks 1987). It has thermal property similar to timber but much better fire resistance (Holt and Raivio 2004).

2.3.10 Modulus of Elasticity

The modulus of elasticity of Foam concrete is generally between 1.7 and 3.5 GPa ($0.25x10^6$ and $0.5x10^6$ psi), (Neville 2000).

Typical properties of Foam concrete used in United Kingdom are shown in Table 2.1(Neville 2000).

Table 2.1. Guidance Data on Foam Concrete (Neville 2000)

Cement Content (lb/yd^3)	505	540	610	670
As-placed Density (Ib/ft^3)	31	56	81	106
Oven – dry Density (Ib/ft^3)	22	47	74	97
Fine Aggregate Content (Ib/yd^3)	0	710	1320	1900
Air Content (%)	78	62	45	28
Compressive Strength (psi)	150	290	730	1450
Thermal Conductivity (Btu/ft^{2}h F^0/ft)	0.06	0.12	0.23	0.29

2.4 PREVIOUS RESEARCH

Mirza and Al-Noury (1986) used Saudi sands in making of Foam concrete by mixing with cement, lime and FA. Basic properties such as compressive strength and density were investigated. The study also investigated the effectiveness of some common surface treatments to reduce moisture penetration and to improve resistance against sulphate attack. It was observed that the behaviour of autoclaved and non-autoclaved Foam concretes was different when exposed to sulphate attack or very high temperatures.

Al-Noury et al. (1989) carried out experimentations on Foam concrete specimens aerated with FA, and studied their density and strength characteristics in comparison with moist-cured plain mortar specimens. They found that in contrast to normal-weight mortar, there is an increase in dry density and compressive strength, with an increase in water/cement ratio in Foam concrete mixes. Based on their research they suggested empirical relations for predicting the dry density and compressive strength of Foam concrete.

Tonyan and Gibson (1992) studied the structure and mechanical behaviour of Foam concrete ranging in density from 160 kg/m^3 to 1600 kg/ m^3. Various uses of Foam concrete were studied in relation to their requirements. Based on their findings they described the unique set of properties of Foam concrete and compared them with that of polymer foams. It was found that Foam concrete is superior to polymer foam based on one to one comparison of the properties of the two materials.

Kersulis and Laukaitis (1996) investigated the heat engineering properties of Foam concrete at various densities of the material. Properties of Foam concrete such as thermal conductivity, specific heat, vapour permeability and sorption moisture were studied and dependency of these properties on density was highlighted. Their research

work resulted in preparation of a range of the subject properties within which a linear relation exists.

Hunaiti (1997) carried out tests to asses the contribution of Foam concrete to the strength of steel hollow tubes of circular and square cross section. Separate sets of specimen filled with Foam concrete were subjected to axial compression (for squash load) and bending. The results of this investigation showed that Foam concrete's contribution to the squash load is negligible while its contribution to bending strength of hollow steel section is quite significant.

Jones and Giannakou (2004) used Highly-Foamed concrete for thermal insulation of foundations and ground slabs. They concluded that "excellent thermal insulation" is perhaps the most useful property of Foam concrete, and can be classified as controlled thermal fill (CTF). It is also widely used as a simple backfill. Foam concrete can be designed easily for particular densities (800-1600 kg/m^3), flow characteristics (100-300 mm spread), strength (typically less than 10 MPa) and thermal insulation performance (0.2–0.6 W/mk).

Rubio-Avalos et al. (2005) developed inorganic foam instead of the traditional organic foam for the production of Foam concrete. They used sodium bicarbonate as a gas generator. Carbon dioxide gas is released when water is added to the mixture of sodium bicarbonate and β-hemihydrate gypsum powder ($CaSO_4.1/2H_2O$). The stabilization of the foam is achieved when carbon dioxide gas is released and water is absorbed by β-hemihydrate gypsum powder, which subsequently is converted into calcium sulphate dihydrate (gypsum matrix). They concluded that for the same heat flux, the thickness of an inorganic foam slab is 73.4 per cent less than that of a concrete slab. It was further concluded that the process to obtain inorganic foam is environment friendly and has low cost. Hence, it is attractive for a wide range of applications.

Jones and McCarthy (2005) assessed the possibility of development of Foam concrete for its wider use in structural application. Their study revealed that Foam concrete is viable for structural uses.

Schenker et al. (2005) examined the capabilities of Foam concrete in mitigating the effects of blast waves. It was observed that the application of Foam concrete to various structural elements can appreciably enhance their performance in absorbing the dynamic loads, thereby, protecting the structures against explosive hazards.

Laukaitis and Fiks (2006) examined the acoustical properties of Foam concrete in three different types. By analyzing the air permeability coefficient, they observed that its value reduces as density increases. It was further observed that the air permeability coefficient of Foam concrete is lowest of all lightweight concretes because the closed pores dominate in its microstructure.

Chapter 3

EXPERIMENTAL INVESTIGATION

Through out the experimental program, the materials readily available from and in the vicinity of the area were used. The materials and the relevant testing standards are summarized below.

3.1 MATERIALS

3.1.1 Cement

In this research work locally manufactured OPC confirming to ASTM specification C 150 (Type-I) having brand name "Askari Cement" was used. The physical and chemical properties of cement are illustrated in Table 1.1 (Appendix I).

3.1.2 Fine Aggregate

Medium sized natural sand passing ASTM sieves 600 μm to 150 μm (No. 30 to No. 100), procured from Lawrencepur quarry site was used in this research work. These gradation specifications are best suited for air entrainment (PCA 2005). Sieve analysis was carried out according to ASTM C 136 - 01. Relative Density (Specific Gravity) and Water Absorption was determined according to ASTM C 128-01.

The physical properties of fine aggregate are presented in Table 1.2 (Appendix I) and the results of sieve analysis of fine aggregate as compared with the requirement of ASTM C 33 - 03 are summarized in Table 1.3 (Appendix I).

3.1.3 Foaming Agent

The FA used, was according to the provision of ASTM C 796 - 97 and C 869 - 91. It is available under commercial brand name of 'Feb Foam'. Its dosage in control

mixes was varied according to the range identified by the manufacturer and the observations made during trial mixes.

3.1.4 Detergent

Locally manufactured detergent with brand name “Leopard Surf” was used for air entrainment of the mortar mix for production of Foam concrete. Its chemical composition consists of sulphonic acid and caustic soda (sodium hydroxide). Its dosage was varied based on the observation made during trial mixes and in comparison with the variation in dosage of FA.

3.1.5 Mixing Water

Ordinary tap water from Nowshera was used during the entire experimental work.

3.2 SPECIMEN DESIGNATION

Mix designs have been designated in three categories. The control mix designs are abbreviated as 0.3FA70C30S, the detergent mix designs are abbreviated as 0.3D70C30S while the non air-entrained mortar mixes have been abbreviated as M70C30S. In the control mix designation 0.3FA refers to the amount of FA in percent by weight of cement, 70C and 30S refer to the amount of cement and sand, in percent, in the mix. This particular designation represents control mix having 0.3 per cent FA by weight of cement, with 70 and 30 per cent of cement and sand in the mix.

In detergent mix design abbreviation 0.3D70C30S, 0.3D refers to the amount of detergent, in percent, by weight of cement, 70C and 30S refer to the amount cement and sand, in percent, in the mix. This particular designation represents detergent mix having 0.3 per cent detergent, by weight of cement, with 70 and 30 per cent of cement and sand in the mix.

In non air-entrained mortar mix design M70C30S, M stands for mortar, 70C and 30S refer to the amount of cement and sand, in per cent, in the mix. This particular

designation represents non air-entrained mortar mix having 70 and 30 per cent of cement and sand in the mix.

3.3 FOAM CONCRETE MANUFACTURE PROCESS

Required amount of water was first added to the Foam concrete mixer. Then required dosage of FA or the detergent was added to the mixer. Mixer was allowed to run for about 2 to 3 minutes, till uniform foam was created. Dry mix of cement and sand was then added simultaneously to the running mixer. Mixer was allowed to run for further 2-minutes, till a uniform, flowing mix of Foam concrete was achieved. This procedure was repeated for all mix designs throughout the experimental program.

3.4 EXPERIMENTAL PROGRAM

Experimental program comprised of two phases, Phase I and Phase II. Mix designs in Phase I had more number of variables as compared to the mix designs of Phase II.

3.4.1 Experimental program Phase I

In Phase I, 12-control mix designs and 12-mix designs of Foam concrete using detergent were prepared. Mix designs with variation in dosage of FA, detergent, cement content, and sand content were prepared. Water to cement (w/c) ratio of 0.65 was kept constant. Type of FA and detergent were kept same. Details of the two types of mix designs are shown in Table 1.1 and Table 1.2 (Appendix II).

Each mix was tested for ‘as-placed density’ in fresh state. Properties that were tested in hardened state include; air-dry density, oven dry density, compressive strength, water absorption, drying shrinkage, and effect of acid attack.

3.4.1.1 As-Placed Density

This test was carried out as per ASTM C 138/C 138M - 01a. Standard 6-inch cube molds were filled with fresh Foam concrete, and the as-placed density was calculated from the weights of filled molds and their volume.

3.4.1.2 Oven-Dry Density

For each mix, oven-dry density was determined in accordance with ASTM test method C 642 - 97. Standard 2-inch cubes were prepared. After 28-days curing, these cubes were oven dried for 24-hours at a temperature of 100^0C. Oven-dry density of each mix was calculated from the oven-dry mass.

3.4.1.3 Compressive Strength

Compressive strength of each mix design was determined according to ASTM Specifications C 109/C 109M - 02 and C 796. Standard 6-inch cube specimens were prepared for this test. In accordance to the provisions of ASTM C 192/C 192M - 02, specimens were moist cured till the date of testing. Testing was carried out at the age of 3, 7 and 28-days.

3.4.1.4 Water Absorption

This test was performed in accordance to ASTM Specification C 642 - 97. Standard 2-inch cubes were prepared from each mix design. After 28-days of moist curing, test specimens were removed from curing tank. Specimens were wiped out with a cloth and transferred to laboratory oven. At a temperature of 100^0C, these specimens were oven dried for 24-hours. After removal, the specimens were weighed. These were then immersed in water for 48-hours. Upon removal from water, their weight was again recorded. Water absorption was thus calculated from the difference of the two weights.

3.4.1.5 Drying Shrinkage

Drying shrinkage test of different mix designs was carried out according to ASTM Specifications C 596 - 01 and C 157/C 157M - 04. Test specimens (Bars) were prepared in accordance with ASTM specification C 490. These bar specimens were moist cured in lime saturated-water for 48-hours, after de-molding at the age of 24-hours. Lengths of specimens were recorded after removal from curing tank. Specimens were then air-dried for 25-days and their lengths were again recorded on completion of air-drying period. Drying shrinkage was calculated from the change in length of the specimens.

3.4.1.6 Thermal Conductivity

Low thermal conductivity is probably the most important property of Foam concrete. Thermal conductivity of different mix designs of Foam concrete was calculated from its oven-dry density, as thermal conductivity of Foam concrete varies with its oven-dry density (Neville 2000). An oven dry density of 22 lb/ft^3 will have a thermal conductivity of 0.06 $Btu/ft^2h^0F/ft$, similarly an oven dry density of 97 lb/ft^3 corresponds to 0.29 $Btu/ft^2h^0F/ft$ (Neville 2000).

