# THE PROPERTIES OF FLY ASH BASED CONTROLLED LOW STRENGTH MATERIALS

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**by**
Selçuk TÜRKEL

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**İZMİR**

## Ph.D.THESIS EXAMINATION RESULT FORM

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as thesis for the degree of Doctor of Philosophy.

**Prof. Dr. Bülent Baradan**
(Advisor)

**Prof. Dr. Mehmet Uluçaylı**
(Committee Member)

**Prof. Dr. Hikmet Aydın**
(Committee Member)

Approved for the
Graduate School of Natural and Applied Sciences

**Prof. Dr. Macit Toksoy**
Director
Graduate School of Natural and Applied Sciences

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**Selçuk TÜRKEL**

# ABSTRACT

Controlled low strength material (CLSM) is a flowable fill that can be used as a backfill material in place of compacted soils. Flowable fill requires no tamping or compaction to achieve its strength and typically has a load carrying capacity much higher than compacted soils, but it can still be excavated.

In this study, a mixture of Soma B fly ash, crushed limestone powder (filler) and a low percentage of pozzolana cement has been tried in different compositions. The weight of cement (TÇ 32.5) was kept constant for all mixes as a 5% of fly ash weight. The amount of mixing water was chosen to provide optimum pumpability by determining the spreading ratio of CLSM mixtures using flow table.

The mechanical and physical properties of CLSM mixtures such as ; compressive strength, flexural and splitting tensile strength, direct shear, modulus of elasticity, coefficient of permeability, water absorption by capillarity, freezing and thawing by vacuum saturation, durability in different temperature and humidity condition, thermal conductivity, EP toxicity have been investigated by a series of laboratory tests. On the other hand, chemical durability of CLSM mixtures in aggressive environments such as salt, sulfates, and various types of acids solutions was also investigated.

The test results indicated that CLSM mixtures have superior mechanical and physical properties than the compacted soils. Besides, these materials are more durable in many situations than the normal concrete when subjected to the salt, sulfates and acids' solutions due to the high content fly ash.

# ÖZET

Bu çalışmada ; C sınıfı uçucu kül, kalker kökenli mıcır tozu ve bağlayıcı madde olarak çok düşük oranda çimento kullanılarak, sıkıştırma gerektirmeden yerleştirilebilecek, pompalanabilecek kıvamda, akışkan karışımlar elde edilmiştir. Dolgu işlerinde kullanılmak amacı ile geliştirilen karışımların basınç dayanımları, gerektiğinde kolayca kazılabilmesi düşüncesi ile kasıtlı olarak düşük tutulmuştur.

Bu amaçla yapılan çalışmada kullanılan uçucu kül Soma B termik santralından temin edilmiştir. Bağlayıcı madde olarak TÇ32.5 çimentosu kullanılmış ve bütün karışımlarda uçucu kül ağırlığının %5' i olarak alınmıştır. Bu çimento oranı, yapılan ön deneyler sonucunda istenen düşük dayanım için gerekli en uygun oran olarak belirlenmiştir. Deneylerde kullanılan karışımlarda, uçucu kül ve çimento ağırlıkları toplamı bağlayıcılar olarak dikkate alınmıştır. Mıcır tozu ise bağlayıcılar ağırlığının katları olarak seçilmiştir. Karışım suyu miktarı, pompalanabilecek akışkanlığı sağlayacak şekilde belirlenmiş ve sarsma tablası ile yayılma miktarları ölçülmüştür.

Bu şekilde hazırlanan karışımların ; basınç, eğilme, çekme ve kayma dayanımları, elastisite modülü, permeabilite ve kapilarite katsayıları, hızlı donma-çözülme dayanıklılıkları, değişik sıcaklık ve bağıl nemde basınç dayanımları, ısı iletkenliği gibi özellikleri belirlenmiştir. Ayrıca, karışımların çeşitli kimyasal etkilere dayanıklılığı ve içerisinde bulunabilecek bazı zararlı kimyasal maddelerin yeraltı sularına etkisi gibi konular da incelenmiştir.

Bu deneyler sonucunda ; gerektiğinde sonradan kolayca kazılabilecek şekilde dayanımı kasten düşük tutulan malzemelerin, bilinen klasik zemin türü dolgulara kıyasla mekanik ve fiziksel özelliklerinin daha üstün olduğu belirlenmiştir. Ayrıca, bu malzemeler yüksek oranda uçucu kül içerdiğinden, tuz ve asit gibi bazı kimyasal etkilere karşı dayanıklılığının normal betona kıyasla daha iyi olduğu görülmüştür.

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# CHAPTER ONE
# INTRODUCTION

The use of controlled low strength materials (CLSM) is getting more popular in many countries within last decade. The material being described is not concrete and it's not soil. The material is also known by other names such as controlled density fill, flowable mortar, flowable fill and lean mix backfill. Its mechanical properties has been deliberately kept low so that it can be excavated easily.

CLSM is basically a mixture of cement, fly ash, fine aggregate and water and can be used as a backfill material in place of compacted soils. CLSM requires no tamping or compaction to achieve its strength and typically has a load carrying capacity much higher than of compacted soils.

The ease in placement, its strength and economy make CLSM superior to standard backfilling methods. The material is convenient and it can be manufactured and delivered by a ready-mix concrete producer. Uses include, but are not limited to, placement under existing bridges, around and within box culverts or culvert pipes, in open trenches, in open mine fills and other specified filling purposes.

CLSM achieve strengths on the magnitude of 0.35 MPa to 2.00 MPa. Much higher strength values can be obtained by arranging the quantity of ingredients. However, these controlled strengths far exceed most natural soils, therefore the replacement would be stronger than the surrounding materials. Nevertheless, CLSM fills can still be excavated with conventional methods where it become necessary.

The superior properties of the product, made CLSM as a research topic for many public, private institutions and Universities especially in USA.

Fly ash, the main ingredient of CLSM is a by-product of power plants. Coal burning power plants annually produce millions of tons of fly ash as a waste product, world wide. The environmentally acceptable disposal of the material has become of increasing concern. Past and recent research have established the potential of fly ash for use in a variety of construction applications due to its Pozzolanic properties.

However, there is still a need to find new environmentally acceptable uses and increase utilization, so less ash will need to be disposed. The use of fly ash in large volumes in CLSM mixtures seems to be a perfect utilization method.

CLSM fills incorporating fly ash has been defined by ACI committee report No 229. Fly ashes, both F or C classes can be incorporated to CLSM fills with relatively low proportions of cement to activate pozzolanic reactions.

Spherical shapes of fly ash particles and rather high water/binder ratios improve the fluidity of the CLSM mixtures so that the mortars can be placed with ease requiring no tamping or compaction. This unique property saves the operation time. For example, a fill of $8m^3$ volume have been realized in just 3 minutes of working period (Gianetti & Rear & Callander, 1995). Also, there is little to no spreading required. In tight locations the spreading and compaction is usually accomplished by hand making the operation, time consuming and costly.

Different proportions of fly ash (Class C) - pozzolana cement and crushed limestone sand have been used as the main ingredients of CLSM in this research. The basic physical and mechanical properties of different CLSM mixtures using local materials have been determined. The investigation of the durability of CLSM mixtures in different temperatures and humidity conditions and determination their possible hazardous effects to the environment by EP toxicity tests are the original parts of this thesis.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. Controlled Low Strength Material (CLSM)

CLSM is a self compacted, cementitious material used primarily as a backfill in lieu of compacted fill. Several terms are currently used to describe this material including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry K-Krete (K-Krete is a trade name for this type of material) and other various names. CLSM are defined by "Cement and Concrete Terminology (ACI 116R)" as materials that result in a compressive strength of 1200 psi (8.27 MPa) or less at 28 days. It is used primarily for nonstructural applications below grade where low strength is required; in some cases, it is intended to be no stronger than the surrounding soil after it has attained the final set. The type of CLSM selected should be based on technical and economical considerations for the specific applications.

The available information on the subject of high volume fly ash-cement composite is limited. To the best of the writers' knowledge, the only comprehensive report available on this subject is a draft document on controlled-low-strength materials (CLSM) to be published by American Concrete Institute Committee 229 (Concrete International, 1994).

Most current CLSM applications require unconfined compressive strengths of 300 psi (2.07 MPa) or less. This lower strength requirement is necessary to allow for future excavation of CLSM (Concrete International, 1994).

CLSM should not be considered as a type of low strength concrete, but rather a self-compacted backfill material that is used in place of compacted fill. Also, CLSM should not be confused with compacted soil-cement. Soil cement, as defined by ACI Committee 230 on Soil-Cement, requires compaction and curing. CLSM typically requires no compaction (consolidation) or curing to achieve the desired strength. Long-term compressive strengths for compacted soil-cement often exceed the 1200 psi (8.27 MPa) maximum limit established for CLSM.

Long-term compressive strengths of 50 to 300 psi (0.35 to 2.07 MPa) are very low when compared to concrete. However, in terms of allowable bearing pressure, which is a common criterion for measuring the capacity of a soil to support a load, 50 to 100 psi (0.35 to 0.7 MPa) strength is equivalent to a well compacted fill.

The Detroit Edison Company and the Kuhlman Corporation, Toledo formed the company K-Krete Inc., which developed and patented a low strength filler material (Funston et al.1984). The mixture composition contained large sand contents compared to fly ash contents. Subsequently, four more patents were granted for this new cement composite. Currently, different trade names such as Flowable Fill, N-Crete, and M-krete are being used to describe the low-strength, high-volume fly ash cement composite. A number of state transportation departments (Ohio, Indiana, and Iowa) have developed their own specifications for use of low strength composite containing large volume of fly ash and sand. (MAHER & BALAGURU, 1993).

K-Krete (The CLSM mixtures which are often referred to as K-Krete or flowable mortar) is a group of CLSM products for which patent rights are held by the National Ready Mixed Concrete Association. Its first use in Iowa was to backfill an 2.4 by 30.5 m metal culvert pipe that had been undermined over its full length by water. K-Krete mix is produced under an Iowa Department of Transportation (IDOT) specification. IDOT's flowable mortar filler is usually a very fine sand with a specified gradation, while a K-Krete mixture is designed for a specific filler material.

Initial research dealt with these basic properties; strength, durability, elasticity, removability, fluidity, permeability, and quality control. (Coal Ash Utilization, 1978).

In most of the literature reviewed, which covered the period from January 1970 to June 1988, it was noted that the subject of flowable fly ash slurry required further development and additional research. The only work identified that directly relates to the present project was reported in 1979 by Funston, Krell, and Zimmer, who developed a flowable fly ash material that was used as a backfill either above or below water.

Flowable fly ash is a relatively new material, using Class F fly ash stabilized with small amounts of portland cement. Four to five percent portland cement is added to the dry weight of fly ash along with enough water to provide the desired flowability or consistency for the specific application (KRELL, 1989).

One of the main attractions of flowable fill is that it gives an opportunity to use non-standard materials. Oil-shale fly ashes (OSFA) and cement kiln dust (CKD) have been used in flowable fill instead of coal fly ash and cement. OSFA mainly contains quick lime, anhydrite, calcite, quartz and a vitreous phase (PERA & AMOURA & AMBROISE, 1996).

BHAT & LOVELL (1996) used waste foundry sand as a fine aggregate. Waste foundry sand is a by-product of metal casting industries. The use of waste foundry sand in applications, such as construction of highway embankments, and as a substitute for conventional aggregate in concrete and in flowable fill.

Phosphogypsum (PG)as a component of flowable fill material have been used by GANDHAM & SEALS & FOXWORTHY (1996). Phosphogypsum is a by-product of the production of phosphoric acid, a key ingredient in the manufacture of fertilizers.

### 2.2. Advantages of fly ash slurry (CLSM Mixtures) backfill

Environmental consideration was the main reason for developing this product. Local granular materials are difficult to obtain and their cost has been rising. Obtaining both the site and environmental permits to open and operate new sources of material is very difficult, thus the material commands a much higher price (KRELL, 1984). According to ACI Committee Report 229, future CLSM mixtures may be developed as anticorrosion fills, thermal fills and durable pavement basis.(Concrete International, 1994).

Fly ash slurry is a useful, low strength backfill material. Using either Class C or stabilized Class F fly ash, slurry backfills have been found to be a reliable, competitive alternative to compacted soil (cohesive or granular) materials. Fly ash slurry backfill has been shown to be faster, less expensive, and in many ways, better than compacted soil backfills.

Fly ash slurry backfill provides many innovative advantages. It flows, therefore it can be placed with minimal effort, then hardens as it develops strength. No discing or compaction is required, which keeps labor costs and placement time to a minimum. Fly ash slurry backfills can support higher loads than soil backfill, yet properly designed can be excavated with little or no difficulty.

The use of fly ash as a slurry backfill component advantages include; improved ability to flow, enhanced strength, available dry at low or competitive costs, and low unit weight.

Although fly ash slurry backfills derive their strength from cement and pozzolanic reactions, fly ash backfill is used as a replacement for compacted soil backfills, rather than concrete. Although the strength of fly ash slurry backfill is much less than that of concrete, it is still 1 to 2 orders of magnitude stronger than soil backfills. The fact that the slurry can flow, then harden, means that:

- It is easy to place in inaccessible locations.
- It can fill large areas from a single entry point.
- It needs no compaction.

Fly ash slurry has many of the same advantages as a backfill that it has as a grout. Like grout, fly ash slurry flows into hard-to-reach areas, then develops strength through cementitious and pozzolanic reactions. More specifically, slurried backfill:

**a) Flows**:

- Fills voids under structures without removing the floor
- Fills irregular or hard-to-reach surfaces
- Minimizes danger to workers in excavated trenches
- Self-levels
- Seals pipe joints

**b) Sets up:**

- Will not swell or shrink significantly (after set)
- May gain strength more quickly than cement (Class C ash)
- Can be varied to achieve desired properties
- Minimizes settlement, eliminates “dips” in roads

**c) Needs no compaction or vibration:**

- Reduces labor costs
- Accelerates construction
- Provides a uniform bedding
- Allows for narrower trenchs

**d) Can be placed in wet/cold and hot/dry weather**

**e) May be more readily available than granular fill**

**f) Has a lower density than soil or concrete (high ash slurry and foamed mixes)**

**g) Is less subject to leaching than unstabilized ash**

**h) Displaces free-standing water**

**i) May be re-excavated**

Mix design should also take into consideration the long-term properties of the fly ash slurry backfill, including: strength, durability, density, permeability.

## 2.3. Materials of CLSM

Conventional CLSM mixtures usually consist of water, portland cement, fly ash or other similar by-products, and fine or coarse aggregates or both. Some mixtures consist of water, portland cement and fly ash only. Special low density CLSM (LD-CLSM) mixtures, consist of portland cement, water and preformed foam. In addition, a new chemical admixture packaged in sealed, egg-shaped wax capsules have been used for non-shrink flowable fill. (GIANETTI, REAR & CALLENDER, 1995)

Although materials used in CLSM mixtures may meet ASTM or other standard requirements, the use of standardized materials is not always necessary. Selection of materials should be based on availability, cost, specific application and the necessary characteristics of the mixture including flowability, strength, excavatability, density, etc.

The following summary can be made regarding the materials used to manufacture CLSM:

### 2.3.1. Cement

Cement provides the cohesion and strength for CLSM mixtures. For most applications, Type I or Type II Portland cement conforming to ASTM C 150 (Standard Specification for Portland Cement) is normally used. Other types of cement, including blended cements conforming to ASTM C 595 (Standard Specification for Blended Hydraulic Cements), may be used if prior testing indicates acceptable results.

Cement contents generally range from 50 to 200 lb/yd$^3$ (29.7 to 18.9 kg/m$^3$ ), depending upon strength and hardening time requirements. Increasing cement content while maintaining all other factors equal, that is, water, fly ash, aggregate and ambient temperature will normally increase strength and reduce hardening time.

### 2.3.2. Fly ash

Fly ash is normally produced by burning coals which have been crushed and ground to a fineness of 70 to 80 percent passing a No.200 sieve. Specification for the use of fly ash in concrete are given in ASTM C 618 (Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete), which defines two classes of fly ash-Class F and Class C. Class F fly ash is usually produced by burning anthracite or bituminous coal while the Class C fly ash is normally produced by burning subbituminous coal or lignite.

Bituminous and anthracite coals rarely contain high-calcium mineral matter in significant proportion; the sub-bituminous coals and lignites may or may not contain a high amount of calcium (ROY, LUKE & DIAMOND, 1984). The seperation of fly ash into two classes reflects differences in composition which affect cementitious and pozzolanic properties. Class C fly ashes usually have cementitious properties in addition to pozzolanic properties, while Class F fly ash is rarely cementitious when mixed with water alone (ACI Committee Report 226, 1987).

Fly ash is sometimes used to improve flowability. Their use may also increase strength and reduce bleeding, shrinkage and permeability. High fly ash content mixtures result in lower density CLSM when compared to mixtures with high aggregate contents. Most fly ashes used conform to either Class F or Class C as described in ASTM C 618. However, fly ashes not conforming to ASTM C 618 may be used. In all cases, whether or not fly ashes conform to ASTM C618 specifications, trial mixes should be prepared to determine whether the mixture will meet the specified requirements.

Class F fly ash contents range from none to as high as 2000 lb/yd$^3$ (1187 kg/m$^3$ ) where fly ash serves as the agregate filler. Class C fly ash is used in quantities of up to 350 lb/yd$^3$ (208 kg/m$^3$ ). The quantity of fly ash used will be determined by availability and flowability needs of the project.

### 2.3.2.1. Chemical composition, physical, pozzolanic and engineerig properties of fly ash

Fly ashes are complex in their range of chemical and phase compositions. They consist of heterogeneous combinations of glassy and crystalline phases. Table 2.1 gives typical fly ash composition for Class F and Class C fly ashes (MEYERS & PICHUMANI, 1976).

Wide ranges exist in the amounts of the three principal constituents-$SiO_2$ (25 to 60 percent), $Al_2O_3$ (10 to 30 percent) and $Fe_2O_3$ (5 to 25 percent). If the sum of these three ingredients is 70 percent or greater, the fly ash is technically considered Class F. Because Class C fly ashes generally contain significant percentage of calcium compounds reported as CaO, the sum of three constituents just mentioned is required only to be greater than 50 percent. The MgO content of fly ash is generally not greater than 5 percent.

Class C fly ashes usually have loss on ignition values less than 1 percent, but Class C fly ashes range from this low level to values over 10 percent.

The pH values generally range from 6 to 11. Minor elements that may be present in varying amounts, depending on the origin of the coal from which a particular fly ash is derived, include titanium, iron, magnesium, phosphorus, sulfur, oxygen, potassium, sodium, carbon and others as traces.

Active compounds in addition to calcium alumino-silicate glass that may be present in Class C fly ash are free lime (CaO), anhydrate ($CaSO_4$), tricalcium aluminate ($3CaO.Al_2O_3$), calcium sulfoaluminate ($4CaO.3Al_2O_3.SO_4$) and rarely calcium silicates (Mehta 1983). The strength-related properties of concrete containing Class C fly ash, as compared to Class F fly ash, are influenced by the cementitious calcium aluminosilicate glass and, in many instances, by the presence of crystalline phases which contribute to the hydration of Class C fly ashes (DIAMOND, 1981 & EPRI CS-3314).

**Table 2.1. Chemical Composition of Typical Bituminous and Lignite Fly Ashes**

| Compounds | Bituminous Ash (Class F) | Lignite Ash (Class C) |
|---|---|---|
| $SiO_2$ | 49.10 | 32.60 |
| $Al_2O_3$ | 16.25 | 10.70 |
| $Fe_2O_3$ | 22.31 | 10.00 |
| $TiO_2$ | 1.09 | 0.56 |
| CaO | 4.48 | 18.00 |
| MgO | 1.00 | 7.31 |
| $Na_2O$ | 0.05 | 0.87 |
| $K_2O$ | 1.42 | 0.68 |
| $SO_3$ | 0.73 | 2.60 |
| C | 2.21 | 0.11 |
| Loss on ignition | 2.55 | 0.62 |
| $H_2O$ soluble | 2.51 | 8.55 |

High-calcium (Class C) fly ashes often react directly with water to form cementitious phases such as C-S-H (calcium-silicate-hydrate), calcium hydroxide and ettringite. In addition, the glassy phase in these fly ashes, while still predominant, is often less abundant but more reactive with the calcium and alkali hydroxides released from the cement-fly ash system.

The shape, fineness, particle-size distribution, density and composition of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete. The color of fly ash ranges from tan to gray or black. The tan color usually indicates a higher lime content and iron oxide, and gray to black indicates higher carbon content, in some cases, magnetic iron oxide or magnetit content(ANDRES, GIBALA & BARENBERG, 1976).

As a pozzolan, fly ash improves the strength and durability of cement grout as well as its resistance to sulfate attack. Pozzolans tend to harden slowly, which is advantageous in certain applications. Also, fly ash as a pozzolan tends to lower the heat of hydration of a cement grout. This advantageous in mass grouting or where temperatures are naturally high, as in massive grouted aggregate columns or deep wells. Rate of the pozzolanic reaction is a function of several factors (CHOU, 1986); these are:

a) Quantity of stabilizer (lime or cement)
b) Total amount of silica ($SiO_2$) and alumina ($Al_2O_3$) in the fly ash
c) Presence of adequate moisture
d) Compacted density
e) Presence of carbon in the fly ash
f) Fineness of the fly ash
g) Temperature
h) Age

The engineering properties of fly ash studied most frequently are permeability, compressibility and shear strength. Standard Proctor maximum dry densities for fly ash generally range from 1.10 to 1.50 gr/cm$^3$ ; however, values as high as 1.80 gr/cm$^3$ have also been reported for F type fly ashes (COLLINS & EMERY, 1982). These values are obtain at optimum moisture contents that vary between 15 and 30 percent; the lower moisture content is associated with higher densities. The moisture-density relationship for fly ash is similar to that for cohesive soils (GRAY & LIN, 1972). Generally, dry density varies with specific gravity.

### 2.3.3. Aggregates

Aggregates are often the major constituent of a CLSM mixture. The type, grading, and shape of aggregates can affect the physical properties such as flowability and compressive strength. Aggregates complying with ASTM C33 (Standard Specification for Concrete Aggregates) are generally used because concrete producers have these materials in stock.

Granular excavation materials with somewhat lower quality properties than concrete aggregate are a potential source of CLSM materials, and should be considered. However, variations of the physical properties of the mix components will have a significant effect on the mix performance. Silty sands with up to 20% fines (minus #200 sieve) have proven satisfactory. Also, soils with wide variations in grading have shown to be effective. However, soils with clayey fines have exhibited problems with incomplete mixing, stickiness of the mix, excess water demand, shrinkage, and variable strength. These types of soils are not usually considered for CLSM applications. Aggregates that have been used succesfully include:

- ASTM C 33 specification aggregates within specified gradations,
- Pea gravel with sand,
- 3/4 in. minus aggregate with sand,
- Native sandy soils, with more than 10% passing a #200 sieve, and
- Quarry waste products, generally 3/8 in. minus aggregates.

Non-standard materials, which may be available and more economical, can also be used in CLSM mixtures depending upon project requirements. These materials, however, should be tested prior to use to determine their acceptability in CLSM mixtures.

In all cases, the characteristics of the non-standard material should be determined, and the suitability of the material should be tested in a CLSM mixture to determine whether it meets specified requirements. In certain cases, environmental regulations may require prequalification of the raw material or CLSM mixture or both prior to use.

The majority of specifications call for the use of fine aggregate. The amount of fine aggregate varies with the quantity needed to fill the volume of the CLSM after considering cement, fly ash, water, and air contents. In general, the quantities range from 2600 to 3100 lb/yd$^3$ (1543 to 1839 kg/m$^3$ ). Coarse agregate is generally not used in CLSM mixes as often as fine aggregates. When used, however, the coarse aggregate content is approximately equal to the fine aggregate content.

### 2.3.4. Chemical admixtures and water

Chemical admixtures such as air-entraining, water-reducing admixtures have been used succesfully in CLSM mixtures, pretesting sould be performed to determine acceptability Caution should be exercised with air contents in excess of 6 percent as they may increase segregation (CPCA, 1990). Also, chemical admixtures may not be cost effective unless they are needed to satisfy specific requirements.

More water is used in CLSM than in concrete. Water serves as a lubricant to provide high flowability characteristics and promote consolidation of the materials. Water contents typically range from 320 to 580 lb/yd$^3$ (193 to 344 kg/m$^3$ ) for most CLSM mixes containing aggregate. Water content for class F fly ash and cement only mixes can be as high as 1000 lb/yd$^3$ (593 kg/m$^3$ ) to achieve good flowability. This wide range is due primarily to characteristics of the materials used in CLSM and the degree of flowability desired. Water contents will be higher with mixtures using finer aggregates.

Water that is acceptable for concrete mixtures is acceptable for CLSM mixtures. ASTM C 94 (Standard Specification for Ready-Mixed Concrete) on Ready-Mixed Concrete provides additional information on water quality requirements.

## 2.4. Properties of CLSM

The properties of CLSM cross the boundaries between soils and concrete. CLSM is manufactured from materials similar to those use to produce concrete and in placed from equipment in a fashion similar to that of concrete. But in-service CLSM exhibits characteristic properties of soils. The properties of CLSM are affected by the constituents of the mix and the proportions of the ingredients in the mix.

### 2.4.1. Plastic Properties

#### 2.4. 1.1. Flowability

Flowability is the property that makes CLSM unique as a fill material. It enables the materials to be self-leveling, to flow into and readily fill a void, and be self-compacting without the need for conventional placing and compacting equipment. This property represents a major advantage of CLSM compared to normal fill materials that must be mechanically placed and compacted. Due to its similarity to concrete and grout materials in the plastic state, flowability in best viewed in terms of concrete and grout technology.

A major consideration in using highly flowable CLSM is the hydrostatic pressure it exerts. Where fluid pressure is a concern, CLSM may be placed in lifts, with each lift being allowed to harden before placement of the next lift. Examples where multiple lifts may be required are in the case limited strength forms that are used to contain the material, or where buoyant items such as pipes are encapsulated in the CLSM.

CLSM mixes must contain flow characteristics to be placed economically. Flowability can be varied from stiff to fluid depending upon requirements The measurement for flow is usually expressed in inches.

Method of expressing flowability include the use of the standard concrete slump cone (ASTM C 143 Test for Slump of Portland Cement Concrete), flow cone (Corps of Engineers Spec. CRD-C611, or ASTM C 939 Standard Test Method for Flow of Grout for

Preplaced Aggregate Concrete), and a 3 x 6 in.open ended cylinder modified flow test. Poor flow characteristics indicate poor quality.

Flowability ranges associated with the slump cone can be expressed as follows:

Low flowability minus 6 in.
Normal flowability 6-8 in.
High flowability plus 8 in.

ASTM C 939, for determining flow of grout, has been used successfully with very fluid mixtures containing aggregates not greater than 1/4 in. The Florida and Indiana Departments of Transportation require an efflux time of 30 seconds + 5 seconds as measured by this method.

The modified flow test, uses a 3 x 6 in. open ended cylinder and is best adapted to mixtures containing primarily fine aggregates. For good flowability, the diameter of spread material should be at least 8 in.

### 2.4.1.2. Segregation

Separation of constituents in the mixture can occur at very high levels of flowability when the flowability is primarily produced by the addition of water.This situation is similar to segregation experienced with some high slump concrete mixtures. With proper proportioning, a high degree of flowability can be attained without segregation.

For highly flowable CLSM without segregation, adequate fines are required to provide suitable cohesiveness. Fly ash generally accounts for these fines, although silty or other noncohesive fines up to 20 percent of total aggregate have been used. Some CLSM mixtures have been designed without sand or gravel, using only fly ash as filler material. These mixtures require much higher water content, but produce no noticeable segregation (KRELL, 1989).

### 2.4.1.3. Hardening time

Hardening time is the approximate period of time required for CLSM to go from the plastic state to a hardened state with sufficient strength to support the weight of a person. This time is greatly influenced by the amount and rate of bleed water released. When this excess water leaves the mixture, solid particles realign into intimate contact and the mixture becomes rigid. Hardening time is greatly dependent on the type and quantity of cementitious material in the CLSM. Normal factors affecting the hardening time are:

- Type and quantity of cementitious material,
- Permeability and degree of saturation of surrounding soil which is in contact with CLSM,
- Fluidity of CLSM,
- Proportioning of CLSM,
- Mixture and ambient temperature,
- Humidity,
- Depth of fill.

Hardening time can be as short as one hour, but generally takes 3 to 5 hours under normal conditions.(SMITH, 1991).

### 2.4.1.4. Pumping

CLSM can be successfully delivered by conventional concrete pumping equipment. As with concrete, proportioning of the mixture is critical. Voids must be adequately filled with solid particles to provide adequate cohesiveness for transport through the pump line under pressure without segregation. Inadequate void filling results in mixtures that may segregate in the pump and may cause line blockage.

Pumpability can be enhanced by careful proportioning to provide adequate void filling in the mixture. Fly ash can aid pumpability by acting is microaggregate for void filling. Cement can also be added, for this purpose. However, whenever cementitious materials are added care must be taken to limit the maximum strength levels if later excavation is a consideration.

The fact that many fly ash particles are spherical, creates a ball bearing type of lubricating action in the grout. This results in improved pumpability, easier injection, and greater penetration. Lower penetration grouts require more injections points, increasing the cost of the grouting program. The lubricating action also reduces wear on the grouting equipment and makes thicker grout less viscous, needing less water to pump. Finally, the lower water requirement for grouts containing fly ash results in higher strength at equivalent amounts of cement.

#### 2.4.1.5. Injectability

The main factors affecting penetration of the grout are the particle size and viscosity. Particle size will determine the minimum groutable pore size while viscosity determines the pressure needed for injection. In general, a grout which is too viscous requires more injection points whereas a grout which is too thin requires a long injection time.

Another property of fresh grout is the stability of the suspension. Unstable grouts can settle out and create blockages while the bleed water can create discontinuities. this problem increases with higher water contents.

#### 2.4.1.6. Bleeding and Shrinkage

Low strength mixes with high water contents tend to release large amounts of bleed water. This occurs in the first day or two after placement and often results in shrinkage of 1/8 to 1/4 inch per foot (10.4 - 20.8 mm/m) (1 to 2%). If desired, this can be partially offset by the addition aluminum powder, which cause expansion. Normally, no additional shrinkage or settlement occurs after curing. Shrinkage of fly ash slurry mixes is not generally a concern except where a tight seal against existing material is required (GAI Consultants Inc., 1986).

Shrinkage and shrinkage cracks do not affect the performance of CLSM. Several reports have indicated very little shrinkage occurs with CLSM. Typical linear shrinkage is in the range of 0.02 to 0.05 percent (Concrete International, 1994).

#### 2.4.1.7. Heat of Hydration

The heat of hydration is related to the of reaction. In massive fills, heat of hydration may build up, cracking and weakening the fill. In extreme cases, highly reactive mixes have been known to actually blow apart as the result of steam created by intense heat While Class F ash hydrates slowly, making it beneficial in mass fills, Class C fly ash may contribute substantialy to early heat evolution. This can be controlled by placing the slurry in lifts or using a retarder.

### 2.4.2. Hardening properties

#### 2.4.2.1. Strength

In general, the strength of fly ash slurry backfill increases with an increase in cement, Class C fly ash, coarse aggregate, and time. Strength usually decreases with greater additions of water and class F fly ash.

Unconfined compressive strength is a measure of the load carrying ability of CLSM. A CLSM compressive strength of 50 to 100 psi (0.34 to 0.68 MPa) equates to an allowable bearing capacity of a well compacted soil. Curing methods specified for concrete are not considered essential for CLSM.

Maintaining strengths at a low level is a major objective for projects where later excavation may be required. Some mixtures that are acceptable at early ages continue to gain strength with time, making future excavation difficult.

Strength is usually determined by the unconfined compression test. This test evaluates the cohesive strength of a cured mix. Normally, the effect of friction is ignored in stabilized fly ash mixes, as it is insignificant compared to the high cohesion value. With very high-aggregate, low-strength mixes under specific field conditions, the friction angle may be considered to determine total strength.

As fly ash slurry backfills usually replace compacted soil backfill, the major concern is that a high, long-term strength may make any required excavation very difficult. An unconfined compressive strength limit of 0.69-1.03 Mpa at 28 days (about 5% cement) is normally given as the limit of diggable backfill. Compressive strengths for K-Krete mixes usually fall within a range of 0 to 11 Mpa. While a 28 strength is usually specified, in reality the backfill strength will continue to increase with time. Compressive strengths have been observed for mixes at time intervals of 10 days, 28 days, 6 months and one year.

For removability characteristics, lower compressive strengths are naturally required. Compressive strength will vary because of the material available and the designed proportions selected.

Shear strength of the grout should be determined by laboratory testing. Strength is needed to resist both surface loading and hydraulic gradients (flow of groundwater). while permeability is an important characteristic of grout, the permeability of grouted subsurface strata is dependent more on the strength of the seal than the grout permeability. Strength of mass grouting may be adversely affected by cracking from high heat of hydration or by shrinkage cracks. Strength is a function of mix components, time and temperature of curing, and environmental conditions.

#### 2.4.2.2. Density

Density of normal CLSM in place is in the range of 115 - 145 lb/ft$^3$ (1842 - 2323 kg/m$^3$ ), which is greater than most compacted materials. A CLSM mix with only fly ash, cement, and water should have a density between 90 to 100 lb/ft$^3$ (1442 - 1602 kg/m$^3$ ). Lower unit weights can be achieved by using light-weight aggregates, high entrained air contents, and foamed mixes.

High ash slurry is lighter than compacted soil or concrete. It is heaviest when wet and, because fresh slurry is fluid, not self-supporting, the critical loading condition will occur during or immediately after placement. Density can be reduced by the use of foaming agents, and will increase with the addition of aggregate.

### 2.4.2.3. Settlement

Settlement of compacted fills may occur even when compaction requirements have been met. CLSM does not settle after hardening occurs. Measurements taken months after placement of a large CLSM fill showed no measurable deformation (FLECHSIG, 1990).

### 2.4.2.4. Thermal insulation/conductivity

Conventional CLSM mixtures are not considered good insulating materials. Where insulation is desired, the mixture should be proportioned to obtain low density and high porosity. Air entrained conventional mixtures reduce the density and increase the insulating value. Lightweight aggregates, including bottom ash, can be utilized to reduce density. Foamed or cellular mixtures have very low densities and exhibit good insulating properties.

Where high thermal conductivity is desired, such as backfill for underground power cables, high density and very low porosity (maximum surface contact area between solid particles) are desirable. As the moisture content and dry density increase, so does the thermal conductivity. Other parameters to consider, but of lesser importance, include mineral composition, particle shape and size, gradation characteristics, organic content and specific gravity (PARMAR, 1992).

### 2.4.2.5. Permeability

Permeability of most excavatable CLSM is similar to compacted granular fills. Typical values are in the range of $10^{-4}$ to $10^{-5}$ cm/sec. Mixtures of higher strength and higher fines content of CLSM can achieve permeabilities as low as $10^{-7}$ cm/sec. The permeability values (k) changes $5.1\times10^{-4}$ to $1.5\times10^{-5}$ cm/sec for K-Krete mixes. Permeability is increased as cementitious materials are reduced and aggregate contents are increased to percentages above 80% (McLAREN. & BALSAMO, 1986). Materials normally used for reducing permeability, such as bentonite clay and diatomaceous earth, may affect other properties, however, and should be tested prior to use.

The permeability of fly ash slurry mixes is determined by the permeability of the pore space in the cementitious material. Permeability is inversely proportional to strength over a wide range of values. For mixes with a high proportion of aggregate, 80% or more, permeability increases substantially due to an increase in porosity. Additions of fine material to the slurry tends to reduce the permeability. Bentonite, diatomaceous earth, and silica fume dust are useful for this purpose.

#### 2.4.2.6. Durability

Durability is a measure of strength loss over time. In general, high strength mixes are more durable than low strength mixes. For permanent control of groundwater, the grout must be able to resist deterioration and loss of strength. It must be able to resist leaching from groundwater flow or being dissolved by chemicals in the subsurface environment. Durability can be tested with the fresh water soak test and should also be tested for any unusual chemicals in the groundwater.

#### 2.4.2.7. Erosion

Research indicates that K-Krete CDF mixes react in much the same way as compacted granular fills. They do not have any greater resistance to direct wearing erosion than comparable granular fill. It is therefore necessary to provide a protective wearing surface to contain the fill and to prevent erosion due to the elements.

#### 2.4.2.8. Corrosion

Several agencies are testing K-Krete mixes for corrosion. All indicators point to the fact that for selected materials, cement (ASTM C 150), fly ash (ASTM C 618), and aggregates (ASTM C 33), no corrosive effects should be encountered. The basic K-Krete mixes exhibit a pH of 10. For materials other than those indicated, laboratory tests on the combined ingredients are required.

In 1990, CG & E (The Cincinnati Gas & Electric Company) sponsored field research on corrosion using CLSM mixtures wiyj steel pipe. The research report for this study contains the following conclusion statement: "CLSM-CDF is less corrosive around metal pipe than conventional backfills because of its high resistivity, permeability, and uniformity" (BREWER & ASSOCIATES, 1993).

### 2.4.2.9. Subsidence

Subsidence is the compaction process by which K-Krete mixes consolidate. The selected suspended material particles settle through the water medium. Subsidence could result in approximately 1/4" material reduction per foot. This reduction is naturally replaced in preceding lifts for deep K-Krete mix placements. Water within the K-Krete mix is loss in three ways: evaporation, absorption in the surrounding soil and/or surface runoff. Water requirements for a K-Krete mix are determined by the flow requirements for the materials used in the designed mix.

### 2.4.2.10. Excavatability

The ability to excavate CLSM at later ages is an important consideration on many projects. In general, CLSM with a compressive strength of 50 psi (0.34 MPa) or less may be excavated manually. Mechanical equipment such as backhoes are used for compressive strengths of 100 to 200 psi (0.68 to 1.36 MPa). The limits for excavatability are somewhat arbitrary depending upon the CLSM mixture. Mixtures using high quantities of coarse aggregate can be very difficult to remove by hand even at low strengths. Mixtures using fine sand or only fly ash as the aggregate filler may be excavated with a backhoe at strengths of 300 psi (2.05 MPa) (KRELL, 1989).

Where later age excavatability is of concern, the type and quantity of cementitious materials is important. Acceptable long term performance has been achieved with cement contents from 40 to 100 lb/yd$^3$ (23.7 to 59.3 kg/m$^3$ ) and class F fly ash that exceed 10 percent by weight may be a concern where long term strength increases are not desired (TANSLEY & BERNARD, 1981).

Since CLSM will typically continue to gain strength beyond the conventional 28 day testing period, it is suggested, especially for high cementitious content CLSM, that long term strength test be conducted to estimate the potential for later age excavatability.

In addition to limiting the cementitious content, entrained air can be used to keep compressive strengths low.

### 2.5. Mix Proportioning

Proportioning for CLSM has largely been done by trial and error until mixtures with suitable properties have been achived. Most specifications available provide of recipe ingredients that will produce an acceptable material, although some specifications call for performance features and leave proportioning up to the supplier. "Selecting Proportions for Normal, Heavyweight and Mass Concrete," (ACI 211)(KRELL, 1989) has been used;however, much work remains to be done in establishing consistent reliability when using this method. Currently, where a recipe does not exist, trial mixtures are evaluated to determine how well they meet certain goals for strength, flowability, density, etc. Adjustments are then made to achieve the desired properties.

### 2.6. Mixing, Transporting, and Placing

The mixing, transporting, and placing of CLSM generally follows methods and procedures given in ACI 304 (Guide for Measuring, Mixing, Transporting and Placing Concrete). However, other methods may be acceptable if prior experience and performance data are available. Whatever methods and procedures are used, the main criteria is that the CLSM be homogeneous and consistent and satisfy the requirements for the purpose intended.

### 2.6.1. Mixing

CLSM may be mixed by several methods, including central-mixed concrete plants, ready-mixed concrete trucks, and pugmills. For high fly ash mixtures where fly ash is delivered to the mixer from existing silos, batching operations may be slow.

Funston, Krell, and Zimmer (1984) reported that the material, which can be produced in pug mills turbine type mixers, and in central concrete mix plants, could be excavated if necessary with stable sidewalls. According to Swaffar and Price (1987), this material was used successfully for many applications, one of the more notable being to support a distressed tunnel internally prior to exterior grouting.

For CLSM mixtures consisting of fly ash, cement, water, and no aggregate filler, an effective mixing method consists of initially charging the truck mixer with cement then water. After throughly mixing these materials, the fly ash is added. Additional mixing for a minimum of 15 minutes was required in one case to produce a homogeneous slurry.(NAIK, RAMME &KOLBECK, 1990)

### 2.6.2. Transporting

Most CLSM mixtures are transported in truck mixers. Agitation of CLSM is required during transportation and waiting time to keep the material in suspension. CLSM has been transported effectively by pumps and conveyor belts. In pumping CLSM, the fly ash serves as a lubricant to reduce the friction in the pipeline.

### 2.6.3. Placing

CLSM may be placed by chutes, conveyors, buckets, or pumps, depending upon the application and its accessibility. Internal vibration or compaction is not required since the CLSM consolidates under its own weight. Although it can be placed year round, CLSM should be protected from freezing until it has hardened.

For trench backfill, CLSM is usually placed continuously. For pipe bedding, CLSM may have to be placed in lifts to prevent floating the pipe. Each lift should be allowed to harden before continued placement.

## 2.7. Quality Control

The extent of a quality control (QC) program for CLSM can vary depending upon previous experience, application, raw materials used, and level of quality desired. A QC program may be as simple as a visual check of the completed work where standard, pretested mixtures are being used. Where the application is critical, the materials nonstandard, or where product uniformity may be questionable, regular tests for consistency and strength may be appropriate.

For most projects CLSM is pretested using the actual raw materials to develop a mix design having certain plastic (flowability, consistency, unit weight) and hardened (strength, durability, permeability) characteristics. The following procedures and test methods have been used to evaluate CLSM mixtures.

### 2.7.1. Consistency and unit weight

Depending upon application and placement requirements, flow characteristics, can be important. The test methods are; ASTM C 939, Modified flow, CRD C611 for fluid mixtures; ASTM C 143 for plastic mixtures. Unit weight test methods are ASTM C 138 and ASTM D 4380 (Standard Test Method for Density of Bentonitic Slurries).

### 2.7.2. Strength tests

The strength of CLSM can be measured by several methods. Unconfined compressive strength tests are the most common; however, other methods such as penetrometer devices or plate load tests can also be used. Compressive strength specimens can vary in size from 2 x 2 in. cubes to 6 x 12 in. cylinders. Special care may be needed in removing very low strength CLSM mixtures from test molds. Some ASTM test methods used to determine strength of CLSM are ASTM C 403 (Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance), ASTM D 4832 (Standard Test Method for Preparation and Testing of Soil-Cement Slurry Test Cylinders), ASTM D 1196 (Standard Test Methods for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements), and ASTM D 4429 (Standard Test Method for Bearing Ratio of Soils in Place).

## 2.8. Applications of CLSM

As stated earlier, the primary application of CLSM is a structural fill or backfill in lieu of compacted soil. Because CLSM needs no compaction and can be designed to very fluid, it is ideal for use in tight or restricted-access areas where placing and compacting fill is difficult. If future excavation is anticipated, the maximum long term compressive strength should generally not exceed 300 psi (2.07 MPa). The following applications are intended to present a range of uses for CLSM.

### 2.8.1. Backfills

CLSM can be readily placed into a trench, hole, or other cavity. Compaction is not required, hence the trench width or size of excavation may be reduced. Granular or site excavated backfill, even if compacted properly in the required layer thickness, may not achieve the uniformity of CLSM.

When backfilling against retaining walls, consideration should be given to the lateral pressures exerted on the wall by flowable CLSM. Where the lateral fluid pressure may be a concern, CLSM may be placed in layers with each layer allowed to harden prior to placing the next layer.

### 2.8.2. Trench backfill

Probably the most common use of fly ash slurry backfill to date is a trench backfill. Fly ash slurry backfill is not labor intensive and requires less skill to place than compacted soil backfill. It is especially advantageous when local soils are susceptible to shrinkage, swelling, and large settlements. Its use minimizes the danger and the cost of working in a deep trench. Fly ash slurry is also useful in pipe bedding, as support is uniform and compaction of soil along the sides of the pipe is often difficult.

### 2.8.3. Structural fills

CLSM may be used for foundation support. Compressive strengths may vary from 100 to 1200 psi (0.69 to 8.27 MPa) depending upon application. In the case of weak soils, it can distribute the structure's load over a greater area. For uneven or non uniform subgrades under foundation footings and slabs, CLSM can provide a uniform and level surface.

Because of its strength, CLSM may reduce the required thickness or strength requirements of the slab.

### 2.8.4. Abandoned underground structures

It includes mines, tunnels, tanks, conduits. Mixes can be designed to flow long distances from a single entry point yet attain strength comparable to, or greater than, the adjacent ground.

Working together with the university of Wisconsin - Milwaukee Center for by product utilization, Wisconsin Electric Company (WE) is identifying mix proportions for flowable fly ash slurry that can be used as backfill for excavation projects and as fill for abandoned underground facilities (TARUN, BRUCE & HENRY, 1990).