3.4.1.7 Acid Resistance Test

This test was performed by casting specimens of 2-inch cubes from each mix design of Foam concrete. Specimens were moist cured for 28-days. After completion of curing period, these specimens were oven-dried for 24-hours at a temperature of 100^0C. The oven-dry weight of specimens was recorded. They were then immersed in 5 per cent solution of Sulfuric Acid and Hydrochloric Acid in two separate acid tanks. Acid curing of the specimens was continued for 28-days. After removal from acid solution, the specimens were oven-dried for 48-hours. Specimens were then removed from oven and their weight was recorded. The percentage of weight loss was calculated from the difference of the two weights.

3.4.1.8 Non Air-Entrained Mortar Mixes

In addition to control mixes and the ones prepared with detergents, non air-entrained mixes of mortar were also prepared in Phase I for comparison purpose. Details of these mix designs are shown in Table 1.3 (Appendix II). All tests of Phase I were carried out for these mixes as well.

3.4.2 Experimental Program Phase II

In Phase II, 7-control mix designs and 7-mix designs using detergent were prepared. In this phase, the dosage of FA, detergent, cement content, and w/c ratio were kept constant while variation in sand content was made. Details of the two mix designs are shown in Table 1.4 and Table 1.5 (Appendix II) respectively.

In this phase, each of the mix design was subjected to same tests that were carried out in Phase I. However, an additional test of tensile strength of Foam concrete was carried out. Test results of Phase II are summarized in Appendix III to Appendix X along with results of Phase I.

3.4.2.1 Tensile Strength Test

This test was carried out in accordance to the provision of ASTM specification C 190. Specimens were prepared in standard briquette molds. These were cured in lime-saturated water for 28-days. Tensile strength test was carried out at the age of 28-days.

Chapter 4

TEST RESULTS AND ANALYSIS

4.1 OBSERVATIONS AND ANALYSIS PHASE I

4.1.1 As-Placed Density

In both control and detergent mixes, as-placed density was observed to increase as the sand to cement ratio (s/c) was increased. As-placed density for different mixes in Phase I is tabulated in Table 1.1 to Table 1.3 (Appendix III).

As-placed density varied in the range of 53 lb/ft^3 to 66 lb/ft^3. For equivalent dosage, the as-placed density of control mixes was comparatively higher than that of the detergent mixes. This shows that there occurs more air-entrainment in case of detergent as compare to that of FA at equal dosage. As-placed density of Foam concrete is about 50 per cent of the density of non-entrained mortar of corresponding mix design. Fig. 1.1 (Appendix III) shows graph of as-placed density versus s/c ratio.

4.1.2 Oven-Dry Density

Oven-dry density was observed to be less than the as-placed density in the range of 10 per cent to 18 per cent. It decreased with increase in dosage of air-entraining agents (FA or detergent). By comparison the oven-dry density of Foam concrete is about 60 per cent less than that of corresponding non air-entrained mortar mixes.

Oven-dry density for different mixes is summarized in Table 1.1 to Table 1.3 (Appendix IV). Fig. 1.1 (Appendix IV) shows the variation in oven-dry density with variation in s/c ratio, for control and detergent mix designs.

4.1.3 Compressive Strength

Detergent mix designs produced higher 3-days and 7-days strengths than the control mix designs. However, the 28-days compressive strength was higher in case of control mixes. It is due to the fact that the strength development in control mixes is slow as compared to detergent mixes. Furthermore, the better evenly distributed structure of bubbles is responsible for comparatively high strength of control mixes than that of detergent mixes at 28-days. It is, however, to be noted that all the detergent mix designs produced in this research work yielded a compressive strength well above the minimum requirement of 200 psi set forth by ASTM Specifications C 796 - 04 and C 869 - 91. Compressive strength test results of different mixes are shown in Table 1.1 to Table 1.3 (Appendix V) for 3, 7, and 28-days.

It was interesting to note that compressive strength in almost all mixes started dropping as the s/c ratio approached 0.82. This is thought to be due to the linearity of mix, in which the air-entrainment is not uniform, as observed from some of the specimens in hardened state. It can, therefore, be concluded that the compressive strength of Foam concrete keeps on increasing with increase in density, however after a certain peak, the strength starts dropping, even if there is a corresponding increase in density. Fig 1.1 (Appendix V) shows the plot of compressive strength versus density. From the figure, it is also clear that the compressive strength decreases with the increase in the dosage of air entraining agent in both cases, that is, control and detergent mixes.

The behaviour of Foam concrete to have higher compressive strength with higher density (linear mixes) is quite different from the plain mortar mixes, in which case the compressive strength dropped as the mix went towards linearity. Generally, the compressive strength of Foam concrete was observed to be 8 to 12 per cent of the compressive strength of corresponding non air-entrained mortar mixes at 28-days.

Compressive strength test results for detergent mixes showed a standard deviation in the range of 80 psi to 98 psi. The coefficient of variation which is the ratio of standard deviation to mean value lied in the range of 10 per cent to 13 per cent,

which has been termed as an excellent control by the U.S. Bureau of Reclamation according to their standards of control (ACI Committee 214).

The failure mechanism (cracks pattern) of Foam concrete at 28-days compressive strength test was almost similar to that of normal mortar. This pattern of failure was, however, quite different in case of specimens produced with high dosage of air-entraining agent, in which case, at failure the specimens did not develop any cracks, rather, they went under compression like soft compressible objects till they were squashed.

4.1.4 Water Absorption

During this study, it was observed that Foam concrete has double water absorption percentage than non air-entrained mortar. Results of water absorption test are summarized in Table 1.1 to Table 1.3 (Appendix VI). As can be seen, the water absorption in Foam concrete increases as the dosage of air entraining agent is increased. This phenomenon holds true for both control and detergent mixes. By comparison, detergent mixes showed higher water absorption than that of control mixes. However, for majority of the mixes the water absorption was with in the limit set by ASTM Specification C 869 - 91. Water absorption of Foam concrete decreased with the increase in density of the mix design in both control as well as detergent mixes.

The results of detergent mixes showed a standard deviation in the range of 2.5 per cent to 3.5 per cent. For most of the mixes, this gives the coefficient of variation well below 15 per cent which is considered quite good (ACI Committee 214). Fig. 1.1 (Appendix VI) shows the graphical presentation of water absorption of different mix designs. Generally, detergent mixes were found to be better at lower dosage of detergent; that is, they had less water absorption as compared to the corresponding control mixes.

An interesting fact was revealed, when few of the 2-inch cube specimens were broken and their inside structure was inspected just after removal from water. It was observed that, water, actually did not penetrate to the core of the specimens, it was

rather confined to the outer most few centimeters. The outer shell being not strong enough to hold all the air bubbles, become porous and hence susceptible to water penetration. In the core structure of Foam concrete, the capillaries are discontinued by the air bubbles and hence water can not penetrate into it. This is the principal reason of high durability of air-entrained concretes, especially Foam concrete. The above mentioned fact also substantiate as to why Foam concrete has lower rate of water penetration (Neville and Brooks 1987).

4.1.5 Drying Shrinkage

Drying shrinkage of detergent mix designs was observed to be slightly higher than the corresponding control mix designs. Results of this test are tabulated in Table 1.1 to Table 1.3 (Appendix VII). Drying shrinkage was observed to decrease with an increase in s/c ratio. It however, increased as the dosage of air entraining agent was increased in both types of mix designs. Fig. 1.1 (Appendix VII) shows the graphical presentation of drying shrinkage of different mix designs.

Drying shrinkage of Foam concrete, turned out to be 100 per cent higher than that of corresponding non air-entrained mixes.

4.1.6 Thermal Conductivity

Thermal conductivity of Foam concrete has linear relation with its oven dry density. It was therefore calculated from the values of oven-dry density for each mix design. Thermal conductivity of different mix designs is tabulated in Table 1.1 to Table 1.3 (Appendix VIII).

Values of the thermal conductivity calculated in this study are excellently located in range prescribed for Foam concrete. Thermal conductivity of different Foam concrete mix designs was found to be one tenth of the thermal conductivity of non air-entrained mortar. Fig. 1.1 (Appendix VIII) shows the plot of oven-dry density versus thermal conductivity.

4.1.7. Acid Resistance

Foam concrete showed much better resistance when immersed in sulfuric acid and hydrochloric acid solutions, as compared to non air-entrained mortar mixes. By comparison, weight loss was slightly higher in case of detergent mix designs as compare to the control mix designs. Physical observation of specimens, made just after removal from acid tanks and the subsequent test data revealed that more deterioration was caused by sulfuric acid than hydrochloric acid. It is due to the fact that in case of sulfuric acid, a product called calcium sulfoaluminate (Ettringite) is formed, which expands and hence causes disruption of the set cement paste (Rawal and Nimityongskul 2004). Whereas, no such product is formed in case of hydrochloric acid. Results of this test are shown in Table 1.1 to Table 1.3 (Appendix IX).

4.1.7.1 Test Conducted in 5 per cent Sulfuric Acid Solution

Colour of almost all specimens had changed from grayish to whitish with scales formed on surface of some of the specimens. It was further observed that mix designs with high cement content suffered more weight loss as compared to those which had less cement content Fig. 1.1 (Appendix IX). This is due to the fact in rich mixes the amount of calcium hydroxide formed is more than that formed in lean mixes. Calcium hydroxide as hydrated compound is easily attacked by acids (Rawal and Nimityongskul 2004).

Average weight loss of Foam concrete mix designs was about 45 per cent less than that of non air-entrained mortar. This is due to the fact that the presence of air bubbles makes the capillaries discontinuous; hence the acid can not penetrate to the core of the Foam concrete. This phenomenon is similar to that of water absorption.

4.1.7.2 Test Conducted in 5 per cent Hydrochloric Acid Solution

Specimens gave pale yellow appearance after removal from hydrochloric acid tank. There were no signs of any scaling or deterioration. The surface of specimens looked quite intact. It can be concluded that the effect of this acid on almost all the mix designs was negligible when compared to that of sulfuric acid. Average weight

loss in this test worked out to just 25 per cent of the weight loss in case of sulfuric acid. The trend of weight loss, however, was similar to that of sulfuric acid test. Fig.1.2 (Appendix IX) shows the graphical presentation of weight loss of different mix designs.

4.1.8 Conclusion of Phase I

Based on the results of Phase I, the mix designs 0.4D60C40S and 0.4D65C35S and their counter part from control mix showed better results. The four FA / detergent mix designs fulfill the requirements of optimum mix designs of Foam concrete. They have highest compressive strength in respective group with oven dry density and water absorption well within prescribed range. However, among the four mix designs, the designs using 60 per cent cement and 40 per cent sand for both air entraining agents had better compressive strength, lower water absorption, and higher tensile. It was therefore realized to carry out further research on the subject mix designs, by reducing the number of variables. Hence, Phase II of the research work was planned.

4.2 OBSERVATIONS AND ANALYSIS PHASE II

4.2.1 As-Placed Density

As-placed density, in this Phase II also followed the trend of Phase I. However, it varied in the range of 57 lb/ft^3 to 73 lb/ft^3. Results of this test are shown in Table 1.4 and Table 1.5 (Appendix III). Fig. 1.2 (Appendix III) shows graph of as-placed density versus s/c ratio.

4.2.2 Oven-Dry Density

Oven-dry density for all the mix designs followed the trend of Phase I. For different mix designs the density is tabulated in Table 1.4 and Table 1.5 (Appendix IV). Fig. 1.2 (Appendix IV) shows plot of oven-dry density versus s/c ratio.

4.2.3 Compressive Strength

It was observed that; as the s/c ratio reached 0.82, the compressive strength in almost all the mixes started dropping, in spite of a corresponding increase in the density. This phenomenon was observed to be more pronounced in Phase I. In some of the mix designs with high s/c ratio, few specimens were observed to have two distinct layers, top layer of air-entrained concrete and bottom layer of non air-entrained concrete. This trend prevailed in the corresponding control mix designs as well. Table 1.4 and Table 1.5 (Appendix V) shows the compressive strength (at 3, 7 and 28-days) of different control and detergent mix designs. Fig. 1.2 (Appendix V) shows graph of compressive strength of different control and detergent mix designs.