Through a joint research project, mix proportions have been developed for low strength flowable fly ash slurries, controlled low strength materials (CLSM) as classified by ACI Committee 229, using fly ash produced at WE's Valley Power Plant in Milwaukee.

### 2.8.5. Filling hard-to-reach spaces

Fly ash slurry may also be used to fill large spaces under buildings and around foundations. It can easily fill irregularities in hard-to-reach places which might otherwise require the removal of surface structures. Fly ash slurry backfill is also self-leveling.

### 2.8.6. Reduced load

On underground structures and soft compressible soil, behind retaining walls. Because high ash slurries or foamed mixes have a lower unit weight than compacted soil or concrete backfill, and can be placed in layers, they apply smaller lateral loads retaining walls and reduce vertical loads on underground structures. The use of a high ash slurry or foamed mix can reduce settlement over soft ground and increase the load supporting capacity of marshy soils by behaving as a light-weight mat.

### 2.8.7. Pavement bases

CLSM mixtures may be used for pavement bases, subbases, and subgrades. The mixture may be placed directly from the mixer onto the subgrade between existing curbs. For base course design under flexible pavements, stuructural coefficients differ depending upon the strength of the CLSM. According to AASHTO (1986), based on structural coefficient values for cement treated bases derived from data obtained in several states, the structural coefficient of a CLSM layer may be estimated to range from 0.16 to 0.28 for compressive strengths from 400 to 1200 psi (2.8 to 8.27 MPa).

### 2.8.8. Conduit bedding

CLSM provides an excellent bedding material for pipe, electrical, telephone, and other types of conduits. The flowable characteristic of the material allows the CLSM to fill voids beneath the conduit and provide a uniform support.

### 2.8.9. Erosion control

Laboratory studies as well as field performance have shown that CLSM resists erosion better than many other fill materials. Tests comparing CLSM with various sand and clay fill materials showed that CLSM, when exposed to a water velocity of 1.7 ft/sec (51.85 cm/sec), was superior to the other materials, both in the amount of material loss and suspended material (KRELL, 1989).

Rip rap for embankment protection and in stilling basins below dam spillways are often filled with CLSM to hold rock pieces in place and prevent erosion. In addition to providing an erosion resistance under culverts, CLSM is used to fill voids under pavements, sidewalks, bridges and other structures where natural soil or non-cohesive granular fill has eroded away.

## 2.9. Low density CLSM using preformed foam

Low density CLSM (LD-CLSM) mixtures are primarily used where a lightweight fill is required. Because LD-CLSM requires different materials and mixing and placing equipment than those associated with conventional CLSM.

The basic materials for most LD-CLSM mixes are portland cement, water, and preformed foam. Other materials such as fly ash may be used to produce LD-CLSM; however, mixtures should be pretested prior to use. Further information on this material can be found in ACI 523 "Guide for Cast-in-Place Low Density Concrete."

Low density CLSM mixtures can be used anywhere conventional CLSM mixtures are considered. LD-CLSM is also effective as an insulating and isolation fill. The air cell structure inherent in LD-CLSM mixtures provides thermal insulation and shock mitigation properties to the fill material.

## 2.10. Load Transfer Comparisons Between Conventionally Backfilled with CLSM-CDF

In early 1990 the Cincinnati Gas and Electric company scheduled laboratory and field research related to of CLSM for load transfer. One of the early researchers to investigate load transfer trough soils was C.A.Coulomb who developed the relationship:

$$p = c + \sigma \tan\Phi$$

where ; p, shearing strength; c, cohesion; σ, normal strength on the shear plane; Φ, internal friction angle. The major difference between a compacted soil and CLSM, is with regard to cohesion and the internal angle of friction. Design engineers usually consider soils have zero cohesion. This not true for CLSM.

To test for load transfer through the trench backfill material a tandem axle dump truck was loaded with coal. The truck's rear axle was placed in several positions with respect to the pressure cells; directly over the cells, and straddling the cells. These positions were duplicated for both types of backfill; conventional and CLSM. Then the measured loads on each pressure cell for the various axle loading positions.

With the truck axle load directly over the cells on both types of backfills, the CLSM backfill reduced the load on the bottom of its trench by 78%. It also shows a reduction for "no load" condition of 86%. These load reductions are significant and create the opportunity for a number of engineering design change considerations.

Well known Rankine equations state that lateral pressure imposed upon a vertical wall, by backfill material, can be computed by the following formula:

$$p = (WH^2N/2) - 2CH\sqrt{N}$$

Where p, total active pressure against a wall; H, height of wall ; C, cohesion; N, constant.

$$N = \tan^2 [45^\circ - \Phi_1 /2]$$

$\Phi_1$ : internal angle of friction

The second part of Rankine equation is extremely important when considering the use of CLSM. This part of the equation takes cohesion into consideration. Design engineers usually consider this portion of Rankine's equation as zero since a soil's cohesion force can be extremely variable. The reason for this variability in cohesion, is that dry clay would have a sizeable cohesion value, but if the same clay were soaked, the cohesion could be a negligible value. Naturally, granular materials have zero cohesion for all practical purposes. Setting the second portion of Rankine equation to zero increases the design load condition and thus resulting in a more conservative design.

The cohesion value C increases with the aging of the CLSM under normal conditions. It should be obvious that the shear resistance attributable to cohesion becomes a significant factor when using CLSM.

The difference between these field measured and calculated conditions, while not significant for this research, are a result of non homogeneous soil backfill, discrepancy in either wheel load placement and cell elevation measurements. The significant thing to note is the for load and no load conditions, the CLSM measured load values are the same. This is because, as with the wall backfill example, the CLSM material through its cohesion and internal friction are bridging the cell (BREWER & ASSOCIATES, 1991).

Evaluation of flowable fly ash backfill under Static loading and Dynamic loading had been investigated by R.Peindll, R.Janardhanam, and F.Burns in 1992. A series of trench backfill tests are performed to evaluate the performance of flowable fly ash backfill versus that of a typical compacted soil backfill. The test site consists of a series of parallel trenches traversing a service road used for hauling fly ash to an on site storage area. Instrumented pipe assemblies are installed in trenches that are backfilled using both compacted soil and previously designed fly ash slurry. Pipes of various sizes and materials are instrumented with strain gages to monitor longitudinal and circumferential strains under static and dynamic loading conditions. Static and dynamic loads are applied by heavy vehicle traffic during normal hauling operations. The project was designed to demonstrate the feasibility and safety using a flowable fly ash backfill in an environment subjected to continual loading. In each case, for static and dynamic loading conditions, the ashcrete backfill performed as well as, or better than the compacted soil backfill.( BREWER & ASSOCIATES, 1991).

### 2.11. Factors Governing The Removability of Controlled Low Strength Materials

Early in 1990, the Cincinnati Gas and Electric Company (CG & E) decided to investigate these factors through laboratory and field research activities. William E. Brewer, P.E, Brewer & Associates, Toledo, Ohio was commissioned to serve as the research coordinator for this investigation.

### 2.12. CLSM Mixture's Affect on Removability

For years the compressive strength of a CLSM mixture has been used as a gage for determining the CLSM's removability. For average removability a compressive strength below 100 psi (0.7 MPa) at 28 days was suggested. Experience has shown that some mixtures, with 28 day compressive strength below 0.7 MPa ,exhibited a strength considerably higher than the 0.7MPa after one year. While compressive strength is a guide for removability, it should not be the only guide. Other material factors to consider are the fly ash and aggregate filler's particle shape, size, and chemical composition ( BREWER & ASSOCIATES, 1991)

### 2.12.1. Excavation Equipment's Affect On CLSM's Removability

When considering the removability of CLSM, the first question that needs to be answered is: what type of equipment will be used for removing the CLSM? While a typical CLSM backfill does not fit any specific soil classification, its measurable strength properties help in the development of removability criteria. Laboratory investigations for the determination of Young's Modulus have help to developed a correlation between removability and strength. The area under the stress/strain curve concept for removability is similar to the toughness modulus used in the study of metals. The larger the area; the more energy required for removability. This concept is also valid for CLSM, however acquiring the area under the curve requires considerable work. The area under the stress/strain curve will be used for CLSM removability calculations. The amount of energy and how it is delivered affects removability. It has always been desirable to have some type of numerical scale to measure removability. This CG&E removability research has lead to such a numerical scale based on a variety of variables. This numerical rating scale is referenced as the **Removability Factor** (RF) and is expressed by the following empirical relationship. The formulation has been converted to SI values (TÜRKEL & BARADAN, 1995).

$$RF = \frac{5.9\text{x}10^{-3}\ \text{x}T\text{x}J\text{x}\left[1+(IP-D^3/\sqrt{IPD})\right]}{S\text{x}A}$$

Where:

RF : Removability Factor
T : Equipment type: hand, air spade, hydraulic backhoe, clam bucket, or dragline. ($T\leq50$)
J : Cutting edge on the excavating equipment: blade, point, teeth. ($J\leq150$)
I : Impact factor. ($I\leq30$)
P : Power factor based on equipment used. ($P\leq10$)

D : Direction of excavation: along trench or across trench and/or edge. (2 along or 1 across)

A : Area under stress/strain curve.

A $\approx 0.678\ C^{1.4}$ (C = 28 day CLSM strength as MPa )

S : Density (g/cm$^3$)

The compressive strength C can be determined than acquiring the area A under the stress/strain curve.

A full explanation and examples for the use of RF equation will follow. All relationship factors require a numerical input based on a set of given conditions. These given conditions relate to the equipment being used (T), cutting edge (J), power applied (P), impact (I), direction of cut (D), and the CLSM strength C. For example, the type of equipment used (T) for excavation could vary from a hand shovel to a backhoe. For these different equipment types, a numerical value is entered into RF equation. These numerical values were based on previous construction experience and current CLSM removability research.

Values for each of the various **Removability Factor (RF)** components referenced in RF equation are found in Table 2.2. Values for table, as referenced previously, were developed from engineering experience and CG & E removability research. Each of these variables Table 2.2 should be considered for possible future research. The cutting edge type can result in different removability characteristics. A shovel's blade provides the least removability; a point provides the highest. The values range in Table 2.2 are set arbitrarily. The impact value references to how the load was applied. If the equipment operator pounded on the CLSM, a higher impact value should be assigned. A hand tool being the lowest rated and a backhoe the highest. Clam buckets and draglines have lower ratings than backhoes because of the backhoe's ability to provide a more controlled impacting force. Power factor relates to the excavating equipment's horsepower. The average value of "5" was for the field excavating equipment used in this research, an end loader/backhoe (JCB 1400B) Columbus Equipment Company. Equipment with more power would be assigned a higher Power Factor (P); not to exceed a value of 10. Field studies show that by cutting across the trench, the removability of CLSM is greatly enhanced. This is because the equipment can bite into the edge of the material. Once the CLSM is fractured, it is easier to remove. This is can best be accomplished by using teeth on the backhoe's bucket or point on air spade.

**Table 2.2. Removability Factor (RF) Components Referenced in RF Equation**

| | | |
|---|---|---|
| Cutting Edge (J) | Blade | 50 |
| | Point | 150 |
| | Tooth | 100 |
| Impact (I) | Low | 10 |
| | Average | 20 |
| | High | 30 |
| Equipment (T) | Hand Tool | 10 |
| | Air Spade | 30 |
| | Backhoe | 50 |
| | Clam Bucket | 20 |
| | Dragline | 25 |
| Power Factor (P) | Low | 1 |
| | Average | 5 |
| | High | 10 |
| Direction of Cut | Along Trench | 2 |
| | Across Trench | 1 |

### 2.12.2. Development of Removability Ranges

Using RF equation and various strength values for CLSM mixtures, the degree of removability ranges can be established (See Table 2.3). This Table 2.3 shows ranges for different removability ranges based on CLSM strengths. The Table 2.3 is based on the following average factors for CLSM removability.

Equipment: Air Spade (T=30)
Cutting Edge: Tooth (J=100)
Impact: Average (I=20)
Power Factor: Average (P=5)
Direction: Along Trench (D=2)

**Table 2.3. Average RF Value Relationship with Compressive Strength (C)**

| RF Value (No Units) | Compressive Strength (C) (MPa) | Removability |
|---|---|---|
| ≥ 100 | 0.7 - 0.85 | Easy Removal |
| 60 - 80 | 0.85 - 1.05 | Fairly Easy Removal |
| 40 - 60 | 1.05 - 1.37 | Removal with Difficulty |
| 20 - 40 | 1.37 - 2.1 | Extremely Difficult To Remove |
| 0 - 20 | 2.1 - 3.5 | Unable To Excavate |

Table 2.3 shows that any RF value greater than 100 will be easily removed using the average values referenced above. The Table 3 represents these average values. The Removability Factor (RF) can be increased or reduced by the excavation equipment and operation method selected. For easy excavation, the Removability Factor (RF) must be great than 100 based on RF equation. For a comparison of the equipment's affect on removability, see Figure 2.1. The same given conditions for cutting edge (J), impact (I), power factor (P), and direction of cut (D) is used in all cases. The only variable changed was the equipment (T) used for excavation.

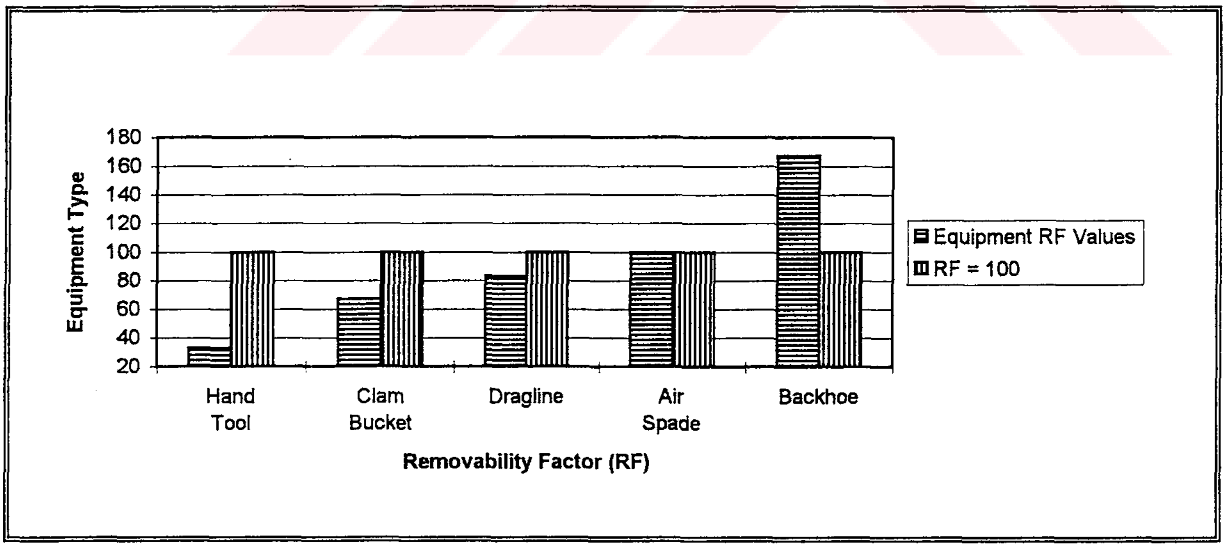

**Figure 2.1. RF versus Equipment Type**

# CHAPTER THREE

# EXPERIMENTAL PROGRAM AND TEST RESULTS

The tests performed in this experimental program has been realized according to ASTM, TS and other relevant standard test methods. The details of the testing program and test data has been presented in the following sections.

## 3.1. Materials

The basic materials used in the controlled low strength materials (CLSM) compositions; are pozzolana cement, crushed limestone as filler, fly ash and tap water. The physical and chemical properties of these ingredients has been presented in Tables 3.1, 3.2 and 3.3.

### 3.1.1. Cement

The purpose of cement in CLSM mixtures is to provide cohesion and strength control besides starting pozzolanic reactions.

According to available technical literature data, Portland cement of Type I (ASTM C150) has been used in previous testing programs on CLSM mixtures. Pozzolana cement has been chosen as the basic binder, due to its better durability properties in this study. The relatively lower mechanical properties of pozzolana cement did not create a problem since cement has been used in small percentages to start pozzolanic reactions. In addition to its durability advantages, pozzolana cement is the most available type in the market due to its lower production costs.

The pozzolana cement (TÇ 32.5) used in this research is a product of Batı Anadolu Cement Plant, İzmir. The physical and chemical properties of pozzolana cement (TÇ 32.5) are shown in Table 3.1. The test data were obtained from the Batı Anadolu Cement Plant's quality control laboratory.

**Table 3.1. Chemical and Physical Properties of TÇ 32.5 Cement**

| Chemical Properties | | Physical Properties | |
|---|---|---|---|
| Element | % | | |
| Silicon dioxide ($SiO_2$) | 3.49 | Specific gravity | 2.88 |
| Aluminumdioxide ($Al_2O_3$) | 8.50 | Blaine , $cm^2/g$ | 4609 |
| Ferric oxide ($Fe_2O_3$) | 3.53 | Remaining 90 μ, % | 0.9 |
| Calcium oxide (CaO) | 45.78 | Remaining 200 μ, % | 0.1 |
| Magnesium oxide (MgO) | 0.79 | Vicat : initial , min. | 135 |
| Sulfur trioxide ($SO_3$) | 2.10 | final , min. | 215 |
| Sodium oxide ($Na_2O$) | 0.87 | Compressive Strength, | |
| Potassium oxide ($K_2O$) | 1.51 | MPa | |
| Insoluble residue | 29.57 | 2 Days | 17.9 |
| Loss on ignition | 2.74 | 7 Days | 29.8 |
| Free lime | 1.20 | 28 Days | 37.1 |

### 3.1.2. Fine Aggregate

The fine aggregate, known as filler aggregate, makes up the major portion of a typical CLSM-CDF mixture. Non-standard filler aggregate (ASTM C33) materials have proven to be more economical (Brewer & Associates, 1993). Crushed limestone aggregate was used as filler in the CLSM mixtures. The material has been procured from Çimentaş, İzmir. The properties of crushed limestone has been presented in Table 3.2.

**Table 3.2. Grading and Physical Properties of Crushed Limestone Filler**

| Sieve Size (mm) | Cum. Per. Passing (%) | Physical Properties | |
|---|---|---|---|
| 8 | 100 | Bulk Specific Gravity | 2.655 |
| 4 | 96 | Unit Weight,($g/cm^3$) | |
| 2 | 66 | Loose | 1.622 |
| 1 | 40 | Compacted | 1.858 |
| 0.5 | 23 | | |
| 0.25 | 11 | | |
| Pan | 0 | | |

### 3.1.3. Fly Ash

Fly ash used in Portland cement concrete usually complies to ASTM C618. This same fly ash specification can be used in the manufacture of CLSM. Specific gravity (ASTM D854), fineness (ASTM D422), pozzolanic activity indexes with portland cement (ASTM C618 and TS 639) were included in the specification.

Some of the chemical and physical compositions of the fly ashes were determined in Batı Anadolu Cement Plant quality laboratory. The test results of fly ash are presented in Table 3.3.

## 3.2. Mixture Characterization

The production of CLSM can be accomplished step by step. The mix design is based on the relationship between the water to cementitious materials ratio W/(C+FA) and 28-day unconfined compressive strength values. By holding the starting point W/(C+FA) constant, the designer will estimate a fixed strength value, regardless of other changes in the mix. This is an advantage over mixes where water is continually added, as the addition of water alone changes all properties of the mix, leaving no single variable known. For every successive step, a procedure is suggested for adjusting the mix, if the desired property has not been achieved (flow, bleeding, etc.). Adjustments are made by increasing various components, rather than substitution, so that testing may be continued with the same batch. It should be noted that the strength development of fly ash occurs very slowly, therefore, fly ash may contribute greatly to strength at periods longer than 28 days. Backfills which may need to be excavated at a later date should be designed to have as low a 28-day strength as possible, as one year strengths may be two or more times the 28 -day strength.

The positive and negative effects of each component in the mixture is shown in Table 3.4.

**Table 3.3. Properties of Fly Ashes**

| Property | Soma B Fly Ash | ASTM SpecificationClass C | TS Specification General |
|---|---|---|---|
| Specific gravity | 2.12 | ----- | ----- |
| pH | 11.86 | ----- | ----- |
| % Retained #30 sieve | 0 | ASTM C593 2.0 max | ----- |
| %Retained #200sieve | 20 | ASTM C593 30 max. | ----- |
| Fineness, % Retained on # 325 sieve | 32.10 | ASTM C618 34 max. | ----- |
| Moisture content, % | 0.72 | ASTM C618 3.0 max | TS 639 3.0 max. |
| Pozzolanic Activity Index with cement, (MPa) (a)* | 9.2 | ASTM C618 75 min. | TS 639 70 min. |
| Pozzolanic Activity Index with lime (MPa) (b)* | 6.3 | ASTM C618 56 min. | ----- |
| Water requirement, % of control | 32 | ASTM C593 105 max. | ----- |
| Lime pozzolan Strength development (MPa) (c)* | 7.6 | ASTM C593 42 min. | -----<br>----- |
| Calcium oxide (CaO) % | 14.63 | ----- | ----- |
| Silicon dixoide ($SiO_2$)% | 49.08 | ----- | |
| Alu.dioxide ($Al_2O_3$) % | 22.99 | ----- | ----- |
| Ferric oxide ($Fe_2O_3$)% | 5.20 | ----- | ----- |
| Sum of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ % | 77.27 | ASTM C618 50 min. | TS 639 70 min. |
| Sulfur trioxide ($SO_3$)% | 1.28 | ASTM C618 5.0 max | TS 639 5.0 max. |
| Magnesi. oxide (MgO) % | 2.15 | ASTM C618 5.0 max | TS 639 5.0 max. |
| Loss on Ignition | 1.45 | ASTM C618 6.0 max | TS 639 10.0 max |

* (a) - Cured 1 day at 23°C plus 27 days at 38°C

* (b) - Cured 1 day at 23°C plus 6 days at 54°C

* (c) - Cured 7 day at 54°C

**Table 3.4. Effect of Components in the Mixtures**

| Component | Effect |
|---|---|
| Water | Reduces strength<br>Improves flow<br>Increases bleeding<br>Increases segregation |
| Cement | Increases strength<br>Improves flow of harsh mixes<br>Reduces bleeding<br>Reduces segregation<br>Reduces permeability |
| Fly Ash | Class C fly ash may develop high strengths without the use of cement or lime |
| Filler or sand | Commonly used mineral filler will segregate without sufficient paste. |

## 3.3. Mixing, Casting and Curing of Specimens

The CLSM compositions that are used in experimental studies are presented on Table 3.5. From each composition type, sufficient number test specimens of various sizes and shapes were casted. In these compositions, the total amount of binder (pozzolana cement+fly ash) was kept constant. Limestone powder as filler material was taken in filler/binder ratios by weight. In all compositions the ratio of pozzolana cement/fly ash was chosen as 5%. KRELL, (1989) also recommends a ratio of 4-5% for normal Portland cement case. The amount of mixing water should be determined to maintain the fluidity and pumpability of CLSM mixtures. Water/solid materials ratio has been chosen as 0.2 as a minimum value according to GAI consultants recommendations (1986).