4.2.4 Water Absorption

Water absorption trend of Phase I prevailed here as well, however, generally the control and detergent mix designs showed better results than Phase I. A standard deviation of 3 to 3.5 per cent was observed in the results, giving a coefficient of variation below 15 per cent which is good. Table 1.4 and Table 1.5 (Appendix VI) shows the results of this test. Fig. 1.2 (Appendix VI) shows graphical presentation of this test for control and detergent mixes.

4.2.5 Drying Shrinkage

Due to high s/c ratio, drying shrinkage of mix designs in this phase was lower than Phase I. The trend of Phase I hold good here too. Table 1.4 and Table 1.5 (Appendix VII) shows the results of this test. Fig. 1.2 (Appendix VII) presents graphical view of this test.

4.2.6 Thermal Conductivity

Trend was similar to that of Phase I. Thermal conductivity of control and detergent mix designs are shown in Table 1.4 and Table 1.5 (Appendix VIII). Fig. 1.2 (Appendix VIII) show graphical presentation of this property.

4.2.7 Acid Resistance

In case of both, sulfuric acid and hydrochloric acid, mix designs in this phase showed less weight loss as compare to Phase I. Control mixes performed better than corresponding detergent mixes. Results of this test are summarized in Table 1.4 and Table 1.5 (Appendix IX). Fig. 1.3 and Fig. 1.4 (Appendix IX) shows the graphical presentation of the two tests.

4.2.8 Tensile Strength Test

Tested tensile strength was observed to increase with an increase in density of the mix designs. However, it started to drop as the s/c ratio reached 0.82. Like in case of compressive strength, here too, this trend could be due to the non uniform air-entrainment in mix designs with high s/c ratio, which resulted in layered product. As an average, the tensile strength of Foam concrete mix designs was one fourth of the tensile strength of non air-entrained mortar. Test results are shown in Table 1.1 to Table 1.2 (Appendix X). Table 1.3 of subject Appendix shows results of this test in respect of non air-entrained mortar mixes. By comparison, the tensile strength of control mixes was about 8 per cent higher than that of the corresponding detergent mix designs. Fig. 1.1 (Appendix X) shows graphical presentation of variation in tensile strength for different mix designs of control and detergent categories.

4.2.9 Conclusion of Phase II

Although the increase in density of mix designs having air-entraining agents 0.4 per cent by weight of cement, did improve some of the properties like water absorption and drying shrinkage, this however, resulted in loss of compressive strength, increase in thermal conductivity and oven-dry density. The disadvantages thus outweighed the advantages of this variation. Consequently, detergent mix design 0.4D60C40S and its counter part 0.4FA60C40S from control mix designs emerged as the optimum mix designs in phase II.

4.3 COST ANALYSIS OF CONTROL AND DETERGENT MIX

Cost analysis of the materials used, has been carried out based on the market cost, as prevailing in March 2006. Optimum mix designs from both the categories, that is, from control and detergent mixes, were considered for cost analysis. Detailed calculations of cost analysis are shown in Table 1.1 (Appendix XI). Based on cost analysis, mix design 0.4D60C40S was found to be 42.73 per cent less costly than mix design 0.4FA60C40S.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the observations made and the experimental results obtained in this research study, following conclusions are drawn:

- The production of low cost Foam concrete using locally produced detergent as FA in place of commercially available FA is feasible.
- Foam concrete mix produced with a dosage of detergent at the rate of 0.4 per cent by weight of cement, having cement and sand in the ratio of 60 and 40 per cent, respectively was found to be the best mix design when compared with control mix. This mix design exhibited excellent properties, falling well within the range prescribed by ASTM, PCA and ACI.
- Foam concrete with a desired oven-dry density ranging from 60 lb /ft^3 to 40 lb/ft^3 having a compressive strength in the range of 750 psi to 490 psi can be produced using the locally produced detergent. Such Foam concrete has properties comparable with the control mix.
- An increase in compressive and tensile strength with increase in s/c ratio was observed, however, both the strengths started dropping as the s/c ratio approached 0.82. It is due to the uneven air-entrainment of the mix at higher s/c ratio resulting in non-homogeneous mix.
- By comparison, detergent mixes showed lower water absorption at low dosage of detergent than the corresponding control mixes. Although, Foam concrete was observed to have high water absorption than the non air-entrained mortar mix; it has, however, low water penetration. This is due to the fact that the structure of air bubbles in Foam concrete makes the

capillaries discontinuous; therefore, water can not penetrate to the core of the Foam concrete that is why it is called a durable material.

- Foam concrete showed much better resistance to acid attack than the non air-entrained mix. Weight loss was observed to be more in case of sulfuric acid than hydrochloric acid, furthermore, weight loss was observed to increase with increase of cement content in the mix. The reason is availability of more calcium hydroxide for acid attack. Weight loss in case of detergent mixes was slightly higher than the control mixes.
- Cost analysis concluded 0.4D60C40S as to be 42.73 per cent less costly than the corresponding control mix design.

5.2 RECOMMENDATIONS

Following are recommended for future research:

- Use of sugar molasses, as air-entraining agent, for production of Foam concrete.
- Investigating the use of Foam concrete for foundation bedding and as Damp Proof Course (DPC) in the building construction.
- Using detergent in the production of structural concrete, for enhancing, its durability.
- Autoclaving of the Foam concrete produced from detergent for improvement of its physical and mechanical properties.

APPENDIX I
(Properties of Cement and Sand)

Table 1.1. Physical and Chemical Properties of OPC

S/No	Parameter	Result	Standard Requirements*
1	Specific gravity	3.15	3.10 to 3.25
2	Moisture content (per cent)	0.11	-
3	Silicon Dioxide (SiO_2) (per cent)	19	18.7 to 22.0
4	Calcium Oxide (CaO) (per cent)	60	60.6 to 66.3
5	Magnesium Oxide (MgO) (per cent)	1.63	0.7 to 4.2
6	Aluminum Oxide (Al_2O_3) (per cent)	9.87	4.7 to 6.3
7	Ferric Oxide (Fe_2O_3) (per cent)	3.46	1.6 to 4.4
8	Potassium Oxide (K_2O) (per cent)	1.19	1.0 to 1.5
9	Sodium Oxide (Na_2O_3) (per cent)	0.84	0.11 to 1.20
10	Sulfur Trioxide (SO_3) (per cent)	2.63	1.8 to 4.6
11	Loss on Ignition (per cent)	1.03	0 to 3

* Adapted from ASTM C 150-04 , ASTM C 114 and PCA (2005)

Table 1.2. Physical Properties of Sand

S/No	Parameter	Result
1	Dry Roded unit weight (lb/ft^3)	106.5
2	Bulk Specific gravity	2.45
3	Bulk Specific gravity (SSD)	2.48
4	Absorption (per cent)	0.96
5	Fineness Modulus	2.45

Table 1.3. Grading of Sand

ASTM sieve No	Sieve size (mm)	Weight retained (gm)	Percentage retained	Cumulative percentage retained	Percentage passing	
					Actual	ASTM C 33-03
16	1.18	306.78	30.97	30.97	69.03	50 to 85
30	0.60	186.32	18.81	49.78	50.22	25 to 60
50	0.30	371.34	37.49	87.27	12.73	5 to 30
100	0.15	113.24	11.43	98.7	1.3	0 to 10
Pan	-	12.74	1.28	-	-	-
Total		990.42		262.37		

APPENDIX II
(Mix Designs)

Table 1.1. Control Mix Designs (Phase I)

S/No	Mix Designation	Cement (per cent)	Sand (per cent)	Sand/Cement ratio	FA (per cent of OPC)
1	0.3FA70C30S	70	30	0.43	0.3
2	0.3FA65C35S	65	35	0.54	0.3
3	0.3FA60C40S	60	40	0.67	0.3
4	0.3FA55C45S	55	45	0.82	0.3
5	0.4FA70C30S	70	30	0.43	0.4
6	0.4FA65C35S	65	35	0.54	0.4
7	0.4FA60C40S	60	40	0.67	0.4
8	0.4FA55C45S	55	45	0.82	0.4
9	0.5FA70C30S	70	30	0.43	0.5
10	0.5FA65C35S	65	35	0.54	0.5
11	0.5FA60C40S	60	40	0.67	0.5
12	0.5FA55C45S	55	45	0.82	0.5

Table 1.2. Detergent Mix Designs (Phase I)

S/No	Mix Designation	Cement (per cent)	Sand (per cent)	Sand/Cement ratio	Detergent (per cent of OPC)
1	0.3D70C30S	70	30	0.43	0.3
2	0.3D65C35S	65	35	0.54	0.3
3	0.3D60C40S	60	40	0.67	0.3
4	0.3D55C45S	55	45	0.82	0.3
5	0.4D70C30S	70	30	0.43	0.4
6	0.4D65C35S	65	35	0.54	0.4
7	0.4D60C40S	60	40	0.67	0.4
8	0.4D55C45S	55	45	0.82	0.4
9	0.5D70C30S	70	30	0.43	0.5
10	0.5D65C35S	65	35	0.54	0.5
11	0.5D60C40S	60	40	0.67	0.5
12	0.5D55C35S	55	45	0.82	0.5

Table 1.3. Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Cement (per cent)	Sand (per cent)	Sand/Cement ratio)
1	M70C30S	70	30	0.43
2	M65C35S	65	35	0.54
3	M60C40S	60	40	0.67
4	M55C45S	55	45	0.82

Table 1.4. Control Mix Designs (Phase II)

S/No	Mix Designation	Cement (per cent)	Sand (per cent)	Sand/Cement ratio
1	0.4FA60C25S	60	25	0.42
2	0.4FA60C30S	60	30	0.50
3	0.4FA60C35S	60	35	0.58
4	0.4FA60C40S	60	40	0.67
5	0.4FA60C45S	60	45	0.75
6	0.4FA60C50S	60	50	0.83
7	0.4FA60C55S	60	55	0.92

Table 1.5. Detergent Mix Designs (Phase II)

S/No	Mix Designation	Cement (per cent)	Sand (per cent)	Sand/Cement ratio)
1	0.4D60C25S	60	25	0.42
2	0.4D60C30S	60	30	0.50
3	0.4D60C35S	60	35	0.58
4	0.4D60C40S	60	40	0.67
5	0.4D60C45S	60	45	0.75
6	0.4D60C50S	60	50	0.83
7	0.4D60C55S	60	55	0.92

APPENDIX III
(As-Placed Density)

Table 1.1. As-Placed Density of Control Mix Designs (Phase I)

S/No	Mix Designation	As-placed Density* (lb/ft^3)
1	0.3FA70C30S	55.89
2	0.3FA65C35S	58.44
3	0.3FA60C40S	60.63
4	0.3FA55C45S	60.89
5	0.4FA70C30S	55.43
6	0.4FA65C35S	62.00
7	0.4FA60C40S	66.54
8	0.4FA55C45S	67.34
9	0.5FA70C30S	56.42
10	0.5FA65C35S	59.32
11	0.5FA60C40S	64.00
12	0.5FA55C45S	66.20

* As-placed density is taken from average of 3 specimens

Table 1.2. As-Placed Density of Detergent Mix Designs (Phase I)