The fluidity of compositions has been determined by flow table test according to ASTM C124-71. The fluidity ratio of CLSM mixtures were calculated according to the following formula :

Fluidity ratio = [(average spread diameter - 10cm) / 10] * 100

These ratios are also presented on Table 3.5 for every composition. The test specimens have been casted to molds without compaction or vibration.

**Table 3.5. Typical Mixes**

| Mixture Number | Mixture Type F/(C+FA) | W/(C+FA) | Water to Solid Ratio (WSR) | Fluidity Ratio (%) |
|---|---|---|---|---|
| 1 | 3:1 | 1.00 | 0.25 | 120 |
| 2 | 3.5:1 | 1.00 | 0.22 | 110 |
| 3 | 4:1 | 1.10 | 0.22 | 107 |
| 4 | 5:1 | 1.25 | 0.21 | 110 |
| 5 | 5.5:1 | 1.30 | 0.20 | 110 |
| 6 | 6:1 | 1.40 | 0.20 | 105 |
| 7 | 7:1 | 1.60 | 0.21 | 115 |
| 8 | 8:1 | 1.80 | 0.21 | 110 |

* All proportions by weight

F : Filler
C : Cement
FA : Fly ash
W : Water

The compositions with high fly ash contents, could not be demolded after 24 hours following the casting day due to low and late gain of strength. These test specimens were kept in molds for seven days in humid environment under wet burlap covers.

Mix proportions, number, size and shapes of test specimens for every CLSM mixture are presented in Table 3.6 and 3.7. The batch unit weights of CLSM mixtures are also presented in Table 3.6. The densities of CLSM mixtures have been determined between 1.95 to 2.15 g/cm$^3$ by ASTM D 854-58 Pycnometer test method.

**Table 3.6. Mix Proportions of Various CLSM Mixtures**

| Mixture Type | Materials Batch Weight, (kg) | | | | Total Weight (kg/m$^3$) |
|---|---|---|---|---|---|
| | Cement (TÇ32.5) | Fly Ash (Class C) | Crushed. Limestone | Water | |
| 3:1 | 19 | 370 | 1166 | 389 | 1944 |
| 3.5:1 | 17 | 346 | 1272 | 363 | 1998 |
| 4:1 | 16 | 314 | 1319 | 363 | 2012 |
| 5:1 | 13 | 268 | 1407 | 352 | 2040 |
| 5.5:1 | 13 | 250 | 1444 | 341 | 2048 |
| 6:1 | 12 | 234 | 1474 | 344 | 2064 |
| 7:1 | 10 | 208 | 1529 | 349 | 2096 |
| 8:1 | 9 | 182 | 1529 | 344 | 2064 |

**Table 3.7. CLSM Test Specimens Number, Size and Type**

| Test | Specimen Size and Type | Total No. of Specimens |
|---|---|---|
| Compressive Strength | 50/50/50 mm cube | 174 |
| Flexural Strength | 40/40/160 mm prism | 24 |
| Splitting Tensile Strength | 100/200 mm cylinder | 18 |
| Modulus of Elasticity | 100/200 mm cylinder | 6 |
| Permeability | 200/120 mm cylinder | 18 |
| Direct Shear Test | 60/60/20 mm prism | 18 |
| Water Absorption by Capillarity | 40/40/160 mm prism | 18 |
| Thermal Conductivity | 40/40/160 mm prism | 6 |
| Vacuum Saturation Durability | 102/120 mm cylinder | 48 |
| Chemical Durability | 50/50/50 mm cube | 270 |

### 3.4. Compressive Strength Test

The proper control of strength development in a flowable mix is the paramount criteria in developing the design mix. Strength development not only must meet the minimum value to provide structure support, but also, maximum strength development must be controlled since in the cases of backfill applications, often times it may be desired to return to the site and excavate a portion of the backfill to expose buried structures.

Twenty-four specimens were casted to represent each mixture for unconfined compressive strength test. Unconfined compression tests were performed on three specimens of various ages (7,14,21,28,56,90, 120, and 365 days). A compression test machine of two kgf sensitivity was used in the test. Smooth metal sheets were placed to the bottom and top of the specimens during the unconfined compression test to minimize the end effects. The average of test values of three specimens have been recorded for every age. Unconfined compressive strength test results are shown in Table 3.8. Figure 3.1 represents the same observation in graphical form.

**Table 3.8. Compressive Strengths of Various Type of Mixtures**

| Mixture Number | W/(C+FA) | COMPRESSIVE STRENGTH (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 7 Days | 14 Days | 21 Days | 28 Days | 56 Days | 90 Days | 120 Days | 365 Days |
| 1 | 1.00 | 0.28 | 0.58 | 0.84 | 1.15 | 2.14 | 2.27 | 2.32 | 2.80 |
| 2 | 1.00 | 0.24 | 0.38 | 0.65 | 1.06 | 1.69 | 1.88 | 1.99 | 2.21 |
| 3 | 1.10 | 0.22 | 0.37 | 0.63 | 1.02 | 1.31 | 1.45 | 1.49 | 1.69 |
| 4 | 1.25 | 0.19 | 0.39 | 0.72 | 0.92 | 1.01 | 1.14 | 1.21 | 1.30 |
| 5 | 1.30 | 0.17 | 0.34 | 0.64 | 0.88 | 0.95 | 1.02 | 1.10 | 1.22 |
| 6 | 1.40 | 0.16 | 0.31 | 0.61 | 0.85 | 0.91 | 1.00 | 1.06 | 1.16 |

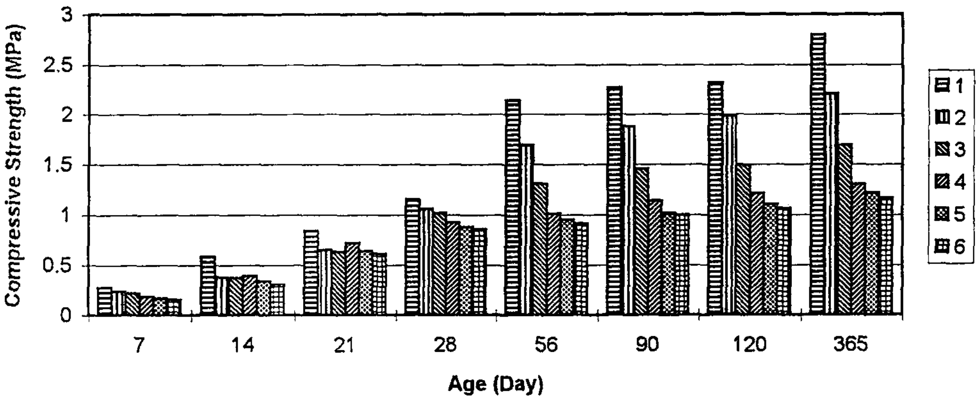

Figure 3.1. Unconfined Compressive Strength of Various Type of CLSM Mixtures

The compressive values of 7:1 and 8:1 mixture types were not determined accurately due to their lower mechanical properties. Besides, due to the segregation problem, these CLSM mixtures are not suitable for the purpose.

### 3.5. Flexural Strength (Modulus of Rupture)

Three 40/40/160 mm prismatic specimens (using Rilem Cembureau mortar molds) were prepared for flexural strength testing. The tests were performed span of 100 mm center-point loading similar to TS 24 (Physical Testing Method of Cement) on 28 days specimens. But, no tamping or compaction applied to the mixtures when during the placement. Test results are presented in Table 3.9. Graphical showing of test results are also given in Figure 3.2.

### 3.6. Splitting Tensile Strength

The 100/200 mm cylinder specimens were loaded along their length according to ASTM C496 (Method of Test for Spilitting Tensile Strength of Concrete) in this test. The splitting tensile strength (by Brasilian method) $f_{ct}$ was computed by using the equation $f_{ct} = 2P / \pi l d$. Where, P = load applied, N ; d = diameter, mm ; l = length, mm

The average value of three 28 days test specimens are given in Table 3.9 and the graphical form of test results are presented in Figure 3.2 respectively.

**Table 3.9. Flexural and Splitting Tensile Strength of Various Types of Mixtures at 28 Days**

| Mixture Number | Flexural Strength (MPa) | Splitting Tensile Strength (MPa) |
|---|---|---|
| 1 | 0.093 | 0.084 |
| 2 | 0.084 | 0.079 |
| 3 | 0.080 | 0.075 |
| 4 | 0.072 | 0.067 |
| 5 | 0.068 | 0.062 |
| 6 | 0.064 | 0.058 |

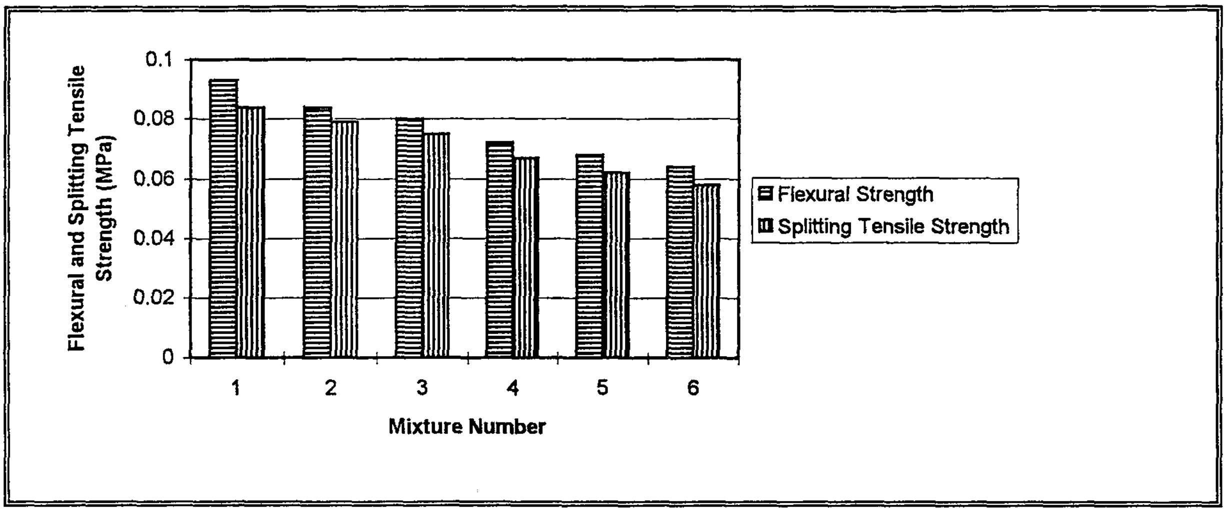

**Figure 3.2. 28 Days Flexural and Splitting Tensile Strength of Various CLSM Mixtures**

## 3.7. Direct Shear

The direct shear test procedure were realized for determining the strength parameters $\Phi$ (angle of internal friction) and $C_h$ (cohesion)of the material. The shear strength of the material is a measure of the materials ability to support imposed stresses on the material. It is a functional intergranular frictional resistance and cohesion. From the each mixture three 60/60/20 mm specimens were tested at 7 days. The shear strength of test specimens was determined by procedures of ASTM D 3080-72 for direct shear testing. A single shear apparatus was used to test specimens. The rate of strain was 0.300 mm/min. The values of shearing load and shearing strain were recorded simultaneously under various loads. The shear stress was determined at failure for each normal load. Shear stress at failure versus normal stress was plotted on the chart, using normal stresses as the abscissa. This straight line cuts the vertical axis. The ordinate of the cutting points was Cohesion value and the angle with horizontal was internal angle of friction (Figure 3.3). Direct shear test data are given in Table 3.10, cohesion and internal angle of friction results also in Table 3.11 for 7 days old specimens. However, direct shear test could not been realized for 28 days old specimens due to the gain of strength. The test apparatus is basically designed for soils, shear strengths over 0.35 MPa can not be measured. The graphical form of cohesion are shown in Figure 3.4.

**Table 3. 10. Direct Shear Test Data**

| Mixture Number | Normal Load (kgf) | Hor. Dial Reading | Corrected Area (cm$^2$) | Load Dial Reading | Hor. Shear Force (kgf) | Shear Stress (MPa) | Normal Stress (MPa) |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 800 | 35.04 | 412 | 32.94 | 0.093 | 0.034 |
| | 24 | 900 | 34.92 | 611 | 48.89 | 0.140 | 0.069 |
| | 36 | 1100 | 34.68 | 789 | 63.12 | 0.182 | 0.104 |
| 2 | 12 | 1200 | 34.56 | 380 | 30.41 | 0.088 | 0.035 |
| | 24 | 1400 | 34.32 | 571 | 45.65 | 0.133 | 0.070 |
| | 36 | 1200 | 34.56 | 752 | 60.13 | 0.174 | 0.104 |
| 3 | 12 | 1000 | 34.80 | 374 | 29.93 | 0.086 | 0.034 |
| | 24 | 900 | 34.92 | 568 | 45.40 | 0.130 | 0.069 |
| | 36 | 1100 | 34.68 | 754 | 60.34 | 0.174 | 0.104 |
| 4 | 12 | 800 | 35.04 | 333 | 26.63 | 0.076 | 0.034 |
| | 24 | 1000 | 34.80 | 487 | 38.98 | 0.112 | 0.069 |
| | 36 | 900 | 34.92 | 646 | 51.68 | 0.148 | 0.103 |
| 5 | 12 | 1100 | 34.68 | 316 | 25.32 | 0.073 | 0.035 |
| | 24 | 1200 | 34.56 | 458 | 36.63 | 0.106 | 0.069 |
| | 36 | 1000 | 34.80 | 605 | 48.37 | 0.139 | 0.103 |
| 6 | 12 | 900 | 34.92 | 314 | 25.14 | 0.072 | 0.034 |
| | 24 | 1100 | 34.68 | 451 | 36.07 | 0.104 | 0.069 |
| | 36 | 1000 | 34.80 | 596 | 47.68 | 0.137 | 0.103 |

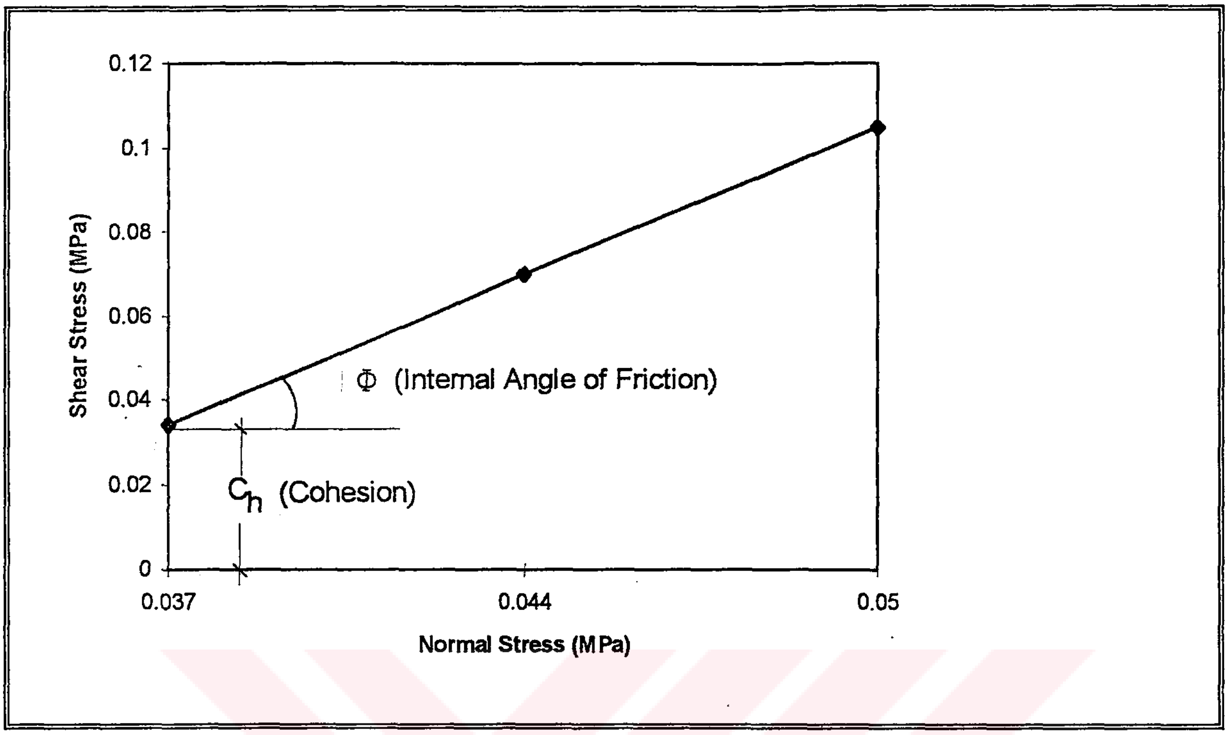

Figure 3.3. Obtaining of Cohesion and Internal Angle of Friction

**Table 3.11. Direct Shear Test Results for CLSM Mixtures at 7 Days**

| Parameters | MIXTURE NUMBER | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Cohesion (MPa) | 0.047 | 0.044 | 0.045 | 0.041 | 0.038 | 0.040 |
| Internal Angle of Friction(Degree) | 54 | 52 | 51 | 47 | 45 | 43 |

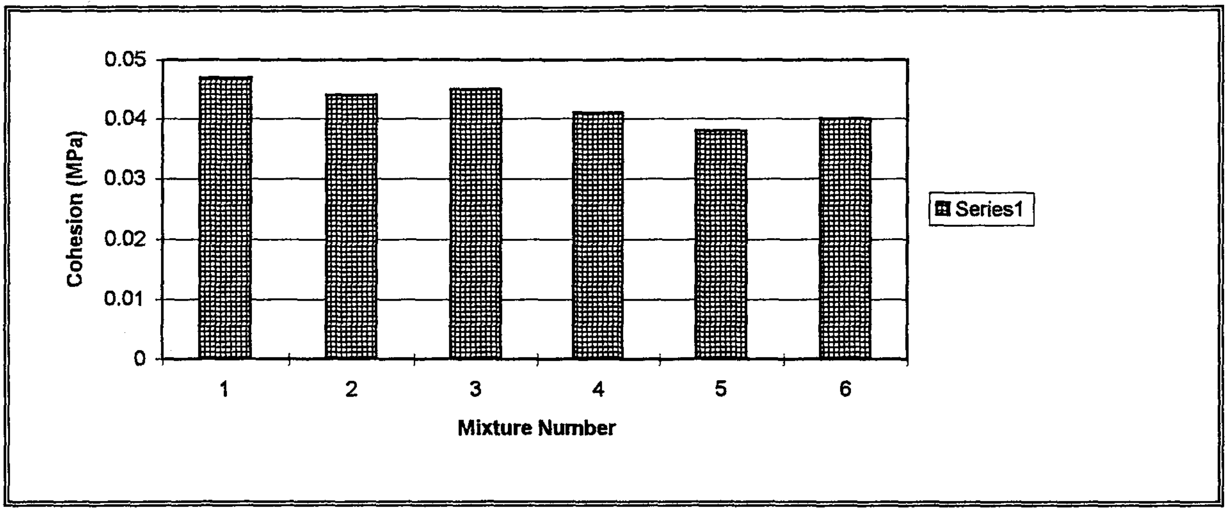

Figure 3.4. 7 Days Cohesion of CLSM Mixtures

### 3.8. Modulus of Elasticity

100/200 mm cylinder specimens were used for the determination of modulus of elasticity of selected mixtures. Because of the low strengths involved, the cylinders were cured in the mold for seven days. Sulfur capping procedures could not be used because the cylinders tend to break when being pryed out of the capping rig. For these tests, different capping procedures were used with gypsum as capping material.

Three axial test machine press with 1000 kgf sensitivity ring and 0.002 mm sensitivity dial gage was used in the test only with a vertical loading rate of 0.225 mm/sec.

A stress-strain curve was obtained from uniaxial compressive test data for a CLSM mixture. The modulus of elasticity can be derived in several ways from this relationship.

The secant modulus of elasticity can be calculated from the tangent of stress-strain curve for stresses below approximately 40 percent of the ultimate strength. The secant modulus is not a reliable, static modulus since its value differs according to the stress level. However, it is still practical enough for estimating the magnitude of modulus of elasticity for CLSM mixtures. Modulus of elasticity value has been calculated in the range of 120 MPa for a 3:1 mixture type of specimen at 28 days age.

## 3.9. Water Permeability

A number of test methods are available for obtaining the coefficient of permeability. In this study, a constant head permeability test was used to measure the permeability of the hardened CLSM specimens.

Permeability tests have been performed on the CLSM mixtures to determine the permeability of the pore space in the material. Each selected CLSM mixtures were poured into three cylindrical molds of 120 mm height and 200 mm diameter. 28 days cured specimens were dried in the oven and subjected to constant hydraulic pressure of 150 KPa in the head permeability test. The coefficient of permeability for each specimen was calculated by using Darcy's formula, $K = q / iA$. Where,

K=coefficient of permeability (cm/s)
q=flow rate (cm$^3$/s)
i=hydraulic gradient (dimensionless)
A=cross sectional area of flow (cm$^2$)

The test results have been presented in Table 3.12.

## 3.10. Water Absorption by Capillarity

40/40/160 mm prisms were prepared to determine the water absorption of CLSM mixtures by capillarity. At the end of 28 days after casting, test prisms were removed from curing tanks and dried in the oven at 105° C to constant weight. The test specimens were placed in a container at the vertical position with the bottom in contact to water. The coefficient of capillarity was calculated by using Jurin's equation, $(Q/A)^2 = k.t$ . Where,

Q=water absorption at 24 hours (cm$^3$)
A=cross sectional area (cm$^2$)
t=time (second)
k=coefficient of capillarity (cm$^2$/s)

Test results are shown in Table 3.12 for each CLSM mixture.

**Table 3.12. Water Permeability and Water Absorption Capillarity Test Results for CLSM Mixtures**

| Mixture Number | Coefficient of Permeability (cm/s) | Coefficient of Capillarity K x $10^{-3}$ ($cm^2/s$) |
|---|---|---|
| 1 | $0.96 \times 10^{-5}$ | 1.43 |
| 2 | $1.07 \times 10^{-5}$ | 1.67 |
| 3 | $2.01 \times 10^{-5}$ | 1.83 |
| 4 | $5.97 \times 10^{-5}$ | 1.91 |
| 5 | $1.09 \times 10^{-4}$ | 2.01 |
| 6 | $1.31 \times 10^{-4}$ | 2.08 |

### 3.11. Freeze and Thaw Test by Using Vacuum Saturation Method

Freeze and thaw durability was tested with the vacuum saturation test described in ASTM C593-76. For each mixture type, six cylinders (102/120 mm) were prepared for this test. Three specimens from each composition were placed in vacuum saturation apparatus one by one and applied a vacuum for 30-45 seconds. Then the specimens were soaked in water for an additional hour under atmospheric pressure. The specimens were removed from the apparatus and subjected to uniaxial compressive test. The compressive strength of the specimens obtained after vacuum saturation process, termed “residual strength” ($q_r$); is compared to the original (unsoaked) strength ($q_o$), and ($q_r/q_o$) is expressed as retention percent. Test results are presented in Table 3.13. Graphic forms of soaked and unsoaked situations have been shown comparatively in Figure 3.5 - 3.6.

**Table 3.13. Variation of Compressive Strength Before and After Vacuum Saturation Test**

| Mixture Number | 28 Days Compressive Strength (MPa) | | $q_r / q_o$ |
|---|---|---|---|
| | Pre-exposure ($q_o$) | Exposure ($q_r$) | |
| 1 | 1.58 | 1.44 | 0.91 |
| 2 | 1.47 | 1.32 | 0.90 |
| 3 | 1.42 | 1.25 | 0.88 |
| 4 | 1.29 | 1.09 | 0.84 |
| 5 | 1.22 | 1.01 | 0.83 |
| 6 | 1.18 | 0.98 | 0.83 |

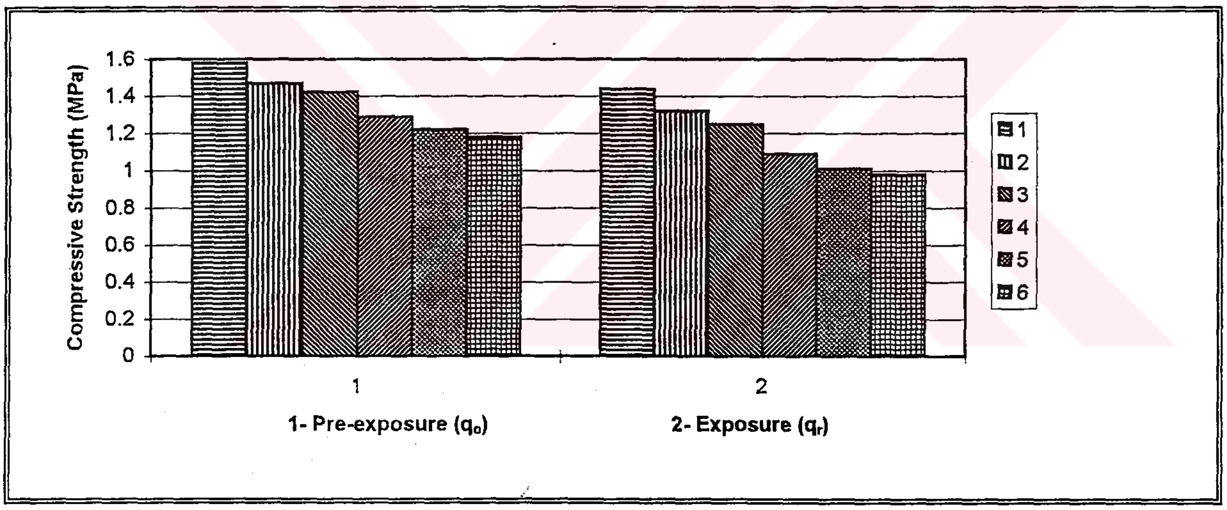

Figure 3.5. Pre-exposed and Exposed Strengths of CLSM Mixtures

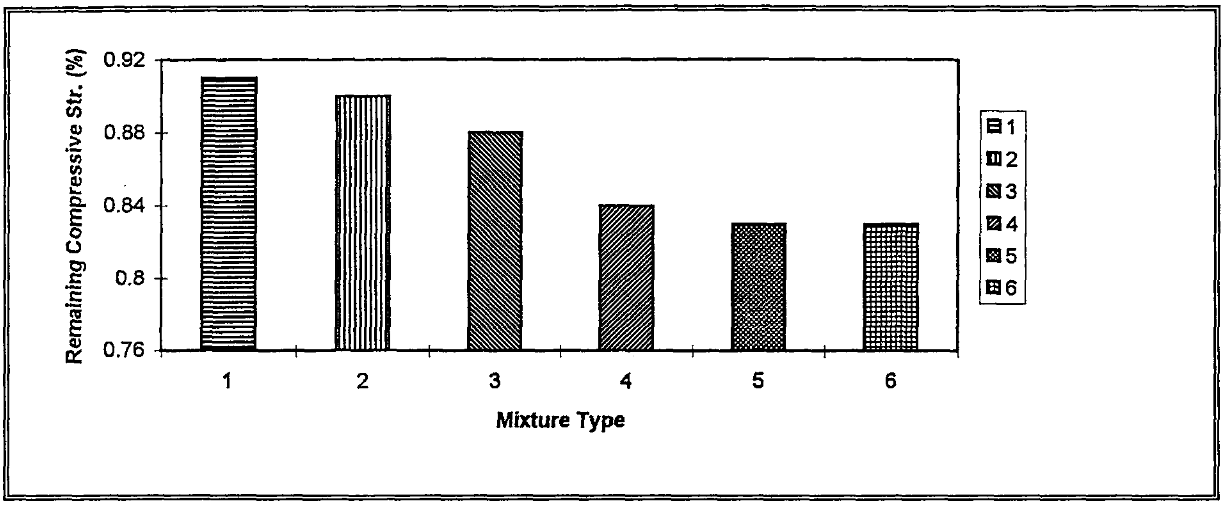

Figure 3.6. Retention Values of CLSM Mixtures

### 3.12. Durability in Different Temperature and Humidity Conditions

Extreme climatic conditions, such as very hot, dry or humid environments may also affect durability of CLSM compositions just like many other construction materials, especially at early ages. For this reason, two different weather conditions were simulated on the samples to observe the performance of CLSM. The desirable weather conditions, were created by Humidity Cabinets (Leec Brand). A wide range of fixed and relative humidities were achieved by adding suitable saturated salt solutions to the base reservoir of the cabinet. The relative humidity of air in contact with saturated salt solutions reaches to stated equilibrium values at certain temperatures.

A mild climate condition (20°C and 45% relative humidity) was simulated by using a saturated Potassium Carbonate salt solution. A hot climate condition (43°C degree and 60% relative humidity) was simulated by using a saturated Sodium nitrite salt solution. 50/50/50 mm cubes were used in the test. Three cube specimens from each mixture were placed immediately in humidity cabinet after molding for each climate conditions. 28 days compressive strength test results are presented in Table 3.14 and Figure 3.7 for two different climatic conditions.

The tests in severe cold environments could not be realized due to lower mechanical properties. The CLSM specimens wer not durable in sub-zero degrees.

**Table 3.14. Durability of CLSM Mixtures in Different Temperature and Humidity Conditions**

| Mixture Number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 28 Days Compressive Strength (MPa) | | | | | | |
| Moist Cured | 1.15 | 1.06 | 1.02 | 0.92 | 0.88 | 0.85 |
| Mild Climate | 2.40 | 2.11 | 1.96 | 1.70 | 1.51 | 1.31 |
| Hot Climate | 2.75 | 2.67 | 1.79 | 1.44 | 1.41 | 1.29 |

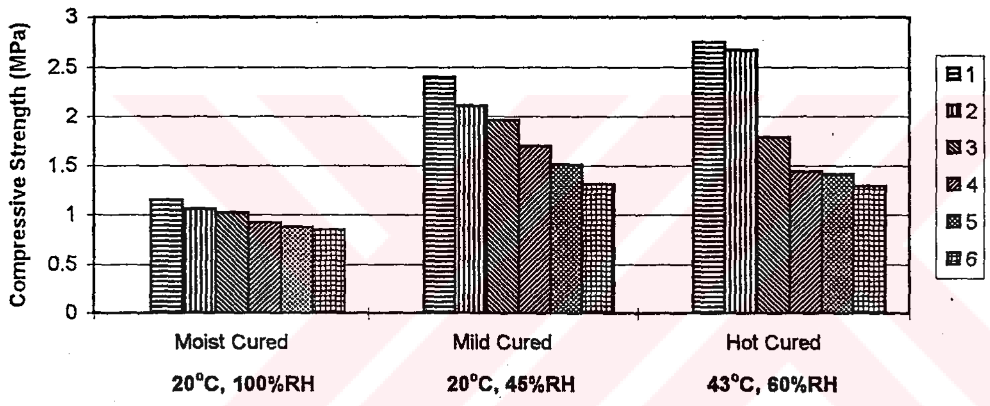

Figure 3.7. 28 Days Compressive Strength of CLSM Mixtures for Different Curing Conditions

### 3.13. Chemical Durability Test

There are no available standardized procedures for chemical durability tests for CLSM mixtures. The tests were performed comparatively according to technical literature.

50/50/50 mm cubes were prepared for chemical durability tests. 28-days old three specimens from each mixture were immersed in solutions of selected chemical compounds for six weeks. The existing chemical media were incorporating sulfate, salt and acidic solutions. Saturated, 2000 - 5000 ppm sodium sulfate and saturated magnesium sulfate solutions were used for sulfate attack. The saturated ammonium nitrate solutions were prepared for salt attack. The acidic media were created with 1% concentration only for sulfuric acid. Nitric acid, hydrochloric acid, formic acid, phosphoric acid, acetic acid solutions were prepared respectively with 5% and 10% concentrations. The test specimens were kept in different chemical media from 1 week to 6 week. At the end of every week, the specimens were taken from present chemical media, and washed, oven dried and weighted. According to original weight and residual weight of mixtures, the percent weights remaining after tests were determined during the test periods. The chemical test results are given in Table 3.15 to 3.26 and their graphical form reprasentation is shown in Figures 3.8 to 3.19.

**Table 3.15. Durability of CLSM Mixtures in Saturated Ammonium Nitrate Solution**

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1 Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 99.86 | 98.15 | 95.27 | 94.86 | 93.95 | 92.55 |
| 2 | 99.95 | 98.87 | 96.13 | 95.10 | 94.17 | 92.87 |
| 3 | 100 | 99.67 | 98.15 | 96.18 | 95.37 | 93.15 |
| 4 | 100 | 99.88 | 98.57 | 96.57 | 95.43 | 93.62 |
| 5 | 100 | 99.94 | 98.82 | 97.11 | 96.14 | 94.26 |
| 6 | 100 | 99.96 | 98.95 | 97.81 | 96.62 | 95.09 |

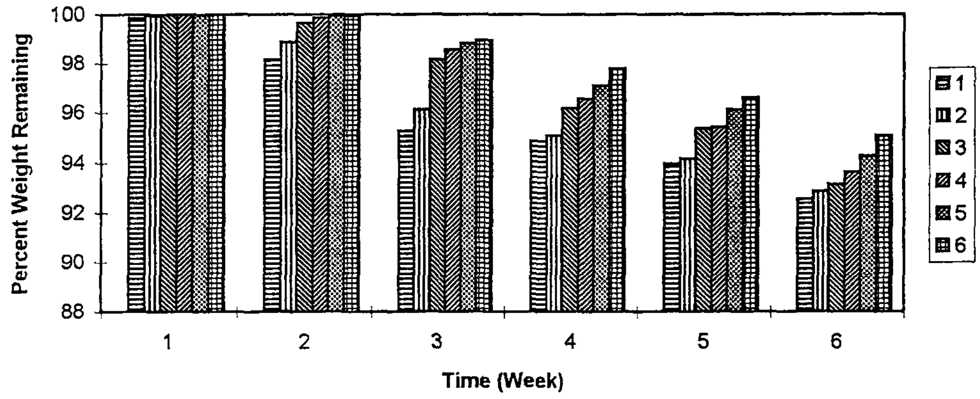

Figure 3.8. Saturated Ammonium Nitrate Solution Durability of CLSM Mixtures

Table 3.16. Durability of CLSM Mixtures in Sulfuric Acid Solution (1% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1 Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 95.36 | 95.05 | 94.85 | 94.61 | 94.50 | 94.02 |
| 2 | 95.75 | 95.45 | 95.31 | 95.12 | 94.92 | 94.80 |
| 3 | 96.65 | 96.52 | 96.40 | 96.28 | 96.14 | 95.92 |
| 4 | 98.58 | 98.48 | 98.26 | 97.65 | 97.32 | 97.15 |
| 5 | 98.89 | 98.78 | 98.56 | 98.40 | 98.22 | 98.05 |
| 6 | 99.18 | 98.98 | 98.77 | 98.52 | 98.36 | 98.20 |

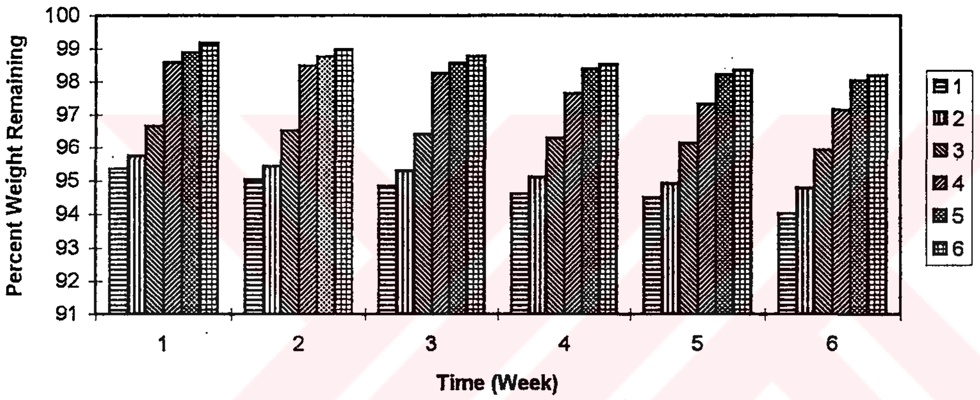

Figure 3.9. Sulfuric Acid Durability of CLSM Mixtures (1% Concentration)

Table 3.17. Durability of CLSM Mixtures in Hydrochloric Acid Solution (5% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 96.06 | 86.90 | 86.03 | 85.59 | 85.15 | 84.28 |
| 2 | 98.13 | 86.45 | 86.45 | 85.98 | 85.51 | 85.18 |
| 3 | 99.16 | 98.75 | 98.33 | 98.08 | 97.88 | 97.71 |
| 4 | 99.18 | 98.77 | 98.48 | 98.24 | 97.45 | 97.05 |
| 5 | 99.58 | 99.16 | 98.82 | 98.56 | 98.25 | 97.93 |
| 6 | 99.67 | 99.56 | 99.31 | 98.90 | 98.71 | 98.41 |

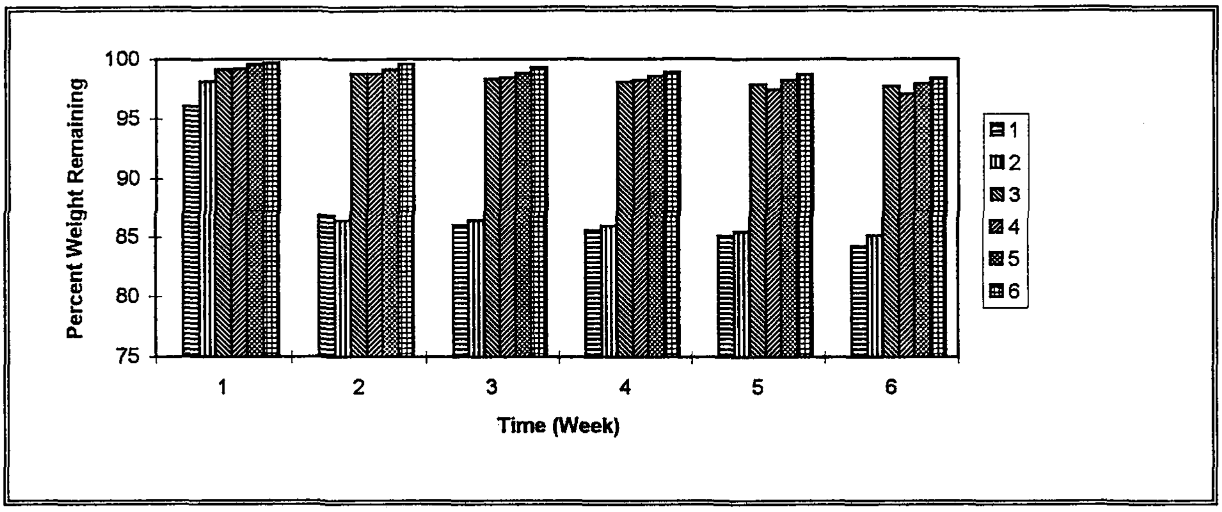

Figure 3.10. Hydrochloric Acid Durability of CLSM Mixtures (5% Concentration)

**Table 3.18. Durability of CLSM Mixtures in Nitric Acid Solution (5% Concentration)**

| Mixture Type | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 3:1 | 95.23 | 90.90 | 90.90 | 90.00 | 89.18 | 88.74 |
| 3.5:1 | 95.93 | 91.40 | 90.95 | 89.14 | 88.69 | 88.24 |
| 4:1 | 96.33 | 91.52 | 91.02 | 89.54 | 88.99 | 88.60 |
| 5:1 | 97.22 | 92.59 | 91.67 | 90.74 | 90.28 | 89.81 |
| 5.5:1 | 97.85 | 93.59 | 92.69 | 91.27 | 90.63 | 90.10 |
| 6:1 | 98.18 | 97.77 | 96.53 | 94.29 | 91.35 | 91.02 |

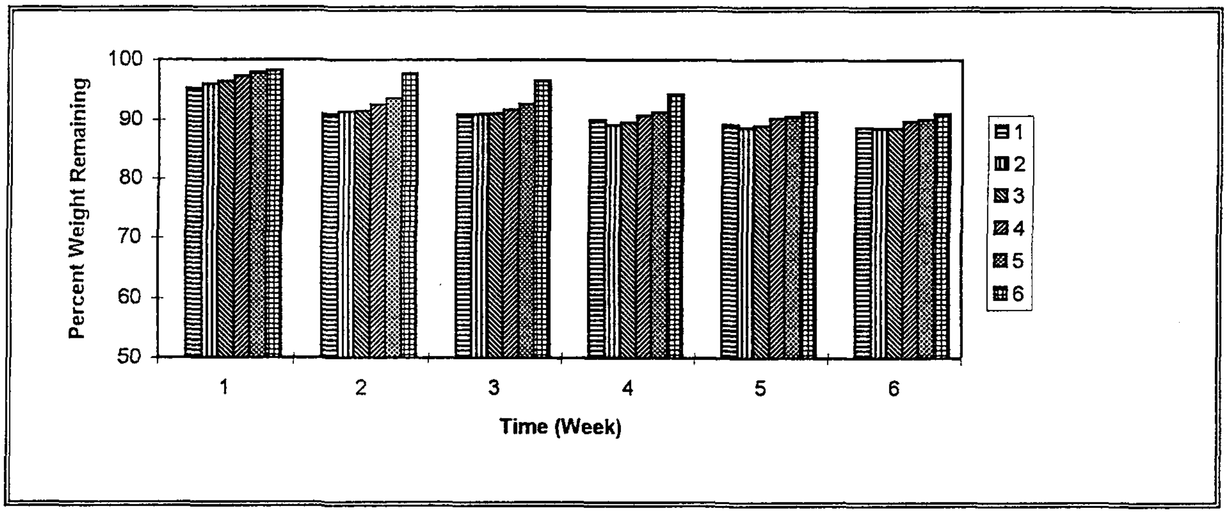

Figure 3.11. Nitric Acid Durability of CLSM Mixtures (5% Concentration)

Table 3.19. Durability of CLSM Mixtures in Phosphoric Acid Solution (5% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 96.77 | 94.93 | 94.85 | 94.47 | 94.10 | 93.86 |
| 2 | 96.85 | 94.97 | 94.90 | 94.58 | 94.25 | 93.97 |
| 3 | 97.73 | 95.45 | 95.05 | 94.69 | 94.38 | 94.12 |
| 4 | 97.95 | 96.05 | 95.78 | 95.32 | 94.97 | 94.81 |
| 5 | 98.68 | 96.92 | 96.49 | 95.74 | 95.15 | 94.92 |
| 6 | 99.17 | 97.93 | 97.69 | 96.89 | 96.74 | 96.23 |

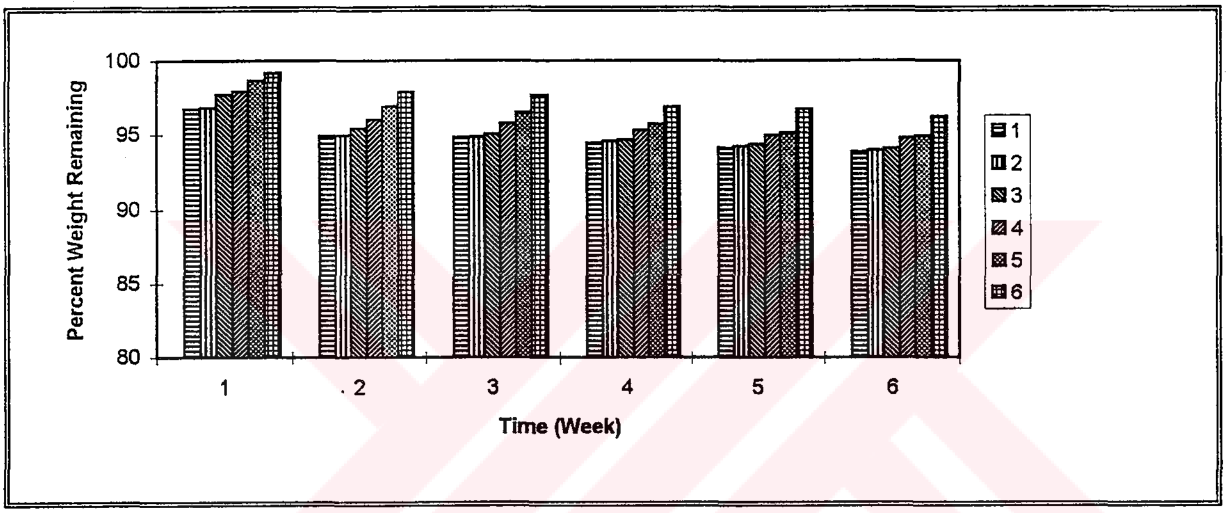

Figure 3.12. Phosphoric Acid Durability of CLSM Mixtures (5% Concentration)

Table 3.20. Durability of CLSM Mixtures in Formic Acid Solution (5% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 72.31 | 71.49 | 70.25 | 69.59 | 69.42 | 69.05 |
| 2 | 72.96 | 72.05 | 71.52 | 71.00 | 69.83 | 69.48 |
| 3 | 75.89 | 75.19 | 74.96 | 74.51 | 74.12 | 73.89 |
| 4 | 82.45 | 82.04 | 81.80 | 81.59 | 81.35 | 81.22 |
| 5 | 83.16 | 82.81 | 82.55 | 82.19 | 81.92 | 81.79 |
| 6 | 84.12 | 83.91 | 83.50 | 83.02 | 82.75 | 82.51 |