S/No	Mix Designation	As-placed Density (lb/ft^3)
1	0.3D70C30S	53.17
2	0.3D65C35S	55.13
3	0.3D60C40S	57.68
4	0.3D55C45S	59.80
5	0.4D70C30S	52.22
6	0.4D65C35S	56.47
7	0.4D60C40S	59.03
8	0.4D55C45S	60.47
9	0.5D70C30S	49.60
10	0.5D65C35S	53.78
11	0.5D60C40S	57.75
12	0.5D55C45S	60.69

Table 1.3. As-Placed Density of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	As-placed Density (lb/ft^3)
1	M70C30S	131.50
2	M65C35S	130.80
3	M60C40S	128.31
4	M55C45S	127.41

Table 1.4. As-Placed Density of Control Mix Designs (Phase II)

S/No	Mix Designation	As-placed Density (lb/ft^3)
1	0.4FA60C25S	58.13
2	0.4FA60C30S	62.00
3	0.4FA60C35S	65.21
4	0.4FA60C40S	66.83
5	0.4FA60C45S	67.23
6	0.4FA60C50S	69.89
7	0.4FA60C55S	71.22

Table 1.5. As-Placed Density of Detergent Mix Designs (Phase II)

S/No	Mix Designation	As-placed Density (lb/ft^3)
1	0.4D60C25S	57.45
2	0.4D60C30S	62.98
3	0.4D60C35S	65.42
4	0.4D60C40S	66.35
5	0.4D60C45S	68.47
6	0.4D60C50S	70.00
7	0.4D60C55S	73.72

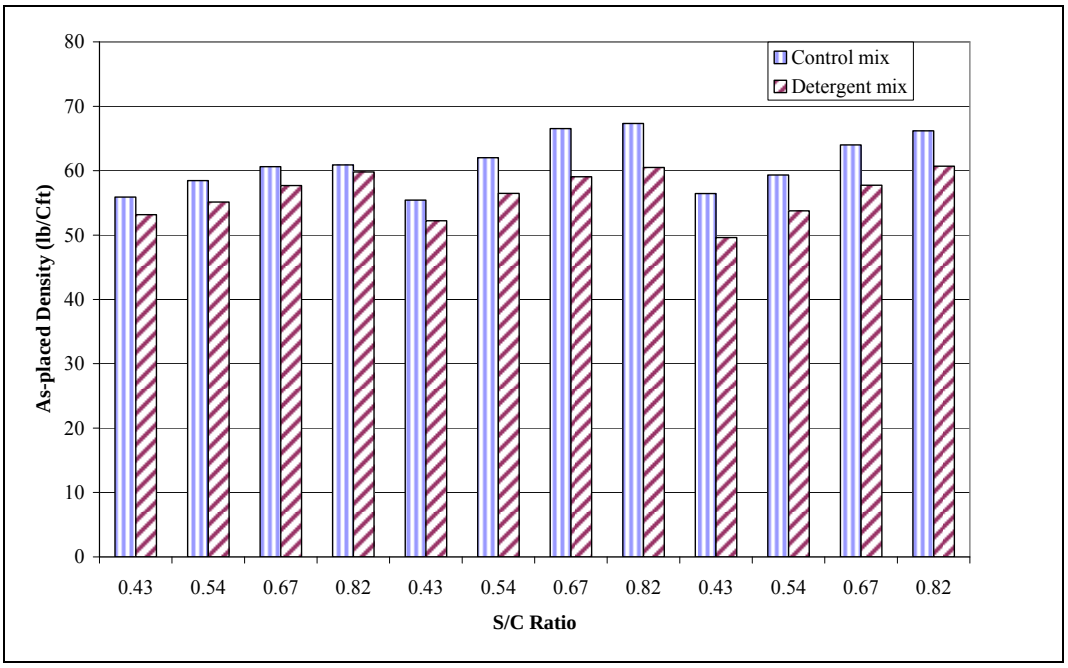

Fig. 1.1. As-placed density versus s/c ratio (Phase I)

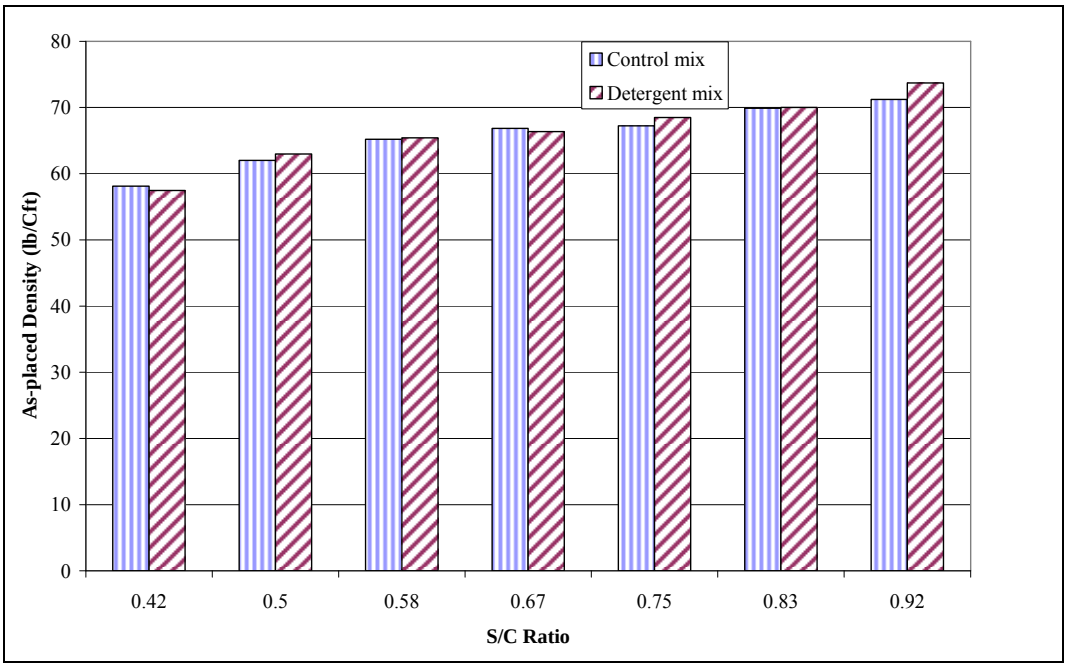

Fig. 1.2. As-placed density versus s/c ratio (Phase II)

APPENDIX IV
(Oven-Dry Density)

Table 1.1. Oven-Dry Density of Control Mix Designs (Phase I)

S/No	Mix Designation	Oven-dry Density* (lb/ft^3)
1	0.3FA70C30S	48.89
2	0.3FA65C35S	50.94
3	0.3FA60C40S	52.13
4	0.3FA55C45S	53.89
5	0.4FA70C30S	48.56
6	0.4FA65C35S	50.47
7	0.4FA60C40S	51.74
8	0.4FA55C45S	53.88
9	0.5FA70C30S	42.62
10	0.5FA65C35S	43.38
11	0.5FA60C40S	45.19
12	0.5FA55C45S	47.12

* Oven-dry density as taken as average of 3 specimens

Table 1.2. Oven-Dry Density of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Oven-dry Density (lb/ft^3)
1	0.3D70C30S	47.17
2	0.3D65C35S	49.13
3	0.3D60C40S	51.18
4	0.3D55C45S	53.08
5	0.4D70C30S	45.22
6	0.4D65C35S	49.47
7	0.4D60C40S	51.31
8	0.4D55C45S	52.57
9	0.5D70C30S	41.10
10	0.5D65C35S	45.28
11	0.5D60C40S	48.85
12	0.5D55C45S	51.89

Table 1.3. Oven-Dry Density of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Oven-dry Density (lb/ft^3)
1	M70C30S	129.92
2	M65C35S	128.56
3	M60C40S	127.27
4	M55C45S	126.32

Table 1.4. Oven-Dry Density of Control Mix Designs (Phase II)

S/No	Mix Designation	Oven-dry Density (lb/ft^3)
1	0.4FA60C25S	47.32
2	0.4FA60C30S	50.78
3	0.4FA60C35S	51.24
4	0.4FA60C40S	52.00
5	0.4FA60C45S	54.31
6	0.4FA60C50S	58.54
7	0.4FA60C55S	61.23

Table 1.5. Oven-Dry Density of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Oven-dry Density (lb/ft^3)
1	0.4D60C25S	47.00
2	0.4D60C30S	49.48
3	0.4D60C35S	50.43
4	0.4D60C40S	51.22
5	0.4D60C45S	53.00
6	0.4D60C50S	56.31
7	0.4D60C55S	58.00

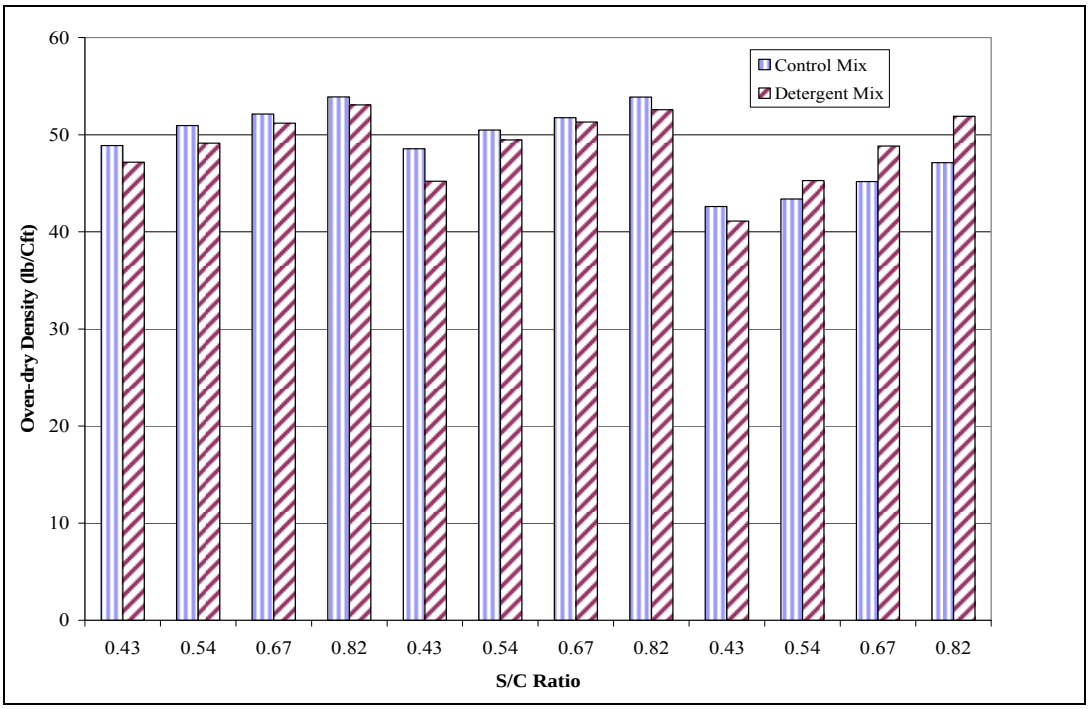

Fig. 1.1. Oven-dry density versus s/c ratio (Phase I)

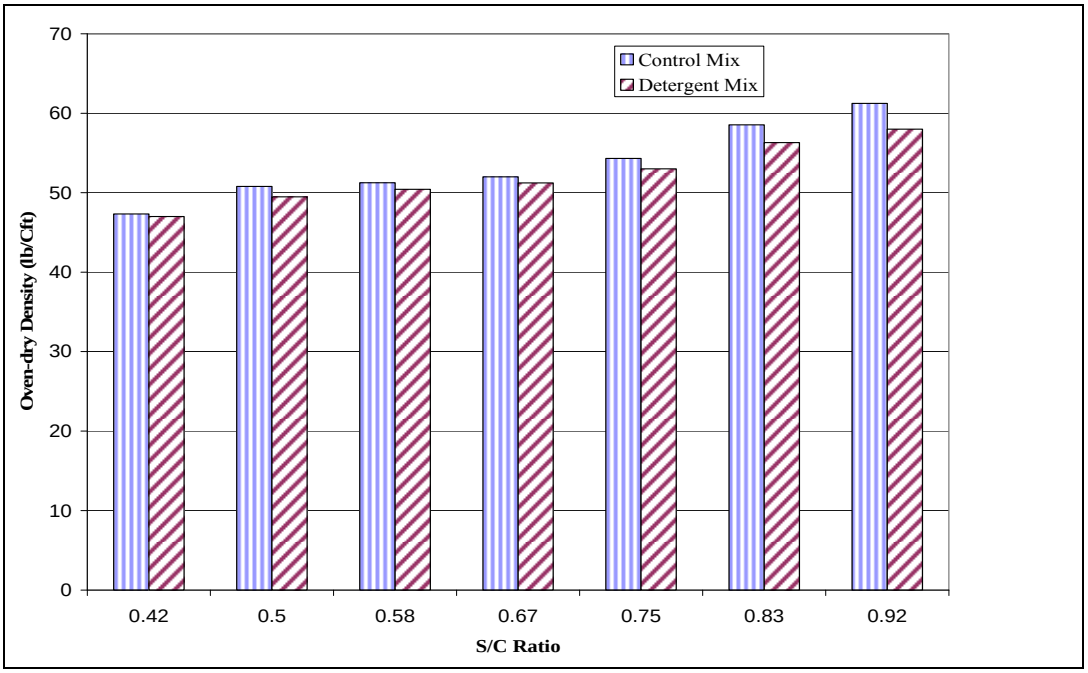

Fig. 1.2. Oven-dry density versus s/c ratio (Phase II)

APPENDIX V
(Compressive Strength)

Table 1.1. Compressive Strength of Control Mix Designs (Phase I)

S/No	Mix Designation	Compressive Strength* (psi) 3-days	Compressive Strength* (psi) 7-days	Compressive Strength* (psi) 28-days
1	0.3FA70C30S	180	258	719
2	0.3FA65C35S	187	250	731
3	0.3FA60C40S	195	264	749
4	0.3FA55C45S	184	280	714
5	0.4FA70C30S	194	259	665
6	0.4FA65C35S	160	240	739
7	0.4FA60C40S	165	317	802
8	0.4FA55C45S	175	265	732
9	0.5FA70C30S	245	314	600
10	0.5FA65C35S	155	238	682
11	0.5FA60C40S	163	271	705
12	0.5FA55C45S	172	225	675

* Compressive strength is taken as the average of 3 specimens

Table 1.2. Compressive Strength of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Compressive Strength (psi) 3-days	Compressive Strength (psi) 7-days	Compressive Strength (psi) 28-days
1	0.3D70C30S	256	391	658
2	0.3D65C35S	213	365	667
3	0.3D60C40S	271	415	691
4	0.3D55C45S	268	423	679
5	0.4D70C30S	424	426	667
6	0.4D65C35S	204	355	705
7	0.4D60C40S	269	398	752
8	0.4D55C45S	265	372	678
9	0.5D70C30S	154	264	560
10	0.5D65C35S	326	412	615
11	0.5D60C40S	296	546	671
12	0.5D55C45S	254	369	590

Table 1.3. Compressive Strength of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Compressive Strength (psi) 3-days	Compressive Strength (psi) 7-days	Compressive Strength (psi) 28-days
1	M70C30S	4872	5156	8563
2	M65C35S	2935	4875	7356
3	M60C40S	2306	3823	6725
4	M55C45S	1639	3002	6236

Table 1.4. Compressive Strength of Control Mix Designs (Phase II)

S/No	Mix Designation	Compressive Strength (psi) 3-days	Compressive Strength (psi) 7-days	Compressive Strength (psi) 28-days
1	0.4FA60C25S	132	202	660
2	0.4FA60C30S	146	225	695
3	0.4FA60C35S	149	230	708
4	0.4FA60C40S	189	311	799
5	0.4FA60C45S	175	293	785
6	0.4FA60C50S	180	295	610
7	0.4FA60C55S	178	296	590

Table 1.5. Compressive Strength of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Compressive Strength (psi) 3-days	Compressive Strength (psi) 7-days	Compressive Strength (psi) 28-days
1	0.4D60C25S	138	234	610
2	0.4D60C30S	176	256	640
3	0.4D60C35S	203	269	685
4	0.4D60C40S	262	399	747
5	0.4D60C45S	248	379	710
6	0.4D60C50S	253	386	600
7	0.4D60C55S	255	368	490

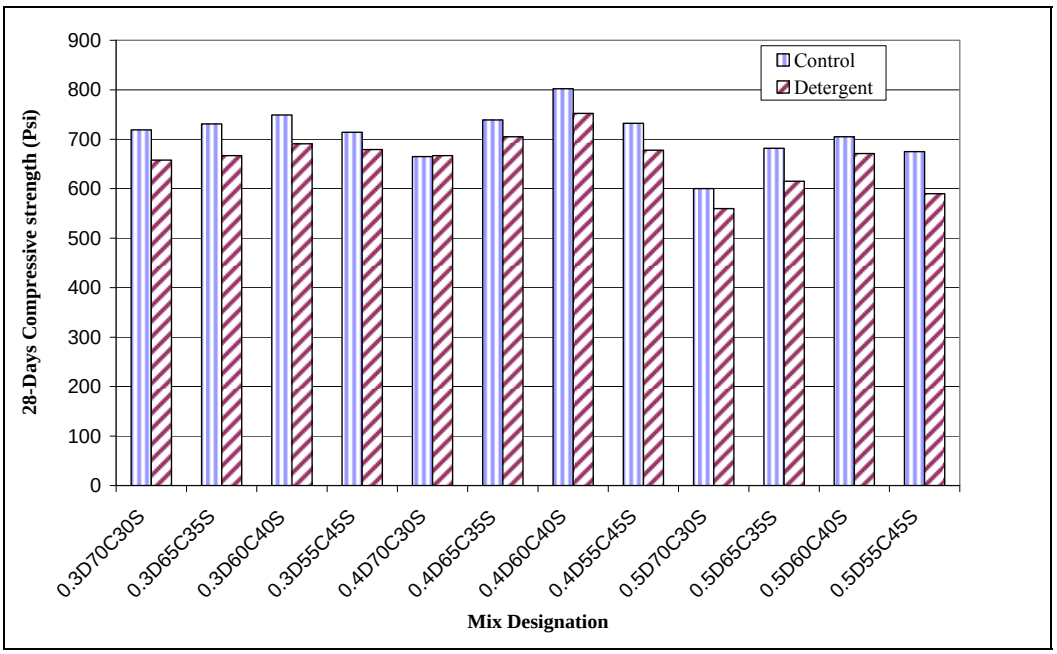

Fig. 1.1. 28-days Compressive strength of different mix designs (Phase I)

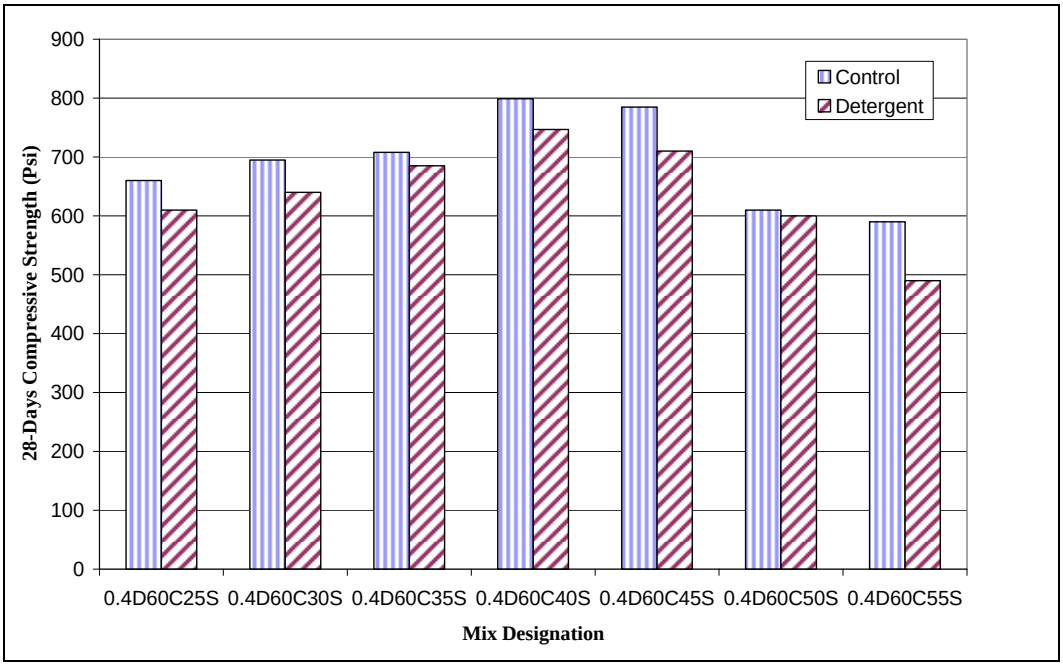

Fig. 1.2. 28-days Compressive strength of different mix designs (Phase II)

APPENDIX VI
(Water Absorption)

Table 1.1. Water Absorption of Control Mix Designs (Phase I)

S/No	Mix Designation	Water Absorption* (per cent)
1	0.3FA70C30S	24.01
2	0.3FA65C35S	22.62
3	0.3FA60C40S	21.34
4	0.3FA55C45S	20.90
5	0.4FA70C30S	33.33
6	0.4FA65C35S	30.72
7	0.4FA60C40S	29.35
8	0.4FA55C45S	28.18
9	0.5FA70C30S	40.45
10	0.5FA65C35S	38.09
11	0.5FA60C40S	37.45
12	0.5FA55C45S	37.34

* Water absorption is taken from average of 3 specimens

Table 1.2. Water Absorption of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Water Absorption (per cent)
1	0.3D70C30S	21.62
2	0.3D65C35S	21.12
3	0.3D60C40S	20.09
4	0.3D55C45S	19.35
5	0.4D70C30S	26.72
6	0.4D65C35S	25.90
7	0.4D60C40S	24.77
8	0.4D55C45S	24.27
9	0.5D70C30S	45.75
10	0.5D65C35S	44.15
11	0.5D60C40S	43.07
12	0.5D55C35S	42.86

Table 1.3. Water Absorption of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Water Absorption (per cent)
1	M70C30S	9.24
2	M65C35S	9.63
3	M60C40S	9.74
4	M55C45S	10.01

Table 1.4. Water Absorption of Control Mix Designs (Phase II)

S/No	Mix Designation	Water Absorption (per cent)
1	0.4FA60C25S	26.01
2	0.4FA60C30S	25.50
3	0.4FA60C35S	25.00
4	0.4FA60C40S	24.82
5	0.4FA60C45S	24.00
6	0.4FA60C50S	23.50
7	0.4FA60C55S	23.24

Table 1.5. Water Absorption of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Water Absorption (per cent)
1	0.4D60C25S	27.23
2	0.4D60C30S	26.90
3	0.4D60C35S	26.23
4	0.4D60C40S	25.50
5	0.4D60C45S	25.00
6	0.4D60C50S	24.59
7	0.4D60C55S	24.00