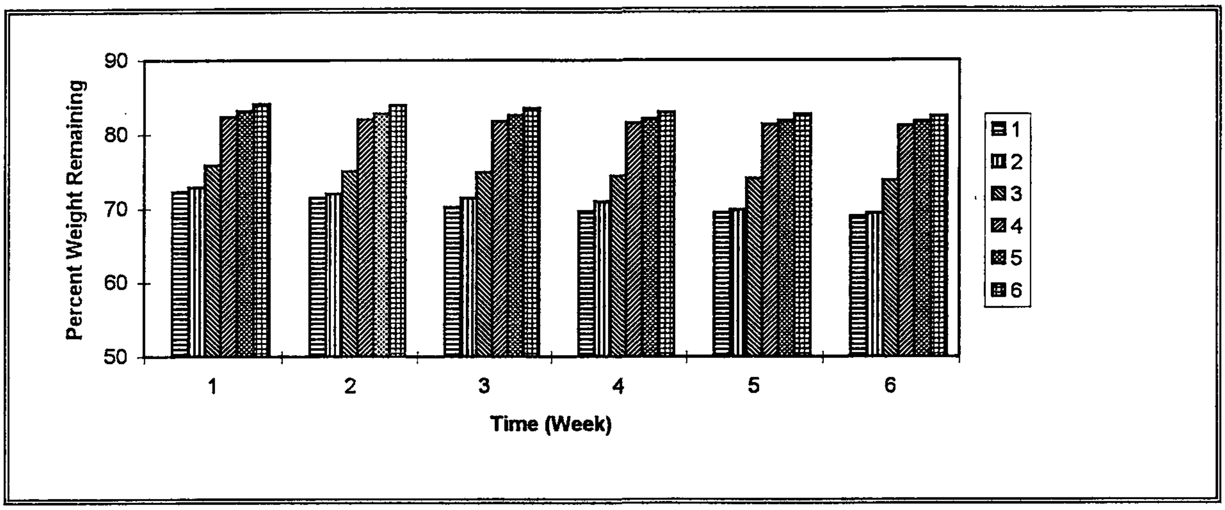

Figure 3.13. Formic Acid Durability of CLSM Mixtures (5% Concentration)

Table 3.21. Durability of CLSM Mixtures in Acetic Acid Solution (5% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 83.33 | 81.67 | 81.08 | 80.83 | 80.42 | 80.25 |
| 2 | 83.51 | 81.98 | 81.35 | 80.98 | 80.58 | 80.33 |
| 3 | 84.92 | 82.75 | 82.58 | 82.17 | 81.92 | 81.58 |
| 4 | 86.42 | 84.77 | 84.24 | 83.95 | 83.62 | 83.35 |
| 5 | 87.15 | 85.09 | 84.92 | 84.60 | 84.28 | 83.78 |
| 6 | 88.79 | 87.28 | 86.75 | 86.10 | 85.82 | 85.21 |

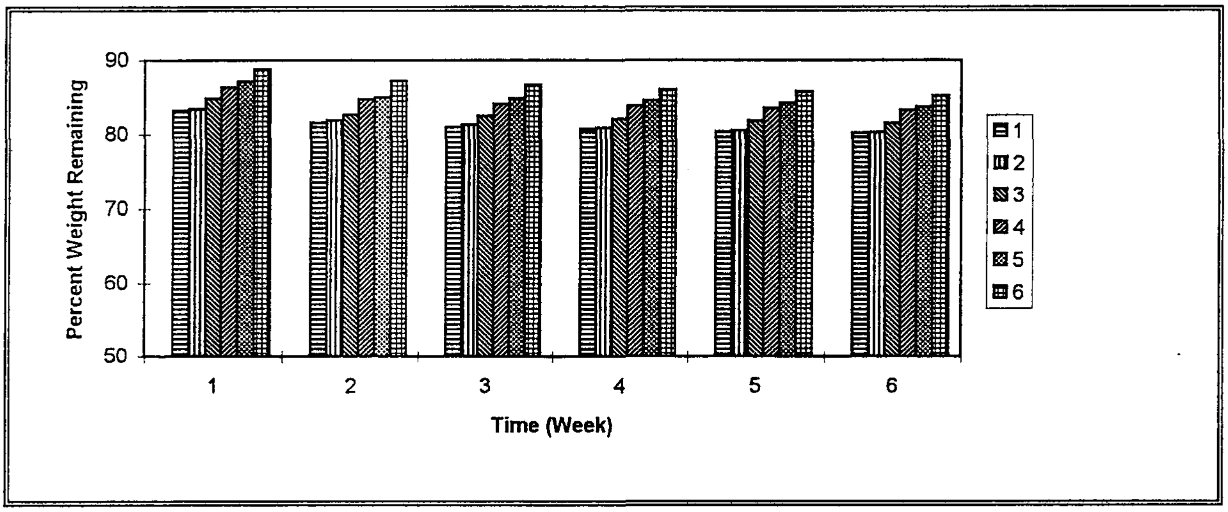

Figure 3.14. Acetic Acid Durability of CLSM Mixtures (5% Concentration)

**Table 3.22. Durability of CLSM Mixtures in Hydrochloric Acid Solution (10% Concentration)**

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 90.15 | 80.06 | 79.10 | 78.65 | 78.03 | 77.35 |
| 2 | 91.10 | 80.92 | 80.16 | 79.71 | 79.11 | 78.20 |
| 3 | 92.05 | 90.15 | 89.52 | 88.92 | 88.15 | 87.62 |
| 4 | 94.12 | 93.55 | 93.10 | 92.05 | 91.20 | 89.95 |
| 5 | 94.82 | 94.43 | 94.15 | 93.95 | 93.78 | 93.50 |
| 6 | 96.10 | 95.58 | 95.21 | 94.83 | 94.50 | 94.02 |

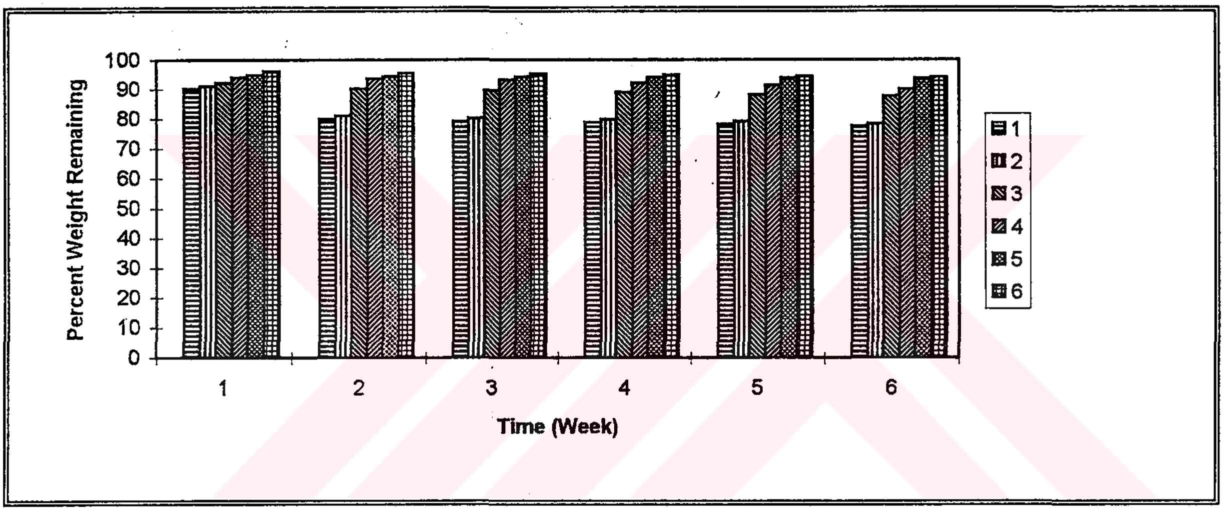

Figure 3.15. Hydrochloric Acid Durability of CLSM Mixtures(10% Concentration)

**Table 3.23. Durability of CLSM Mixtures in Nitric Acid Solution (10% Concentration)**

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 89.96 | 81.75 | 81.15 | 80.52 | 80.10 | 79.16 |
| 2 | 90.10 | 82.52 | 81.20 | 80.79 | 80.21 | 79.86 |
| 3 | 91.58 | 82.15 | 81.86 | 81.15 | 80.69 | 80.15 |
| 4 | 92.65 | 84.23 | 83.78 | 83.10 | 82.75 | 82.20 |
| 5 | 92.91 | 85.78 | 85.10 | 84.76 | 84.12 | 83.77 |
| 6 | 94.25 | 86.43 | 86.10 | 85.72 | 85.16 | 84.72 |

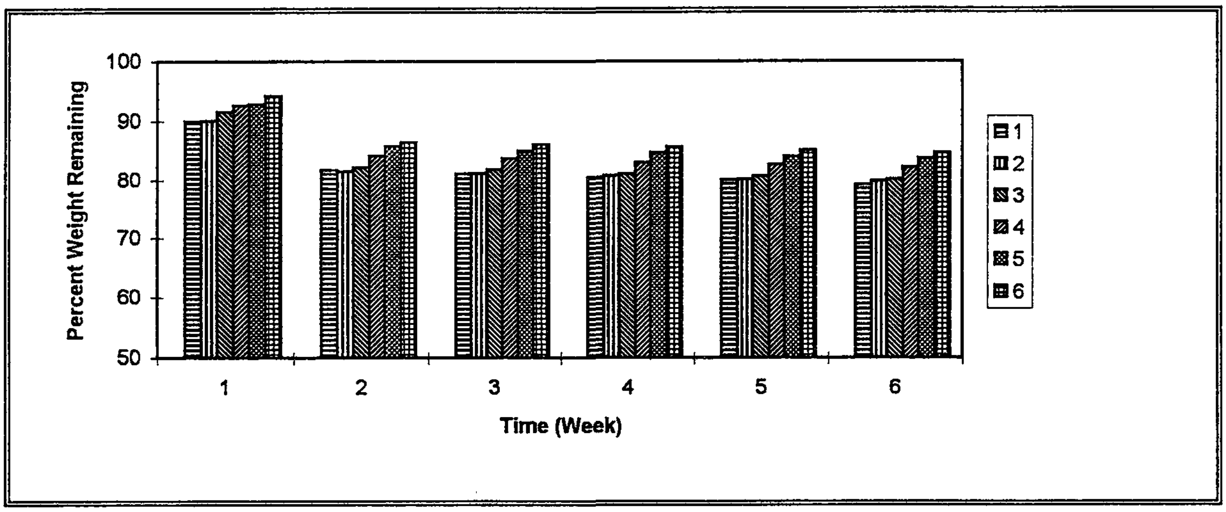

Figure 3.16. Nitric Acid Durability of CLSM Mixtures (10% Concentration)

Table 3.24. Durability of CLSM Mixtures in Phosphoric Acid Solution (10% Concentration)

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1 Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 91.56 | 88.61 | 88.10 | 87.52 | 87.10 | 86.75 |
| 2 | 91.95 | 89.05 | 88.68 | 88.02 | 87.71 | 87.15 |
| 3 | 92.86 | 90.42 | 89.96 | 89.51 | 89.05 | 88.75 |
| 4 | 94.15 | 93.18 | 92.75 | 92.20 | 91.60 | 90.95 |
| 5 | 94.86 | 94.05 | 93.52 | 93.06 | 92.70 | 92.10 |
| 6 | 95.90 | 95.21 | 94.86 | 94.25 | 93.75 | 93.35 |

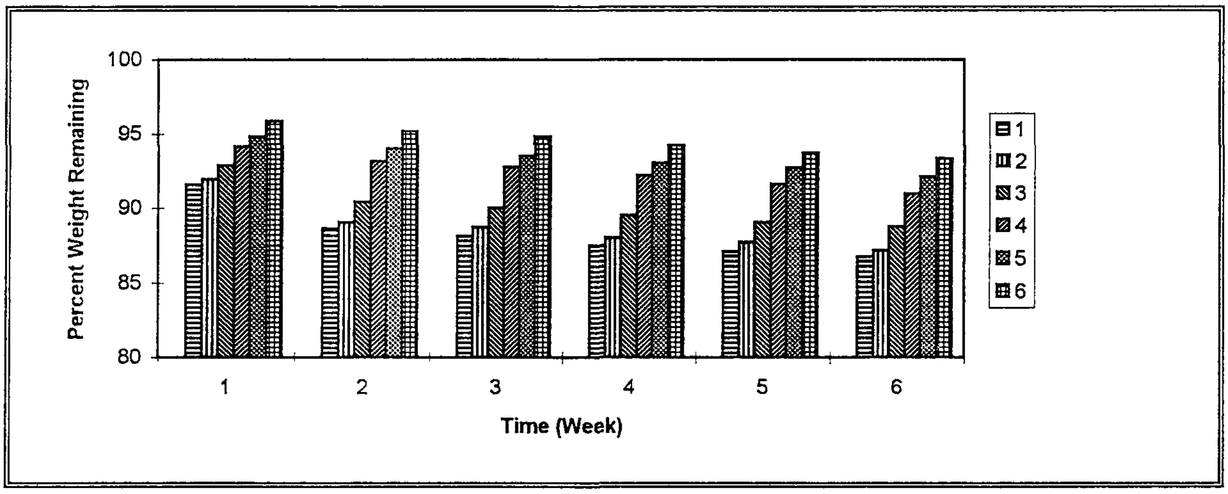

Figure 3.17. Phosphoric Acid Durability of CLSM Mixtures (10% Concentration)

Table 3.25. **Durability of CLSM Mixtures in Formic Acid Solution (10% Concentration)**

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 51.45 | 50.33 | 49.25 | 48.38 | 47.52 | 47.05 |
| 2 | 52.10 | 51.25 | 50.85 | 50.10 | 49.55 | 48.90 |
| 3 | 54.70 | 53.95 | 53.25 | 52.45 | 51.90 | 51.10 |
| 4 | 60.15 | 59.45 | 58.95 | 58.20 | 57.75 | 57.10 |
| 5 | 62.05 | 61.65 | 61.05 | 60.60 | 59.90 | 59.15 |
| 6 | 65.15 | 64.55 | 63.90 | 63.45 | 62.90 | 62.40 |

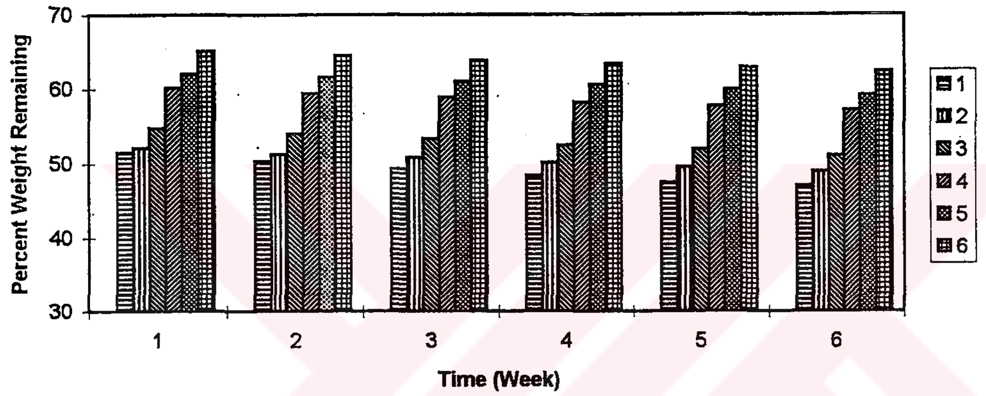

Figure 3.18. **Formic Acid Durability of CLSM Mixtures (10% Concentration)**

Table 3.26. **Durability of CLSM Mixtures in Acetic Acid Solution (10% Concentration)**

| Mixture Number | Percent Weight Remaining After Tests (%) | | | | | |
|---|---|---|---|---|---|---|
| | TIME (WEEK) | | | | | |
| | 1Week | 2 Week | 3 Week | 4 Week | 5 Week | 6 Week |
| 1 | 64.90 | 60.75 | 60.10 | 59.55 | 58.90 | 58.45 |
| 2 | 65.50 | 61.20 | 60.50 | 59.90 | 59.45 | 58.95 |
| 3 | 66.25 | 64.25 | 63.75 | 63.20 | 62.45 | 61.90 |
| 4 | 70.20 | 66.95 | 66.20 | 65.55 | 64.80 | 64.15 |
| 5 | 71.53 | 68.78 | 67.90 | 67.18 | 66.53 | 65.96 |
| 6 | 73.05 | 71.92 | 70.96 | 70.18 | 69.56 | 68.86 |

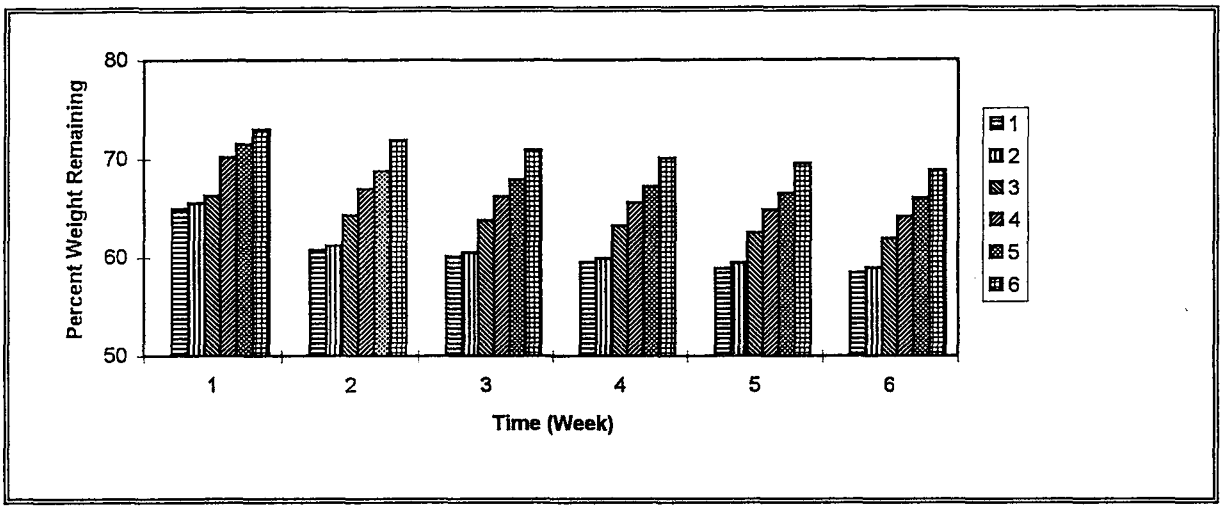

Figure 3.19. Acetic Acid Durability of CLSM Mixtures (10% Concentration)

### 3.14. Thermal Conductivity Test

The thermal conductivity tests were realized, in the Mechanical Engineering thermal laboratory, on the 40/40/160 mm prismatic specimens by using "hot wire method". A Shotherm QTM-D2 apparatus has been used to determined the thermal conductivity of CLSM mixtures in this test.

The thermal properties of CLSM, as well as the flowability, strength, and removability properties, varies by the changes in materials and proportioning methods. To obtain a low thermal conductivity value for CLSM, material selection and proportioning should be made to achieve a low density value. The general ingredients would place CLSM in between clay and sand soil types according to its thermal properties. Naturally, if high thermal conductivity is desired, CLSM compositions with high densities should be designed.

The thermal conductivity was calculated by using " hot wire method formula " ;

$$\lambda = K \frac{I^2 \, Ln\,(t_2/t_1)}{V_2 - V_1} - H \qquad \text{where,}$$

K, H = constants of test apparatus
$V_1, V_2$ = output of thermal element (mV)
$t_1$, $t_2$ = time (hour)
I = current passing through the heating resistor (A)

Based to the test data, the thermal conductivity of selected specimens were calculated between the ranges of 0.55 - 0.60 W/mK (3.67 - 4.00 Btu in./h ft$^2$ °F).

### 3.15. EP Toxicity Test

To analyse hazardous heavy metal existance in CLSM mixtures, the composition were subjected to Extraction Procedure (EP toxicity). Testing prescribed by U.S. Environmental Protection Agency (EPA).The main environmental concern surrounding utilization of CLSM mixtures is the chance of certain constituents leaching into the groundwater at concentrations determined to be potentially hazardous to human health.

The EP toxicity test is meant to act as a surrogate for potential leaching from a municipal solid waste landfill. The EP toxicity test requires first separating the solid and liquid portions of a waste sample. The solid portion is placed in a container with 16 times its weight of deionized water. This mixture is continually agitated at 20 - 40 °C. Throughout the test, the pH of the batch mixture is monitored so that the solution rises above pH 5.0, acetic acid is added to maintain a pH of 5.0. If the solution is less than pH 5.0, no acetic acid is added. If the pH of the batch solution is not below 5.2 after the initial 24-hour agitation period, the pH is adjusted at the beginning of each hour during an additional 4-hour agitation period. After agitation, the leachate is separated from the solid portion and the liquid from the original sample is added. The combined liquids are then tested for constituent characteristics. (U.S.Department of Commerce, 1988).

The EP toxicity tests were realized in the D.E.Ü. Environmental Engineering Departments Chemistry Laboratory on selected CLSM mixtures. At the end of this test the existance eight heavy metal concentrations; arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver are researched. The test results are given in Table 3.27.

**Table 3.27. EP Toxicity Test Results for Selected CLSM Mixtures**

| Element | CONCENTRATION (ppm) | | | |
|---|---|---|---|---|
| | 3:1 Mixtures | 5:1 Mixtures | 6:1 Mixtures | EPA Limits |
| Arsenic | 2.54 | 2.23 | 2.08 | 5.0 |
| Barium | 17.84 | 17.34 | 17.06 | 100.0 |
| Cadmium | 0.12 | 0.10 | 0.09 | 1.0 |
| Chromium | 0.08 | 0.05 | 0.03 | 5.0 |
| Lead | 0.39 | 0.33 | 0.28 | 5.0 |
| Mercury | 0.11 | 0.095 | 0.085 | 0.5 |
| Selenium | 0.32 | 0.25 | 0.22 | 1.0 |
| Silver | 0.00 | 0.00 | 0.00 | 5.0 |

## CHAPTER FOUR

# EVALUATION OF TEST RESULTS

### 4.1. Compressive Strength

The compressive strength test results had been presented in Table 3.8. The following general observations can be made with respect to the compression behavior of CLSM compositions.

a) The 28-day compressive strength values varied from 0.81 to 1.15 Mpa for the first six compositions. It should be noted that mixtures 7:1 and 8:1 had very low strengths, with segregation problems.