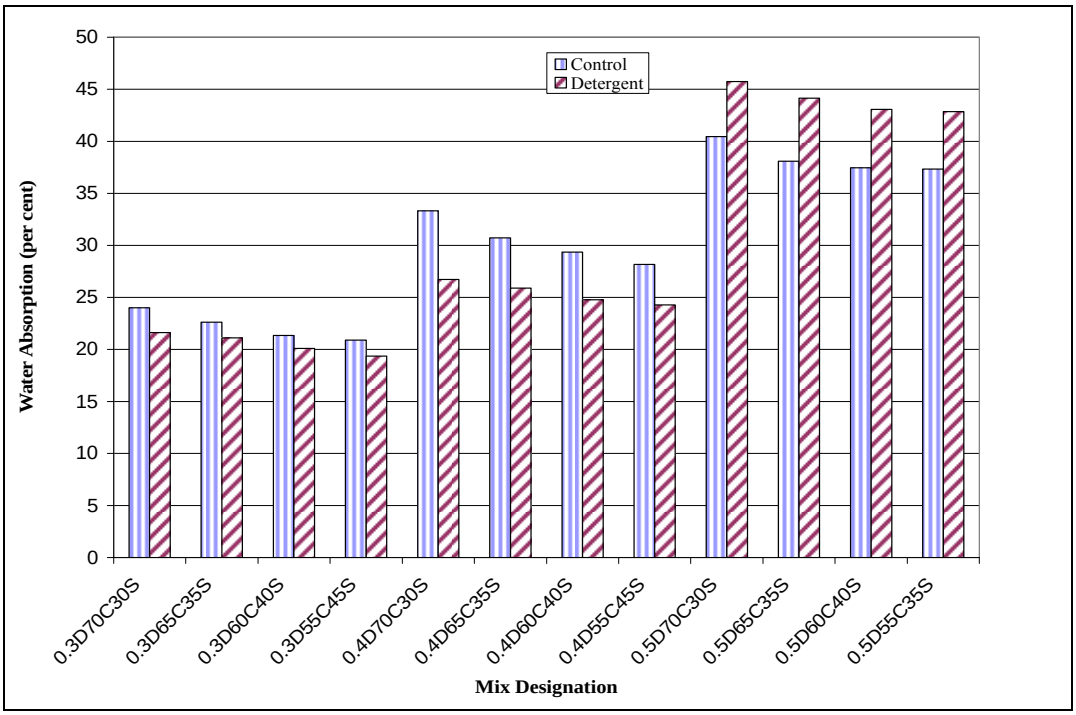

Fig. 1.1. Water absorption of different mix designs (Phase I)

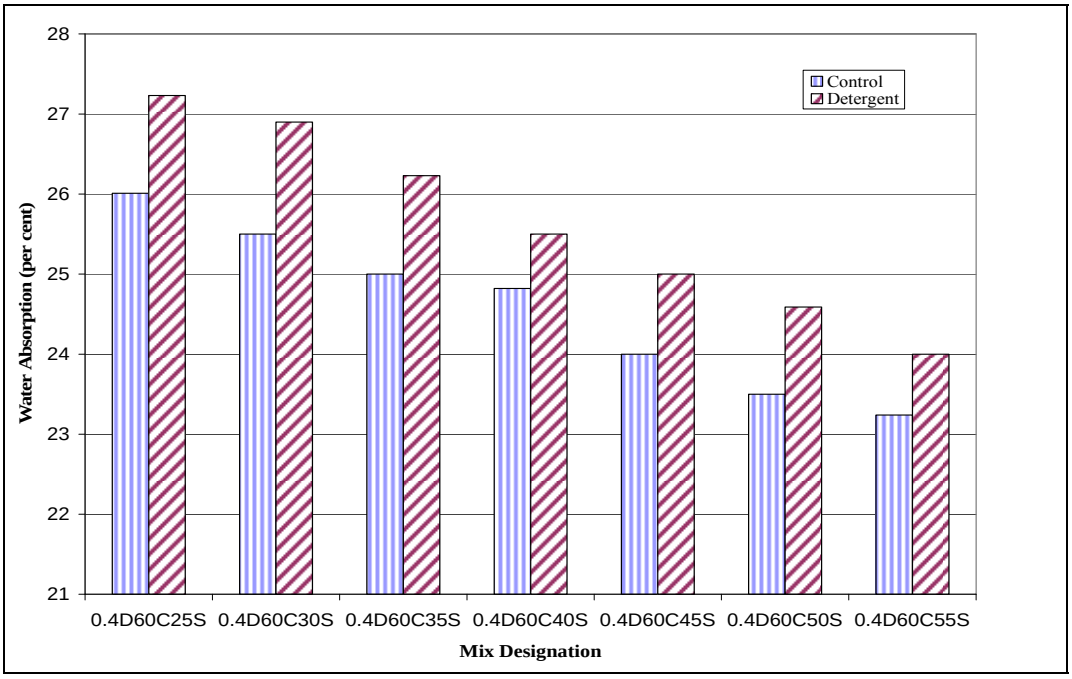

Fig. 1.2. Water absorption of different mix designs (Phase II)

APPENDIX VII
(Drying Shrinkage)

Table 1.1. Drying Shrinkage of Control Mixes (Phase I)

S/No	Mix Designation	Drying Shrinkage* (per cent)
1	0.3FA70C30S	0.15
2	0.3FA65C35S	0.14
3	0.3FA60C40S	0.14
4	0.3FA55C45S	0.12
5	0.4FA70C30S	0.16
6	0.4FA65C35S	0.16
7	0.4FA60C40S	0.15
8	0.4FA55C45S	0.13
9	0.5FA70C30S	0.18
10	0.5FA65C35S	0.18
11	0.5FA60C40S	0.16
12	0.5FA55C45S	0.15

*Drying shrinkage is taken from average of 3 specimens

Table 1.2. Drying Shrinkage of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Drying Shrinkage (per cent)
1	0.3D70C30S	0.17
2	0.3D65C35S	0.17
3	0.3D60C40S	0.15
4	0.3D55C45S	0.15
5	0.4D70C30S	0.18
6	0.4D65C35S	0.17
7	0.4D60C40S	0.17
8	0.4D55C45S	0.16
9	0.5D70C30S	0.20
10	0.5D65C35S	0.19
11	0.5D60C40S	0.18
12	0.5D55C35S	0.17

Table 1.3. Drying Shrinkage of Plain Mortar Mixes (Phase I)

S/No	Mix Designation	Drying Shrinkage (per cent)
1	M70C30S	0.09
2	M65C35S	0.09
3	M60C40S	0.08
4	M55C45S	0.08

Table 1.4. Drying Shrinkage of Control Mixes (Phase II)

S/No	Mix Designation	Drying Shrinkage (per cent)
1	0.4FA60C25S	0.20
2	0.4FA60C30S	0.19
3	0.4FA60C35S	0.17
4	0.4FA60C40S	0.17
5	0.4FA60C45S	0.16
6	0.4FA60C50S	0.15
7	0.4FA60C55S	0.15

Table 1.5. Drying Shrinkage of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Drying Shrinkage (per cent)
1	0.4D60C25S	0.21
2	0.4D60C30S	0.20
3	0.4D60C35S	0.18
4	0.4D60C40S	0.17
5	0.4D60C45S	0.17
6	0.4D60C50S	0.16
7	0.4D60C55S	0.15

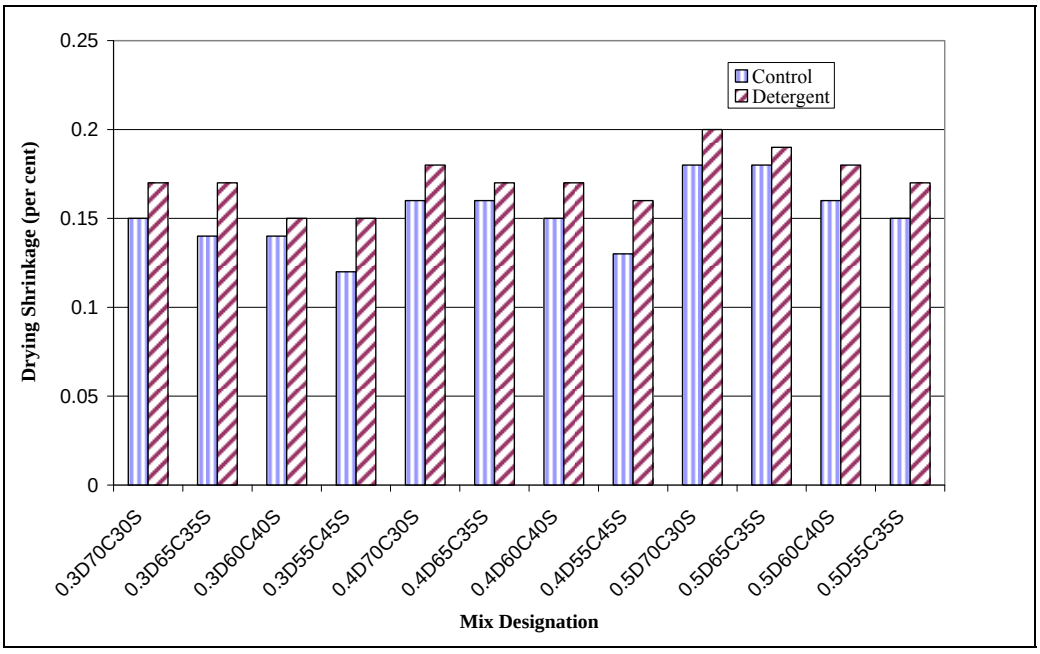

Fig. 1.1. Drying shrinkage of different mix designs (phase I)

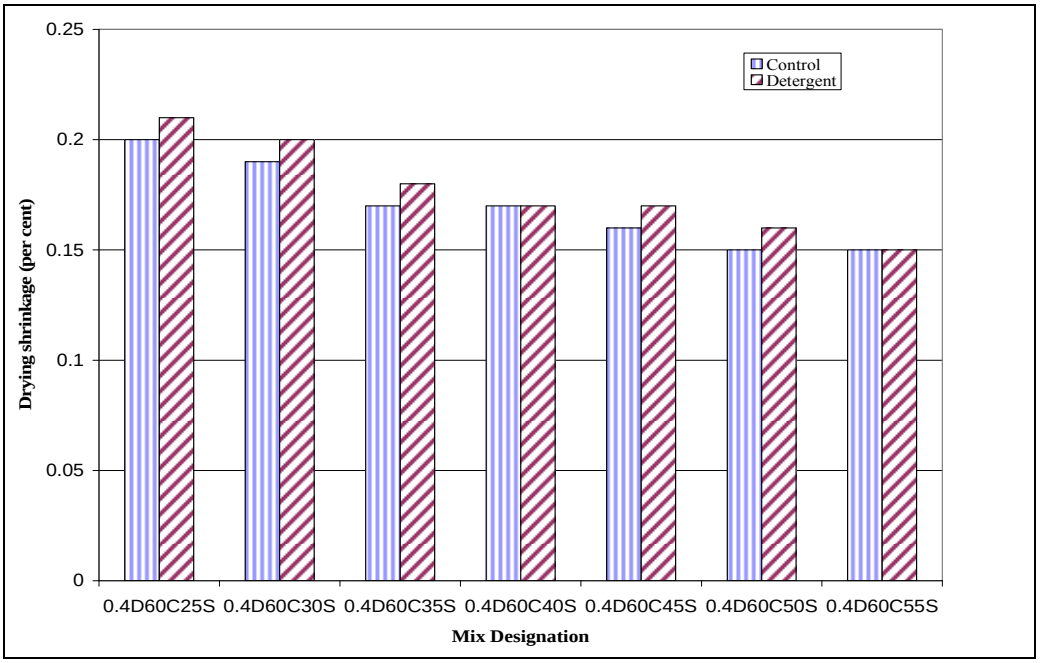

Fig. 1.2. Drying shrinkage of different mix designs (phase II)