The similar results on the compressive strength of the CLSM were found by MAHER & BALAGURU (1993).

b) As expected, lower W/(C+FA) ratios and lower filler contents resulted in higher strengths. For example, mixture 3:1 (three part filler, one part (C+FA)) and W/(C+FA) ratio 1.0 had a 28-day compressive strength value of 1.15 MPa. On the other hand, mixture 6:1 (six parts filler, one part (C+FA)) and W/(C+FA) ratio 1.40 had a compressive strength value of 0.85 MPa at the same age.

c) The ratio of 365-day to 28-day strengths was lower for mixtures with higher filler contents. According to the test results, these ratios ranged from 1.36 to 2.43 for the mixtures 6:1 to 3:1 respectively.

d) Compressive strengths-time relationships of CLSM compositions have been established in logarithmic equations in the form of $f_c =.$ a Ln(t) - b. The regression coefficients have been obtained between 0.93 - 0.97 for these logarithmic equations.

The graphical form of this relationship and the coefficients (a, b, and regression R) of the logarithmic equations are presented in Figure 4.1 and Table 4.1 respectively for six mixtures.

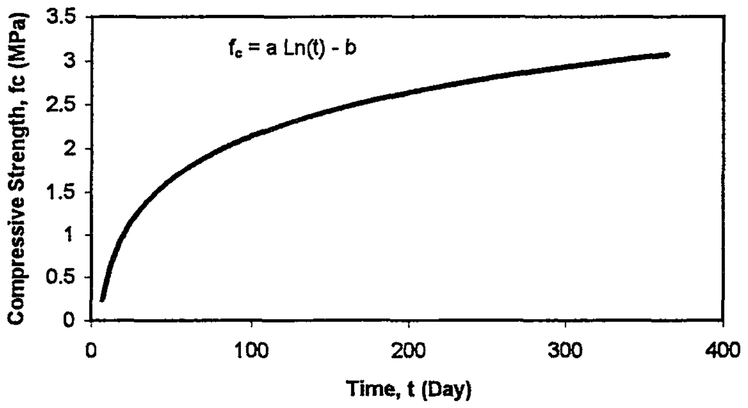

**Figure 4.1. Variation of Compressive Strength with Time**

**Table 4.1. Coefficients of The Logarithmic Functions**

| Coefficient | MIXTURE NUMBER | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| a | 0.7157 | 0.5842 | 0.415 | 0.2928 | 0.274 | 0.2468 |
| b | - 1.1518 | - 0.9408 | - 0.5429 | - 0.2442 | - 0.2435 | - 0.2412 |
| R | 0.97 | 0.96 | 0.96 | 0.94 | 0.94 | 0.93 |

Fly ash gains strength at a slower rate than cement. This factor became very important for the current investigation because of the high fly ash content of CLSM mixtures. According to the compressive strength test results from all the mixes, which were given in Table 3.8, the following observations were made with regard to compressive strength gain with time.

**i.** The rate of strength gain decreased slowly after 56-days.

**ii.** The strength gain continued steadily up to 365 days of testing period.

**iii.** Increase in filler content showed a decrease in the rate of later strength gain. This trend was logical because more filler aggregate provided more inert material that did not hydrate with time (MAHER & BALAGURU, 1993).

The amounts of fly ash and filler aggregate had a higher influence on strength at lower W/C ratios. Based on the test results obtained in this investigation filler aggregate to cementitious ratio of 8 could be used for W/C ratios of 1.8 or higher for situations where low compressive strengths are desired. If higher strengths are needed, filler aggregate to cementitious materials ratio 3 and W/C ratio 1.0 seem to provide the best results.

## 4.2. Flexural Strength (Modulus of Rupture)

The flexural strength test results had been given in Table 3.9. According to the test results flexural strength ($f_{ct}$) values ranged from 0.064 to 0.093 MPa at 28-days. The lower filler aggregate and higher cementitious material contents have higher flexural strengths. The test results showed that the flexural strength of the CLSM mixture changes in the same behavior as compressive strength. Flexural strength to compressive strength ratio ($f_{ct}/f_c$) is approximately 8% at 28 days for all mixtures.

The ratio $f_{ct}/f_c$ is in the range of 15-20% for normal concrete. For normal concrete, the flexural strength had been obtained 3.5 MPa by YAZICI (1996) when the compressive strength 20 Mpa. The CLSM mixtures flexural strength to compressive strength ratio is lower than normal concrete. A number of factors may affect on this result. Especially, using of filler aggregate with no compaction may decrease flexural strength of CLSM due to lower adhesion.

A mathematical relationship had been established between the compressive strength and flexural tensile strength values for CLSM mixtures. The correlation coefficient and the second degree equation are shown in Figure 4.2.

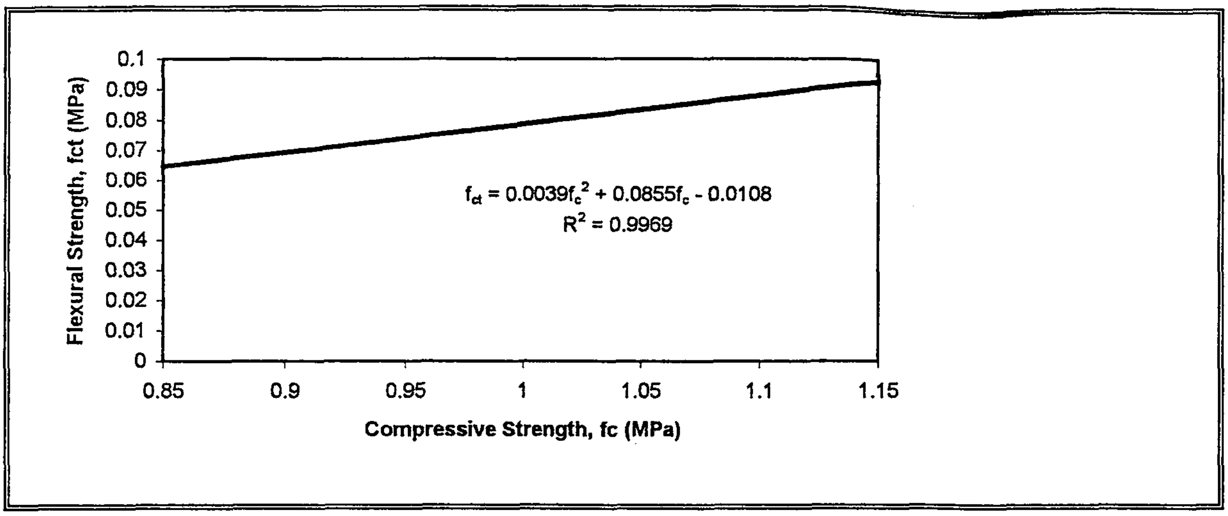

**Figure 4.2. The Relationship Between Compressive Strength and Flexural Tensile Strength at 28 Days**

## 4.3. Splitting Tensile Strength

According to the splitting tensile strength test results, which were given in Table 3.9, the values ranged from 0.058 to 0.084 MPa at 28-days. Increase in filler aggregate to cementitious materials ratio showed a decrease in the splitting tensile strength. The lowest 28-day splitting tensile strength 0.058 MPa , was obtained the mixture 6:1 and the highest 0.084 MPa for the mixture 3:1. Tensile strength values varied from 6.82 to 7.45 percent of the 28 days compressive strength. For the 7.6x15.2 cm size CLSM cylinder specimens, the splitting tensile strength ratio had been obtained 7.5% of the compressive strength by MAHER & BALAGURU (1993).

The ratio of $f_{ctd}/f_c$ is 10-15% for 15x30 cm size standard cylinder concrete specimens. the splitting tensile strength had been obtained 2.3 MPa by YAZICI (1996) for 20 MPa concrete. Splitting tensile strength to compressive strength ratio for CLSM mixture is lower than the normal concrete. The same remarks made for the flexural strength may be valid for this case.

A relationship had been obtained between the compressive strength and splitting tensile strength for CLSM mixtures. This relationship is presented in Figure 4.3.

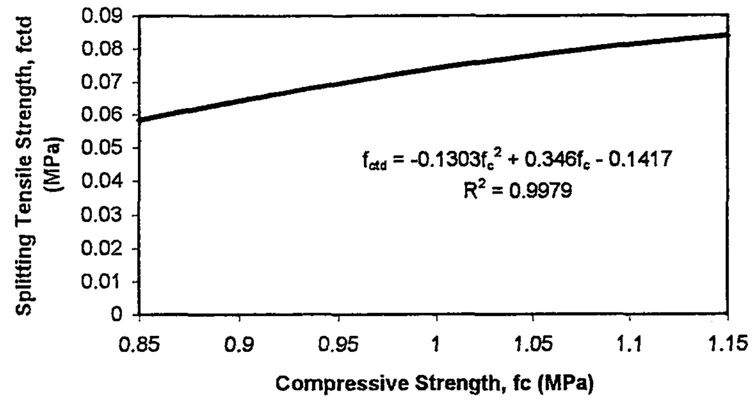

**Figure 4.3. The Relationship Between the Compressive Strength and Splitting Tensile Strength at 28 Days**

## 4.4. Shear Strength

The test results of the shear strength were presented in Table 3.10 and Table 3.11 for the various CLSM mixtures at 7-days. According to the test results, cohesion values ranged from 0.038 to 0.047 MPa and internal angle of friction ranged from 43° - 54°. It should be noted that the higher compressive strength result in higher cohesion values. A mathematical correlation had been developed for determining cohesion coefficients when the compressive strength is known. This correlation is shown in Figure 4.4.

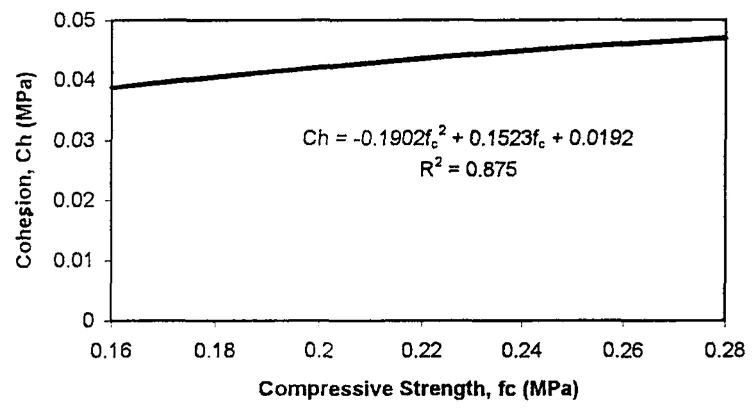

Figure 4.4. The Relationship Between Compressive Strength and Cohesion at 7-Days

For a good soil, the cohesion value is about 0.2-0.25 MPa. 7-days cohesion value of CLSM less than the soil due to the low rate strength gains especially early ages. But, at the 28-day cohesion value of CLSM mixtures exceed the soil cohesion value. Because, the direct shear test apparatus capacity was not sufficient for realizing the test.

It should also be noted that CLSM fills are self levelling, they do not need any compaction. Where as soil fills need compaction with optimum water content.

### 4.5. Water Permeability

Water permeability test results had been presented in Table 3.12. The highest coefficient of the permeability value, $1.31\mathrm{x}10^{-4}$ cm/s, was obtained in the 6:1 mixture, and the lowest permeability value $0.96\mathrm{x}10^{-5}$ cm/s in the 3:1 mixture. These data explained that a trend of decreasing permeability with the proportion of filler aggregate to cementitious material and W/(C+FA) ratio. The permeability of a material is a function of grain size distribution and degree of compactness of the material. It should be noted that CLSM mixtures have no compaction.

Permeability is inversely related to strength and durability. If the permeability of CLSM is lowered, its resistance to chemical attack and strength increases. The two parameters that adversely effect impermeability of CLSM mixes are presence of the large voids in the hydrated cement paste and the microcracks at the aggregate-cement paste transition zone. The use of fly ash is possible only through transformation of large pores into fine pores, and decrease of microcracking in the transition area (MEHTA,1983).

The similar permeability test results had been obtained by several investigators. Typical values are about $10^{-4}$ to $10^{-7}$ cm/s for various CLSM mixtures. For concrete, the permeability coefficient is approximately $3.5\mathrm{x}10^{-7}$ cm/s. The CLSM mixtures are much permeable than concrete due to its self levelling properties.

## 4.6. Water Absorption by Capillarity

The water absorption by capillarity test results had been presented in Table 3.12. The water absorption capillarity values ranged from $1.43 \times 10^{-3}$ to $2.08^{-3}$ $cm^2/s$ at 28 days. The lowest water absorption $1.43 \times 10^{-3}$ $cm^2/s$ was obtained for 3:1 mixtures, the highest for 6:1 mixtures. According to the test results, an increase in filler content showed an increase in the capillarity coefficient. This trend was logical, but these values were not certain for every case. Fly ash in the mixtures reduces voids in the hydrated cement paste and microcrack at the aggregate-cement paste transition zone. The gel porosity is increased, while the capillarity pores are decreased.

For chemical durability of mixtures the capillarity is an important characteristic. If the mixtures have lower capillarity, chemical durability should be expected higher.

## 4.7. Freeze and Thaw Durability by Using Vacuum Saturation

Freeze and thaw test results had been given in Table 3.13 for CLSM mixtures. According to the test results, exposed to pre-exposed compressive strength ratio has changed from 0.83 to 0.91. Laboratory freeze - thaw tests in water require a minimum 10% cement usage. However, vacuum saturation tests suggested by the Michigan Department of Transportation confirm that a 5 percent cement mixture would perform well in a freeze-thaw environment. Evidence from the field thus far indicates that the 5 percent cement mixture can perform as a road base even under severe winter conditions (KRELL, 1989).

## 4.8. Durability in Different Temperature and Humidity

Two different climatic conditions applied to the CLSM mixtures and the test results had been given in Table 3.14. The test results showed that both climatic conditions have positively affected compressive strength of the CLSM mixtures. Mild climate condition on the compressive strength ranged between 0.86 to 2.40 MPa and hot climate condition ranged between 1.02 to 2.75 MPa for same mixtures at 28-day. However, moist cured conditions ranged between 0.81 to 1.15 MPa. According to the test results, the following observations were made with regard to compressive strength gain with temperature and humidity:

a) Hydration of the binders and the rate of strength gain increased with the temperature increases especially at early ages.

b) The moist curing decreased compressive strength due to dissolving of free lime in the hardening CLSM.

In addition, calculated relative gains of compressive strength with two different temperature and humidity conditions compared to moist curing is given in Figure 4.5.

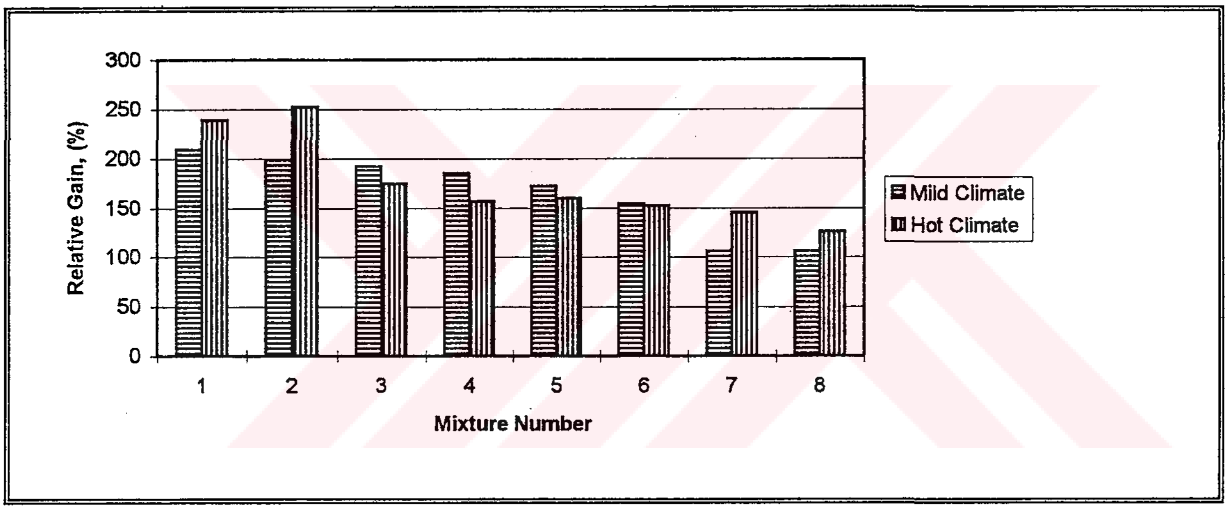

Figure 4.5. Relative Compressive Strengths Compared to Moist Cured at 28-Day

### 4.9. Modulus of Elasticity

For 100/200 mm cylinder and 3:1 mixture type, the secant modulus of elasticity had been obtained about 120 MPa. This value is much lower than the normal concrete. For the CLSM mixtures, an empirical relationship had been obtained between modulus of elasticity and unconfined compressive strength by FUNSTON et al. (1985). The relationship is $E=180\ f_c$ , where the $f_c$ is compressive strength (psi) of the 3x6 in. (7.6x15 cm) cylinders.

Typical modulus of elasticity values for different types of soils varies between 2 - 14400 MPa (BOWLES, 1984). Very soft clay soils and shales have the minimum and maximum values for modulus of elasticity comparatively. Modulus of elasticity values between 96 - 192 MPa are suitable for dense sand and gravel types of soils. The modulus of elasticity of CLSM mixture's in the range of dense sand to gravel.

### 4.10. Thermal Conductivity

The thermal conductivity of selected CLSM mixtures had been obtained between 0.55 - 0.60 W/mK (3.67 - 4.00 Btu in./h ft$^2$ °F). For concrete, these values changes between 0.9 - 1.5 W/mK (6 - 10 Btu in./h ft$^2$ °F) (BREWER & ASSOCIATES). In comparison of concrete and CLSM ; it can easily be observed that the CLSM mixtures have low conductivity properties. Thermal conductivity of CLSM depends upon the composition of the CLSM, especially on its unit weight. On the other hand, increase in the water content increases the thermal conductivity of CLSM mixtures.

The similar results for thermal conductivity of CLSM mixtures 0.45 - 0.75 W/mK (3 - 5 Btu in./h ft$^2$ °F) are obtained by the GIANETTI et al (1995).

### 4.11. Chemical Durability

The chemical durability of CLSM mixtures had been examined three different aggressive chemical groups ; salt, sulfates and acids. The test results for each chemical attack had been given in Chapter Three. According to the obtained test data, the following evaluation had made in this Chapter.

#### 4.11.1. Resistance of CLSM to Salt Attack

The saturated ammonium nitrate solution attack on the CLSM mixtures had been given in Table 3.15. Durability factors of CLSM mixtures were found in the range of 92.55 to 95.09 percent after six weeks. Some industries sewage water includes ammonium nitrates. This salt is a cause of deterioration for many concrete based materials. Several investigators have performed studies on the ammonium nitrate resistance of concrete. Effect of immersion in a saturated ammonium nitrate solution on concrete durability (percent weight remaining after tests) had been examined by YAZICI (1996). In this study, the concrete samples had been disintegrated at the end of four weeks. However, the CLSM mixture's durability factor had been obtained minimum 92.55 percent for 3:1 type mixtures after six weeks. This difference depends upon the lime content in the mixtures. According to SAFWAN (1994), the observed disintegration shows that expansive compounds were formed due to the reaction between the lime and the aggressive solutions. These reactions were decreased in the case of fly ash mortar due to the reduction and stabilization of the harmful lime content in the matrix. The test results showed that CLSM mixtures are more durable than the concrete when subjected to the saturated ammonium nitrate solution.

### 4.11.2. Resistance of CLSM to Sulfate Attack

The sulfate durability test of CLSM mixtures had been realized with saturated magnesium and sodium sulfate solutions. When the all type of CLSM specimens immersed in the saturated sodium sulfate solutions, approximately four hours later some cracks appeared and at the end of 24 hours all specimens had been disintegrated. Later, same types of CLSM mixtures were subjected to 2000 and 5000 ppm concentrate sodium sulfate solutions attack as the second stage of experiments. It is known that the sodium and magnesium sulfate exist in groundwater, seawater and alkali soil up to 2000 ppm and 5000 ppm concentrations. Due to this reason, these values were chosen for tests since CLSM is a suitable backfill material. After six weeks of immersion in 2000 and 5000 ppm sodium sulfate solution, there was no cracks appeared, no disintegration, and no weight loss. Same positive results obtained for the magnesium sulfate case.

The effect of sulfates on the CLSM mixtures may be similar to the concrete. When the concrete is subjected to the sodium and magnesium sulfates attack new compounds are formed as a result of reactions of sulfate with cement hydration products. The sulfates react chemically with the hydrated lime and hydrated calcium aluminate, respectively. These reactions lead to expansion, softening and disintegration of concrete structure. As a result concrete can fail depending on the sulfate type, concentration and exposure time. Indeed, these expectations for the concrete are valid for the CLSM.

Fly ash is a good quality pozzolan, resistant to sulfate attack in the seawater or in other surroundings. In the many national standards there are recommendation of using of fly ash in concrete order to improve the durability against sulfate attack. Positive effects of the fly ash on the sodium sulfate durability of CLSM mixture can be explained by the stabilization of free lime and by creation of additional CSH (calcium silica hydrate) gel as classical pozzolanic reactions.

YEĞİNOBALI & DİLEK (1996) stated that low content lime fly ash had no negative effect on magnesium sulfate durability of the slurries in their study. In this case, magnesium sulfates react with CSH and creates a protective $Mg(OH)_2$ layer. "Visual durability index" of various specimens had been determined in this study. According to their test data, specimens incorporating fly ash, have higher magnesium sulfate durability than the sodium sulfate durability during the 13 months of testing period.

YAZICI (1996) have also explained that fly ash incorporation to Portland cement, may decrease the effect of sulfate attack. For normal concrete ; sodium sulfate durability factor had been obtained as 81.33% and for magnesium sulfate as 96.74% during six weeks of testing period by YAZICI in saturated solutions. In the same study, durability of high strength concrete incorporating fly ash specimens had been found 100% after six weeks in both saturated sulfates solutions. In this case ; the CLSM mixtures are expected to be more durable to saturated magnesium sulfate attack than the concrete due to the incorporation of fly ash in high percentages and due to the usage of pozzolana cement which has better durability properties than Portland cement. $SiO_2$ is an inert material. TÇ 32.5 and fly ash used in this study have 3.49 and 49.08% of silica contents respectively. Higher percentages of $SiO_2$ in the fly ash, increases the sulfate durability of the CLSM mixtures. Besides, the sulfate durability of CLSM mixtures depend also upon the CaO contents in the binder. The TÇ 32.5 cement incorporates 45.78% and fly ash 14.63% of CaO. When the CLSM mixtures subjected to the magnesium and sodium sulfate attack, $Ca^{2+}$ ions in the binder replace the $Na^+$ and $Mg^{2+}$ ions. This is one of the main causes of the specimen's deterioration for binders with the high percentages of CaO. Due to this reason binders incorporating fly ash with low contents of CaO and high percentages of $SiO_2$ are expected to be more durable than the binders composed of plain cement.