APPENDIX VIII
(Thermal Conductivity)

Table 1.1. Thermal Conductivity of Control Mix Designs (Phase I)

S/No	Mix Designation	Thermal Conductivity* (Btu/ft^{2}h^{0}F/ft)
1	0.3FA70C30S	0.13
2	0.3FA65C35S	0.13
3	0.3FA60C40S	0.14
4	0.3FA55C45S	0.14
5	0.4FA70C30S	0.12
6	0.4FA65C35S	0.13
7	0.4FA60C40S	0.14
8	0.4FA55C45S	0.14
9	0.5FA70C30S	0.11
10	0.5FA65C35S	0.12
11	0.5FA60C40S	0.13
12	0.5FA55C45S	0.14

*Thermal conductivity is the average of 3 values

Table 1.2. Thermal Conductivity of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Thermal Conductivity (Btu/ft^{2}h^{0}F/ft)
1	0.3D70C30S	0.13
2	0.3D65C35S	0.14
3	0.3D60C40S	0.14
4	0.3D55C45S	0.14
5	0.4D70C30S	0.13
6	0.4D65C35S	0.14
7	0.4D60C40S	0.14
8	0.4D55C45S	0.14
9	0.5D70C30S	0.11
10	0.5D65C35S	0.11
11	0.5D60C40S	0.12
12	0.5D55C35S	0.13

Table 1.3. Thermal Conductivity of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Thermal Conductivity (Btu/ft^{2}h^{0}F/ft)
1	M70C30S	1.15
2	M65C35S	1.15
3	M60C40S	1.10
4	M55C45S	1.09

Table 1.4. Thermal Conductivity of Control Mix Designs (Phase II)

S/No	Mix Designation	Thermal Conductivity (Btu/ft^{2}h^{0}F/ft)
1	0.4FA60C25S	0.11
2	0.4FA60C30S	0.12
3	0.4FA60C35S	0.13
4	0.4FA60C40S	0.14
5	0.4FA60C45S	0.14
6	0.4FA60C50S	0.15
7	0.4FA60C55S	0.16

Table 1.5. Thermal Conductivity of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Thermal Conductivity (Btu/ft^{2}h^{0}F/ft)
1	0.4D60C25S	0.10
2	0.4D60C30S	0.11
3	0.4D60C35S	0.12
4	0.4D60C40S	0.13
5	0.4D60C45S	0.14
6	0.4D60C50S	0.15
7	0.4D60C55S	0.16

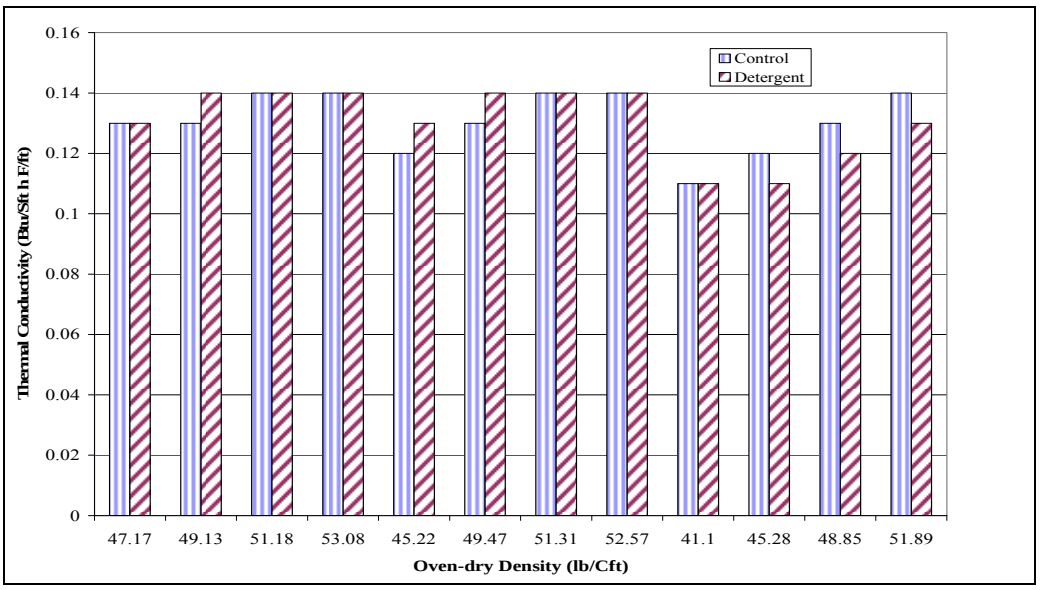

Fig. 1.1. Thermal conductivity versus oven-dry density (Phase I)

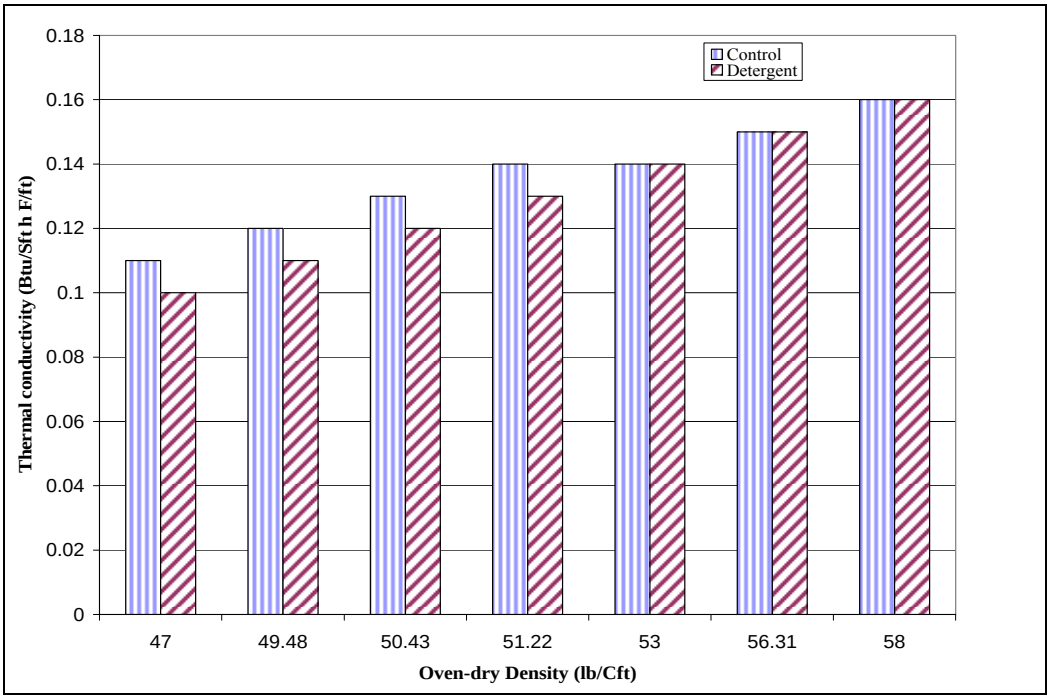

Fig. 1.2. Thermal conductivity versus oven-dry density (Phase II)

APPENDIX IX
(Acid Resistance)

Table 1.1. Acid Resistance of Control Mix Designs (Phase I)

S/No	Mix Designation	Per cent weight loss* in 5 per cent Hydrochloric acid	Per cent weight loss* in 5 per cent Sulfuric acid
1	0.3FA70C30S	1.11	3.60
2	0.3FA65C35S	1.00	3.60
3	0.3FA60C40S	0.98	3.53
4	0.3FA55C45S	0.98	3.48
5	0.4FA70C30S	1.02	3.42
6	0.4FA65C35S	0.99	3.40
7	0.4FA60C40S	0.97	3.40
8	0.4FA55C45S	0.96	3.38
9	0.5FA70C30S	0.92	2.93
10	0.5FA65C35S	0.92	2.88
11	0.5FA60C40S	0.90	2.76
12	0.5FA55C45S	0.88	2.55

* Weight loss is taken from the average of 3 specimens

Table 1.2. Acid Resistance of Detergent Mix Designs (Phase I)

S/No	Mix Designation	Per cent weight loss in 5 per cent Hydrochloric acid	Per cent weight loss in 5 per cent Sulfuric acid
1	0.3D70C30S	1.30	4.11
2	0.3D65C35S	1.28	4.02
3	0.3D60C40S	1.24	3.98
4	0.3D55C45S	1.24	3.98
5	0.4D70C30S	1.27	4.00
6	0.4D65C35S	1.25	3.97
7	0.4D60C40S	1.20	3.94
8	0.4D55C45S	1.20	3.92
9	0.5D70C30S	1.14	3.28
10	0.5D65C35S	1.14	3.11
11	0.5D60C40S	1.11	2.98
12	0.5D55C45S	1.08	2.91

Table 1.3. Acid Resistance of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Per cent weight loss in 5 per cent Hydrochloric acid	Per cent weight loss in 5 per cent Sulfuric acid
1	M70C30S	3.25	7.32
2	M65C35S	3.02	6.85
3	M60C40S	2.87	6.35
4	M55C45S	2.63	5.91

Table 1.4. Acid Resistance of Control Mix Designs (Phase II)

S/No	Mix Designation	Per cent weight loss in 5 per cent Hydrochloric acid	Per cent weight loss in 5 per cent Sulfuric acid
1	0.4FA60C25S	1.10	3.98
2	0.4FA60C30S	1.02	3.59
3	0.4FA60C35S	1.00	3.45
4	0.4FA60C40S	0.99	3.41
5	0.4FA60C45S	0.98	3.37
6	0.4FA60C50S	1.00	3.46
7	0.4FA60C55S	1.07	3.52

Table 1.5. Acid Resistance of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Per cent weight loss in 5 per cent Hydrochloric acid	Per cent weight loss in 5 per cent Sulfuric acid
1	0.4D60C25S	1.28	4.43
2	0.4D60C30S	1.25	4.12
3	0.4D60C35S	1.24	3.97
4	0.4D60C40S	1.21	3.95
5	0.4D60C45S	1.19	3.93
6	0.4D60C50S	1.20	4.50
7	0.4D60C55S	1.21	4.57

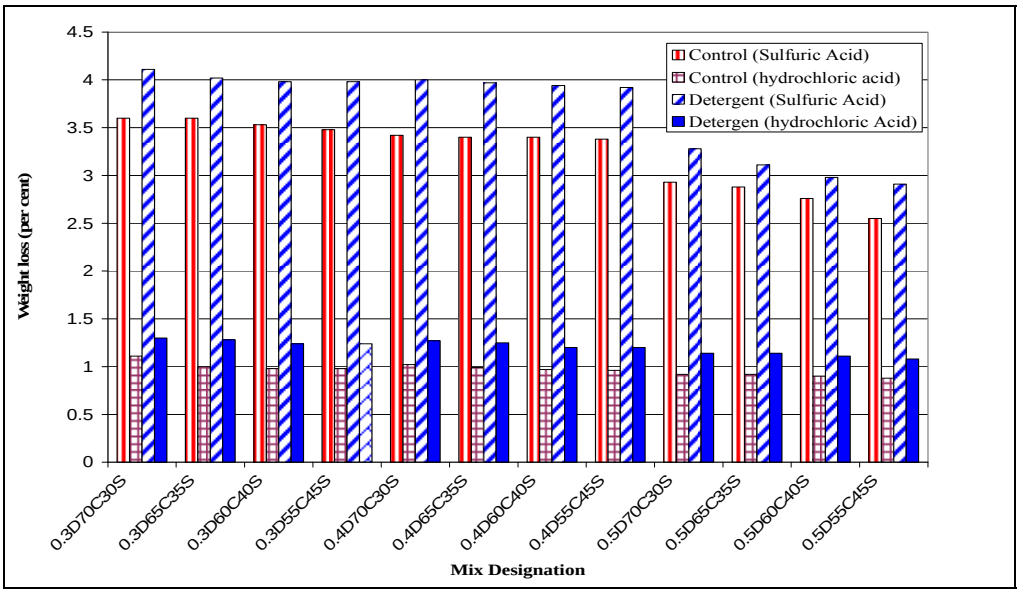

Fig. 1.1. Comparison of loss of weight after immersion in acid solutions (Phase I)

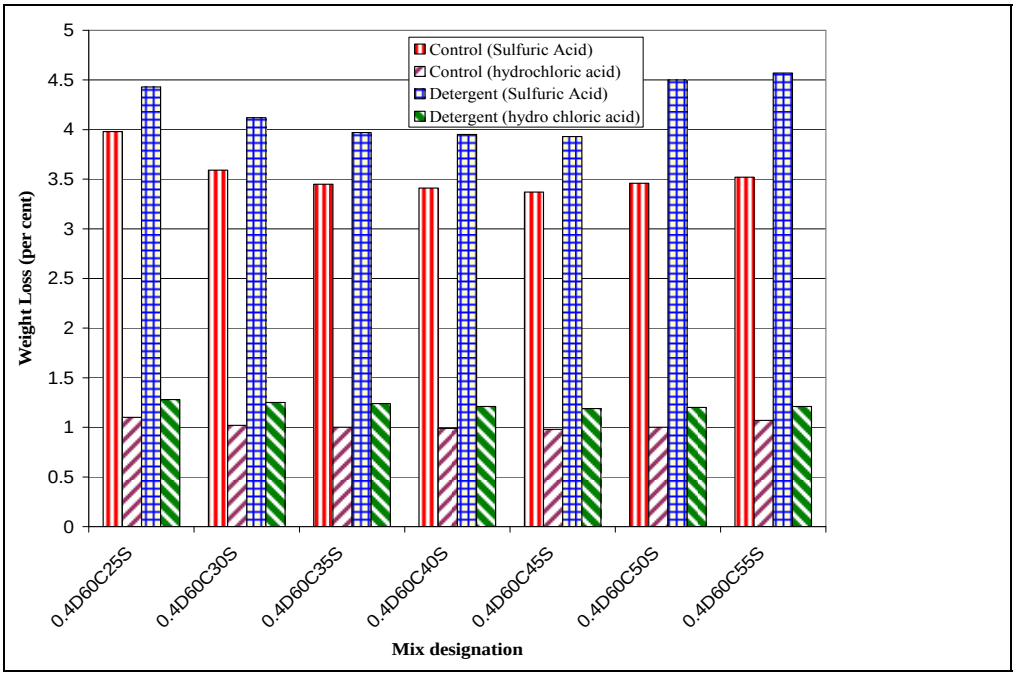

Fig. 1.2. Comparison of loss of weight after immersion in acid solutions (Phase II)

APPENDIX X
(Tensile Strength)

Table 1.1. Tensile Strength of Control Mix Designs (Phase II)

S/No	Mix Designation	Tensile strength* (psi)
1	0.4FA60C25S	165
2	0.4FA60C30S	174
3	0.4FA60C35S	177
4	0.4FA60C40S	200
5	0.4FA60C45S	196
6	0.4FA60C50S	153
7	0.4FA60C55S	148

* Tensile strength is taken from the average of 3 specimens

Table 1.2. Tensile Strength of Detergent Mix Designs (Phase II)

S/No	Mix Designation	Tensile strength (psi)
1	0.4D60C25S	153
2	0.4D60C30S	160
3	0.4D60C35S	171
4	0.4D60C40S	187
5	0.4D60C45S	178
6	0.4D60C50S	150
7	0.4D60C55S	123

Table 1.3. Tensile Strength of Plain Mortar Mix Designs (Phase I)

S/No	Mix Designation	Tensile strength (psi)
1	M70C30S	676
2	M65C35S	635
3	M60C40S	513
4	M55C45S	456

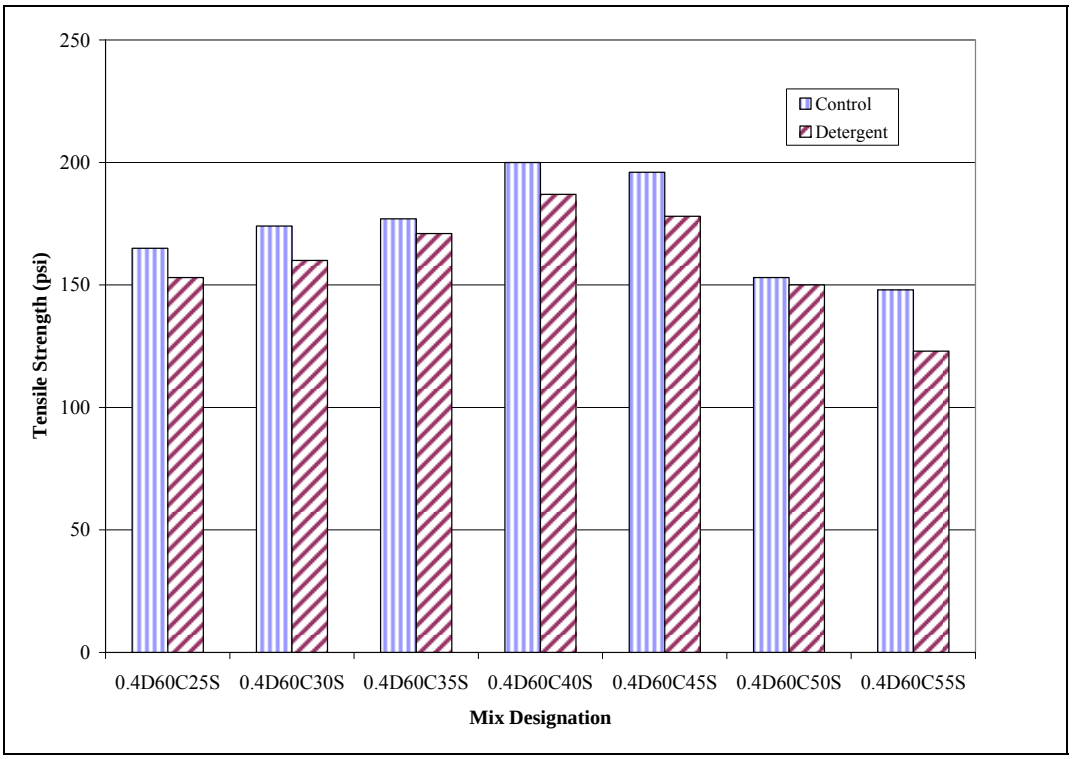

Fig. 1.1. Tensile strength of different mix designs (Phase II)

APPENDIX XI
(Cost Comparison)

Table. 1.1. Comparison of the Cost Analysis

Material	Rate per kg (Rupees)	Control Mix 0.4FA60C40S		Detergent Mix 0.4D60C40S	
		Quantity (kg)	Amount (Rupees)	Quantity (kg)	Amount (Rupees)
Cement	6	42.84	257.04	42.84	257.04
Sand	0.105	57.2	6.00	57.2	6.00
FA	366	0.55	201.3	-	-
Detergent	28	-	-	0.103	2.884
Total	-	-	464.34	-	265.93
Per cent reduction in cost = 42.73					

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ILLUSTRATION-A

Samples of Materials for Manufacture of Foam Concrete

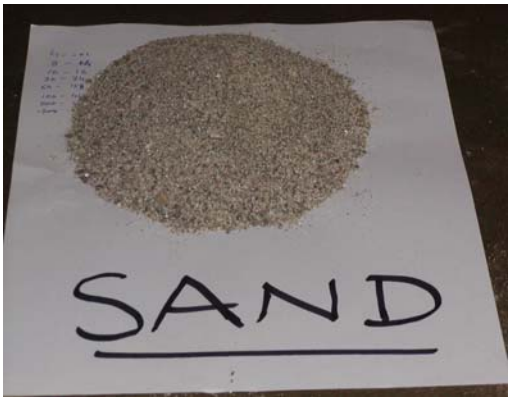

Fig. 1. Sample of Sand

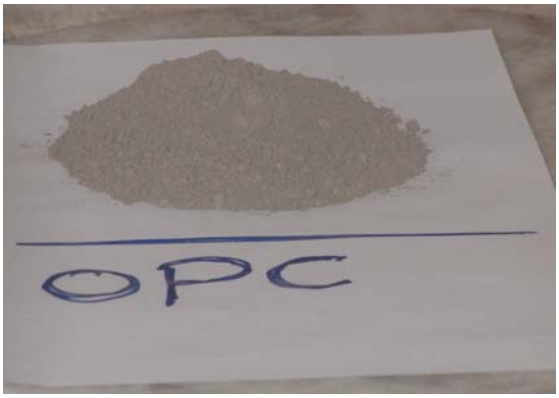

Fig. 2. Sample of Cement

Fig. 3. Sample of Detergent

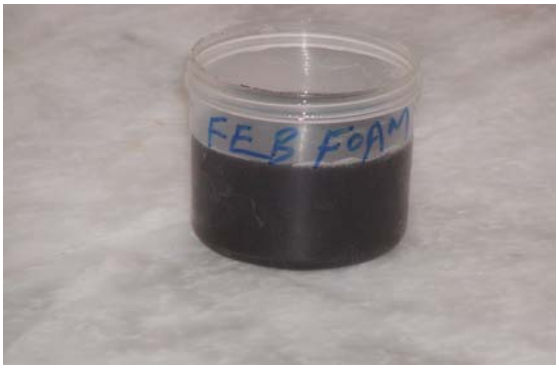

Fig. 4. Sample of Foaming Agent

Fig. 5. Foam produced by Foaming Agent

Fig. 6. Foam produced by Detergent

ILLUSTRATION-B

View of the Apparatus Involved in this Study

Fig. 1. Foam concrete mixer

Fig. 2. 2-Inch cube molds

Fig. 3. Lab. weighing balance

Fig. 4. Tensile strength testing machine

Fig. 5. 6-Inch cube molds

Fig. 6. ASTM sieves

ILLUSTRATION-C

Different Specimens

Fig. 1. A batch of specimens

Fig. 2. Specimens for water absorption test

Fig. 3. Specimens for drying shrinkage test

Fig. 4. Specimens for tensile strength test

Fig. 5. Specimens after H_2SO_4 test

Fig. 6. Specimens after HCL test

ILLUSTRATION-D

Process of Different Tests

Fig. 1. 28-days cracking failure

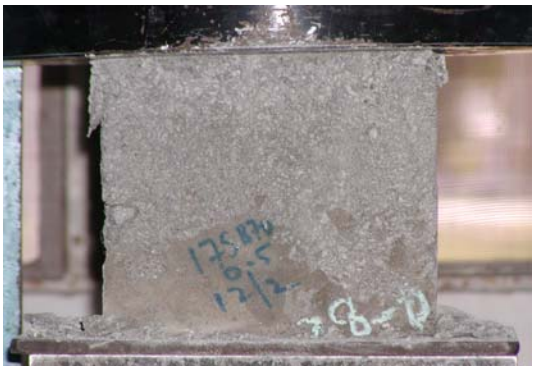

Fig. 2. 28-days failure by squashing

Fig. 3. Tensile strength test

Fig. 4. Oven-drying of specimens

Fig. 5. Specimens just before 28-days test

Fig. 6. Curing of samples in progress