### 4.11.3. Resistance of CLSM to Acid Attack

The durability of CLSM to acid attack had been performed with six different type of acids under two different concentrations and the results were presented in Chapter Three. However, there is no available test procedures that are standard for this case. The test are performed on comparative basis.

According to the NEVILLE (1975) the effect of acids are explained as follows: "In damp conditions $SO_2$, $CO_2$ and other acid fumes present in the atmosphere attack concrete by dissolving and removing part of the set cement, a soft and mushy being ultimately left behind. This form of attack occurs in chimneys and steam railway tunnels. Acid attack is encountered also under industrial conditions. It should be noted that no Portland cement is acid resistant". The CLSM mixtures are also subject to the similar attacks. However, damage of sewers may be more effective, especially on the use of CLSM as a filling material on the sewage pipeline.

Sulfuric acid is the most powerful acid that exists in many industries. First of all, the CLSM mixture had been immersed 5% concentration of sulfuric acid solution. However, all type of CLSM specimens started to disintegration simultaneously when the specimens immersed in the solution. Second, CLSM mixtures subjected to 1% concentration of sulfuric acid solution attack six weeks. The 1% sulfuric acid durability factors were found range among 94.02 to 98.20 for number one to six mixtures. The test results showed that durability factor increases with filler to binder ratio. The durability factor of concrete had been obtained as 83.66% at six weeks' periods by YAZICI for 5% concentration of sulfuric acid.

Hydrochloric acid durability factor of CLSM mixtures varied from 84.28 to 98.41% for 5% and 77.35 to 94.02% for 10% concentrations at six weeks' periods. Durability factor of CLSM mixtures especially depends upon the filler/binder ratio for all types' acids. The similar expectations are valid for hydrochloric acid attacks to the CLSM mixtures. For concrete, hydrochloric acid durability had been found 84.37% for 5% and 74.71% for 10% concentration at six weeks' periods by YAZICI (1996). CLSM specimens exhibited a little more resistance to deterioration by hydrochloric acids than normal concrete in this period. The comparison with concrete and CLSM mixtures are shown in Figure 4.6.

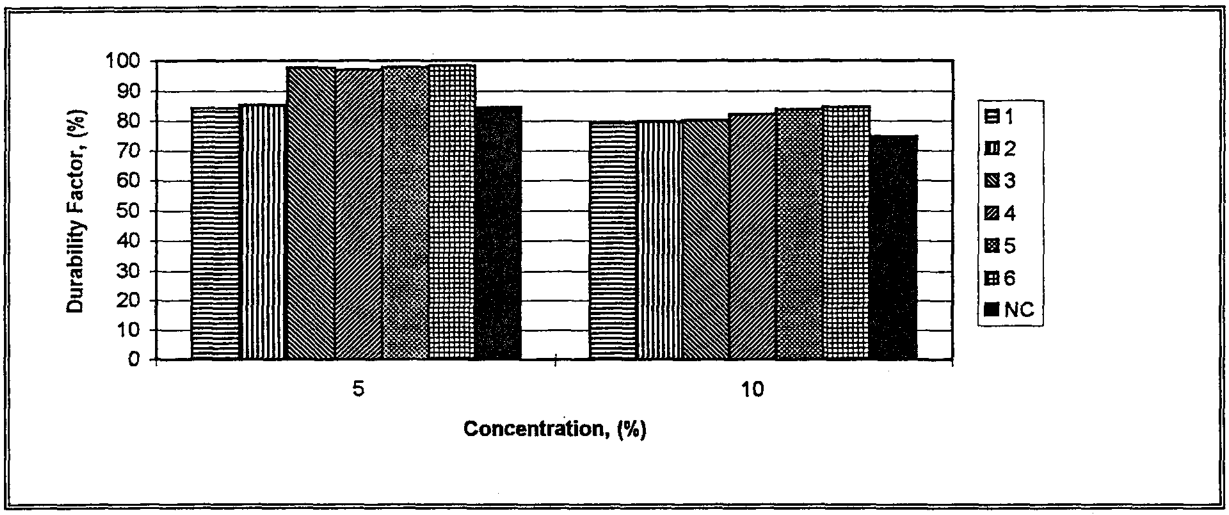

Figure 4.6. The Comparison with Concrete and CLSM Mixtures for Hydrochloric Acid Durability at Six Weeks

Nitric acid solutions are effected on CLSM mixtures as much as hydrochloric acid. Durability factor varied from 88.74 to 91.02% for 5% and 88.74 to 91.02% for 10% concentration of nitric acid at six weeks' periods. According to the test results, nitric acid durability factors of CLSM mixtures have increased with filler to binder ratios. For concrete, durability factor had been obtained 77.24% for 5% and 62.41% for 10% concentration of nitric acid at six weeks by YAZICI (1996). The nitric acid durability comparison with concrete and CLSM mixtures are given in Figure 4.7.

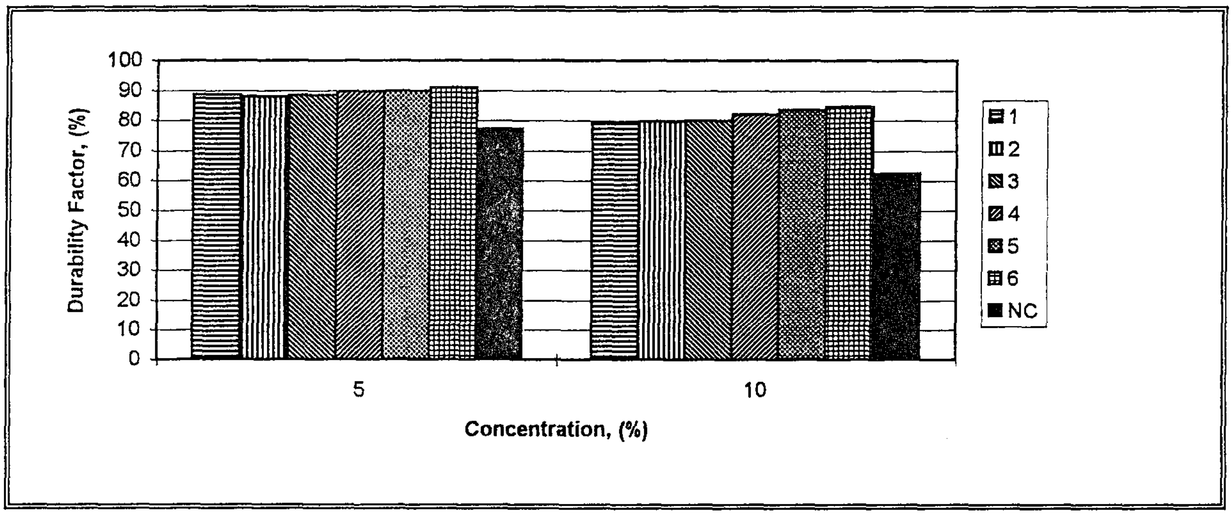

Figure 4.7. The comparison of Nitric Acid Durability with Concrete and CLSM Mixtures at Six Weeks

The durability factor of CLSM mixtures exposed to phosphoric acid attack had been obtained from 86.75% to 93.86% for 5% and 10% concentration. The lowest durability was recorded for lower filler/binder ratio at both concentrations. For concrete, phosphoric acid durability had been found between 91.88% and 88.28% at six weeks by YAZICI (1996). Test results showed that the durability factors of CLSM mixtures were similar to normal concrete. The comparisons of phosphoric acid durability with CLSM mixtures and concrete are shown in Figure 4.8.

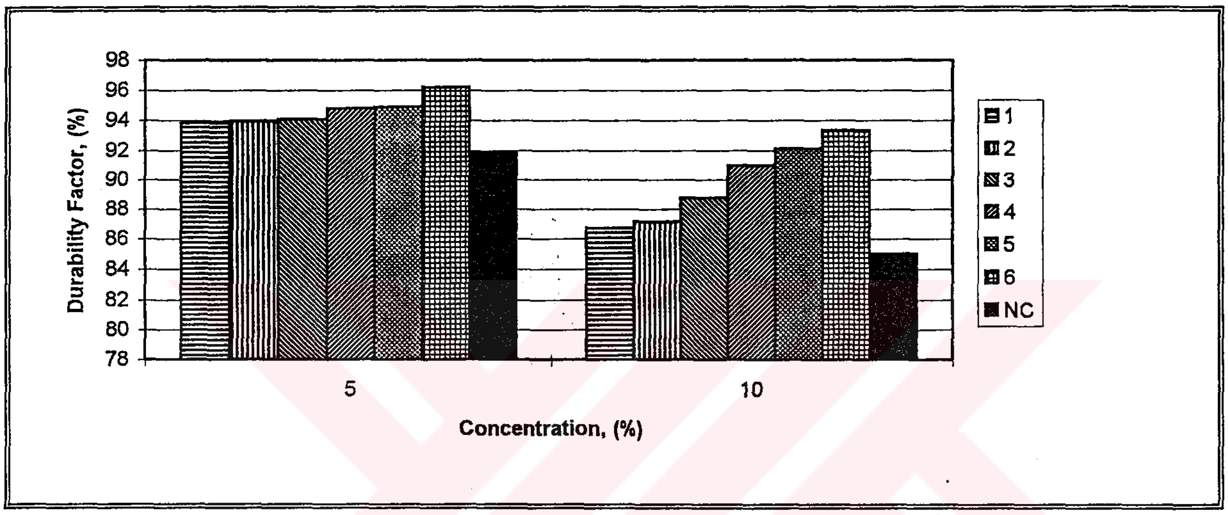

**Figure 4.8. The comparison of Phosphoric Acid Durability with Concrete and CLSM Mixtures at Six Weeks**

Formic acid is one of the most aggressive chemicals on CLSM mixtures. Test results had been recorded 47.05% and 69.05 at six weeks' periods for 5% and 10% concentrations. However, the durability factor of concrete had been obtained among 91.51% to 95.91% at six weeks by YAZICI. In the same conditions, the durability factor of concrete was higher than CLSM mixture's durability. The formic acid durability comparisons for CLSM mixtures and concrete are given in Figure 4.9.

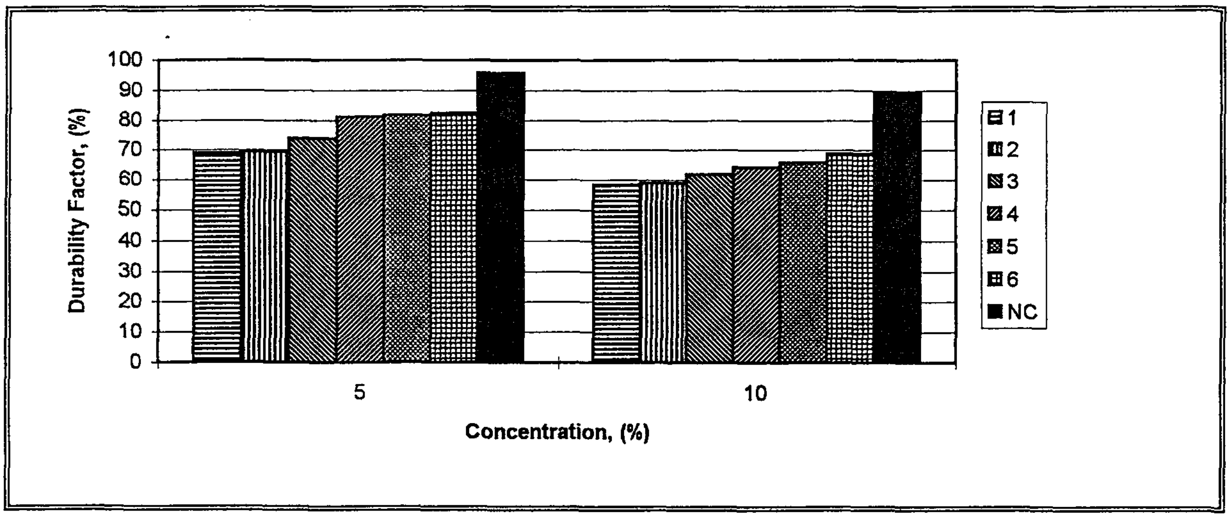

Figure 4.9. The comparison of Formic Acid Durability with Concrete and CLSM Mixtures at Six Weeks

Acetic acid durability of CLSM mixtures had been obtained from 58.45% to 80.25% for 10% and 5% concentrations. The effects of acetic acid on the CLSM mixtures were similar to formic acid especially at 10% concentrations. For concrete, acetic acid durability had been measured between 89.19%-92.51% for 10% and 5% concentration respectively by YAZICI. These results, acetic acid durability of concrete is more than CLSM mixtures at the same periods. The acetic acid durability comparison for concrete and CLSM mixtures are given in Figure 4.10.

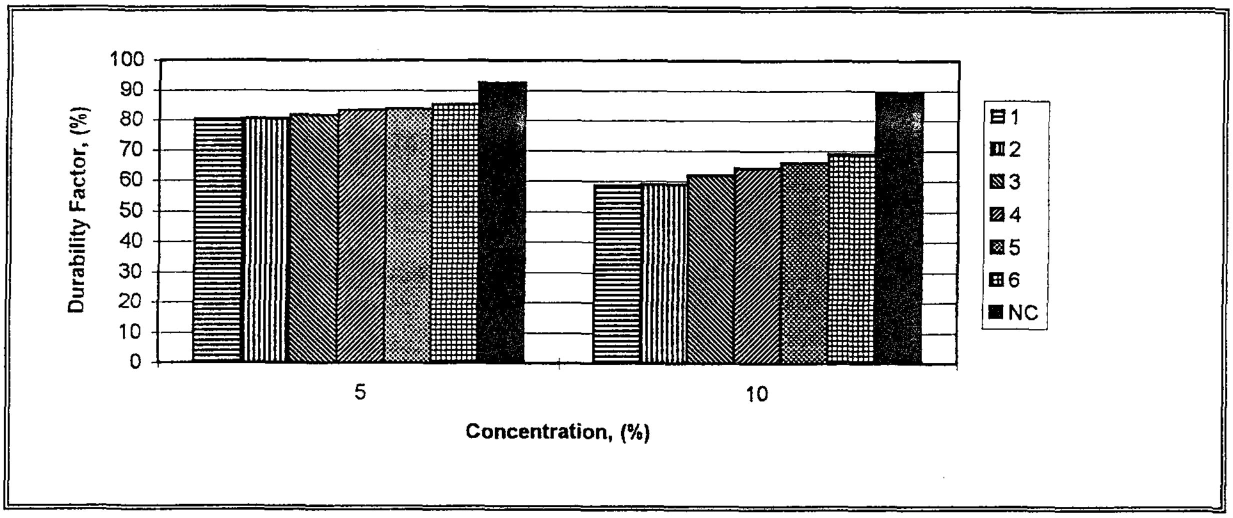

Figure 4.10. The comparison of Acetic Acid Durability with Concrete and CLSM Mixtures at Six Weeks

Experimental studies on the CLSM mixtures with various types of acids showed that the durability factor increases with higher filler/binder ratios. These situations explained that if the pecentage of binder increases the acid durability decreases. Because, fly ash and cement paste matrixes are solved by acid attacks. This means, all of the acids cause a deterioration of the binder paste at the low filler/binder ratios. However, the filler aggregates showed no damage from the acid attacks in the CLSM composition.

## 4.12. EP Toxicity

EP toxicity test results for selected CLSM mixtures had been given in Table 3.27. The test results showed that the concentrations of all heavy metals for selected CLSM mixtures were far below than the stated EPA limits. According to the test results the CLSM mixtures are not hazardous to groundwater.

These results indicates that ; CLSM mixtures are environmentally acceptable filling materials and ideal compositions for liners.

# CHAPTER FIVE
# CONCLUSIONS

The following conclusions can be stated considering the experimental results of this study :

CLSM mixtures with low cement content and high Class C fly ash and limestone filler content can be produced with excellent flowability and a compressive strength in the range of 0.85 to 1.15 MPa at 28-days. The cement content should be kept about 5% of fly ash by weight. Higher strengths can be achieved by increasing cement ratio or by decreasing the amount of mixing water. However, CLSM with higher mechanical properties may have less flowability and would be more difficult to remove by using regular excavation methods. Lower strength materials that have about 1.05 MPa of compression strength value at 28-days can be easily excavated. Due to this reason, fly ash, cement, and filler aggregate ratios should be chosen carefully to satisfy removability requirements. In order to improve flowability and to reduce strength potential, water may be another increasing the amount of solution.

CLSM mixtures are self levelling and flow into place without any compaction. They provide significantly better physical properties than those of conventional soil fill or backfill materials. They become economically competitive whenever a structural well-compacted fill is required. The ease of installation of CLSM mixture makes it attractive from the standpoint of reduced labor cost.

Different curing conditions such as mild and hot cured with different relative humidity provided more strength gain at 28-days strength. Since, strength gain rate was very low for the high volume fly ash especially at early ages.

The permeability test results indicate that the CLSM mixtures have low permeability than the most conventional soil materials in spite of the no compaction. In general, permeability is adversely related with durability. This acceptance has been valid for exposed to vacuum saturation durability conditions. However, it was invalid for chemical durability of CLSM mixtures.

Shear strength, cohesion and internal angle of friction values of CLSM mixtures exceed the most conventional soil materials at 7-days. These parameters are favourable for using of CLSM mixtures behind the retaining walls.

The thermal conductivity ranges between 0.55 - 0.60 watt per meter Kelvin (W/m.K) that is higher insulation value than concrete and conventional fill materials.

In general, there is no significant difference between the chemical durability of CLSM mixtures and concrete for the same concentration of various acids.

If these superior properties to take into consideration, the CLSM mixtures can be successfully used in the following applications:

- Excavation backfill
- Trench backfill
- Underpiling of foundations to reestablish suitable bearing
- Fill for abandoned underground tanks, tunnels, pipelines, and manholes
- Mine and underground void filling
- Retaining wall backfill

In addition to these advantages, CLSM mixtures are environmentally acceptable according to EPA standards.

# CHAPTER SIX

# SUGGESTIONS and RECOMMENDATIONS for FURTHER INVESTIGATION

This study includes the determination of producing of removable controlled low strength materials for filling purposes. In this manner, some physical and mechanical tests were realized such as compressive, flexural, tensile, shear strength, modulus of elasticity, permeability, capillarity, thermal conductivity, vacuum saturation durability, EP toxicity and chemical durability.

The following suggestions and recommendations for further investigations can be made on the topics listed below:

- Different curing and relative humidity conditions' effect on the strength for longer testing periods.

- Load carrying capacity under sustained static and dynamic loads.

- The effect of aggregate type such as sand and gravel on the properties of CLSM.

- Determining size and shape affect for different shapes and dimensions of specimens for low strength materials.

- Chemical durability comparisons of specimens exposed to moist and different curing-relative humidity conditions.

- Economical analyses of the mixtures in terms of the production and labor costs.

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TÜRKÇE ABSTRAKT (en fazla 250 sözcük) :

(TÜBİTAK / TÜRDOK'un Abstrakt Hazırlama Kılavuzunu kullanınız.)

Bu çalışmada; C sınıfı uçucu kül, kalker kökenli mıcır tozu ve bağlayıcı madde olarak çok düşük oranda çimento kullanılarak, sıkıştırma gerektirmeden yerleştirilebilecek, pompalanabilecek kıvamda, akışkan karışımlar elde edilmiştir. Dolgu işlerinde kullanılmak amacı ile geliştirilen karışımların basınç dayanımları, gerektiğinde kolayca kazılabilmesi düşüncesi ile kasıtlı olarak düşük tutulmuştur.

Bu amaçla yapılan çalışmada kullanılan uçucu kül Soma B termik santralından temin edilmiştir. Bağlayıcı madde olarak TÇ 32.5 çimentosu kullanılmış ve bütün karışımlarda uçucu kül ağırlığının %5' i olarak alınmıştır. Bu çimento oranı, yapılan ön deneyler sonucunda istenen düşük dayanım için gerekli en uygun oran olarak belirlenmiştir. Deneylerde kullanılan karışımlarda, uçucu kül ve çimento ağırlıkları toplamı bağlayıcılar olarak dikkate alınmıştır. Mıcır tozu ise bağlayıcılar ağırlığının katları olarak seçilmiştir. Karışım suyu miktarı, pompalanabilecek akışkanlığı sağlayacak şekilde belirlenmiş ve sarsma tablası ile yayılma miktarları ölçülmüştür.

Bu şekilde hazırlanan karışımların ; basınç, eğilme, çekme ve kayma dayanımları, elastisite modülü, permeabilite ve kapilarite katsayıları, hızlı donma-çözülme dayanıklılıkları, değişik sıcaklık ve bağıl nemde basınç dayanımları, ısı iletkenliği gibi özellikleri belirlenmiştir. Ayrıca, karışımların çeşitli kimyasal etkilere dayanıklılığı ve içerisinde bulunabilecek bazı zararlı kimyasal maddelerin yeraltı sularına etkisi gibi konular da incelenmiştir.

Bu deneyler sonucunda ; gerektiğinde sonradan kolayca kazılabilecek şekilde dayanımı kasten düşük tutulan malzemelerin, bilinen klasik zemin türü dolgulara kıyasla mekanik ve fiziksel özelliklerinin daha üstün olduğu belirlenmiştir. Ayrıca, bu malzemeler yüksek oranda uçucu kül içerdiğinden, tuz ve asit gibi bazı kimyasal etkilere karşı dayanıklılığının normal betona kıyasla daha iyi olduğu görülmüştür.

İNGİLİZCE ABSTRAKT (en fazla 250 sözcük) :

Controlled low strength material (CLSM) is a flowable fill that can be used as a backfill material in place of compacted soils. Flowable fill requires no tamping or compaction to achieve its strength and typically has a load carrying capacity much higher than compacted soils, but it can still be excavated.

In this study, a mixture of Soma B fly ash, crushed limestone powder (filler) and a low percentage of pozzolana cement has been tried in different compositions. The weight of cement (TÇ 32.5) was kept constant for all mixes as a 5% of fly ash weight. The amount of mixing water was chosen to provide optimum pumpability by determining the spreading ratio of CLSM mixtures using flow table.

The mechanical and physical properties of CLSM mixtures such as ; compressive strength, flexural and splitting tensile strength, direct shear, modulus of elasticity, coefficient of permeability, water absorption by capillarity, freezing and thawing by vacuum saturation, durability in different temperature and humidity condition, thermal conductivity, EP toxicity have been investigated by a series of laboratory tests. On the other hand, chemical durability of CLSM mixtures in aggressive environments such as salt, sulfates and various types of acids' solutions were also investigated.

The test results indicated that CLSM mixtures have superior mechanical and physical properties than the compacted soils. Besides, these materials are more durable in many situations than the normal concrete when subjected to the salt sulfates and acids' solutions due to the high content fly ash.