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PERFORMANCE ANALYSIS OF LIGHTWEIGHT MORTAR

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PERFORMANCE ANALYSIS OF LIGHTWEIGHT MORTAR

ABSTRACT

This report presents the results of a research program on the mechanical properties and structural characterization of various types of mortar using a fine lightweight aggregate (LWA uncoated) and fine lightweight composite (LWA). The first phase of this research was to develop a rational mix procedure for mortars containing the new LWA materials. The second phase was to establish a comprehensive program to determine the effect of LWA materials on the mechanical properties of the mortars. Mix design diagrams were established for four mortar series. The mix design diagrams allow the user to easily determine a mortar mixture proportion for given performance criteria. To understand the behavior of the different mortar mixtures containing the LWA materials, a microstructural analysis of each mix was conducted using scanning electron microscopy. During this phase of the research, secondary and backscattered electrons were used. Finally, a study of the advantages and drawbacks of the use of the fine lightweight materials in mortars is presented.

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1.0 Introduction

This report will present the results of a research program conducted on the mechanical properties and structural characterizations of various types of mortar using a fine lightweight material (LWA uncoated and composite). The initial task of this research was to establish a rational mix design procedure for mortars containing lightweight aggregate (LWA). After the procedure was established, mix proportions were selected and a comprehensive program was established to determine the effect of the LWA on the mechanical properties of the mortars. Four different mortar series with three water-to-cement ratios per series were designed, cast, and tested. Finally, a careful examination of the microstructure of the LWA mortar was conducted using secondary and backscattered scanning electron microscopy. The report is divided into the following topics:

(a) General introduction and research objectives (chapter 1).
(b) Mix design and description of the experiments (chapter 2).
(c) Details of the research program (chapter 3).
(d) Curves and graphs of the experimental results (chapter 4).
(e) Microscopy results (chapter 5)
(f) Conclusions and recommendations for future work (chapter 6)

2.0 Concrete Mix Design Methods

2.1 Terminology

Before presenting the main concepts about mix design methods, it is very important to define some of the most frequently used terminology.

- **Workability** is the property of the mortar, or concrete that determines its capacity to be placed, consolidated properly, and finished without harmful segregation. It is affected by the characteristics of the aggregates, cement content, entrained air, and the consistency of the mix. There is no standard method to measure workability.

- **Consistency** can be loosely define as the wetness of the concrete mix. It is quantitatively characterized by the measure of the slump (the higher the slump, the wetter the mixture). It is frequently used as a synonym for workability, however it must be pointed out that high slump values do not necessarily mean "high workability", since the mix may lack of cohesiveness (thus, segregation probably occurs). At the same time, low slump values may result in mixes difficult to place and consolidate without the use of the adequate equipment . There are different methods to measure consistency. The method used in this work follows the ASTM C 143 Standard.

- **Cohesiveness** is a measure of compactability and finishability (without segregation and bleeding). This is generally evaluated visually or by checking the trowelability of the mix.

- **Strength.** The minimum required compressive strength of a mortar, or concrete, is provided by the structural performance specifications. Thus, this is the minimum required strength without considering the possible variations due to manufacturing, transporting, and placing the concrete. Due to variability of the compressive strength, the mixture must be designed to achieve a mean or average strength that is higher than the specified strength. The determination of the average strength, from the specified minimum strength, is done by statistical analysis. The average strength values are used in this report.

- **Durability** can be defined as the ability of the mortar, or concrete to resist weathering action, chemical attack, or any other process of deterioration. The ability of the mixture to resist deterioration processes is usually evaluated by the analysis of some of its performance characteristics such as chloride permeability and/or carbonation depth. During the mix design process, the designer of the mix tries to comply with the requirements, by setting limits of the main variables influencing the performance characteristics. This can be accomplished by reducing water cement ratios, using additives to incorporate air, adding special mineral admixtures, and choosing the correct cement type.

2.2 Mix Design

To obtain a mortar or concrete that performs according to required criteria, it is not only necessary to select the different materials that will be included in the mix, but also their proper proportions. The most common performance criteria used during the mix design process are the workability of the fresh mortar and the compressive strength at a specific age (usually 28 days). There are several different methods that can be used in designing a mortar or concrete mixture . The following section presents the mix design method used for this research.

2.2.1 Adopted Mix Design Method

The selection of the mix design method used in this research was based on the following considerations:

- The method should provide means for adjusting mortar mixtures based on workability criteria

- The method should be able to show a comparison of the behavior for different mortar mixtures.

The standard practice recommended by ACI committee 211 does not easily allow one to design a set of mixes with the same workability and consistency with different properties. Unlike the ACI method, the adopted method considers the following fundamental behavior laws as the foundation for the mix design method:

- **Abrams' Law:** It correlates the compressive strength of the mortar or concrete (made with the same materials), with the water-to-cement ratios for different ages. It is an exponential behavior law formulated in 1918 by Duff Abrams(1).

- **Lyses's Law:** It correlates the total amount of water per unit volume of mortar (or concrete) with the consistency of the mix. It was formulated in 1947 by Inge Lyse(2).

- **Molinari's Law:** It correlates the cement content with the aggregate-to-cement ratio (by weight). It is a hyperbolic function presented by Tango(3) in 1978.

- **Cement Content Law:** It correlates the cement content per unit volume of mortar (or concrete) to the compressive strength for a given consistency.

The method used for mix proportioning is the absolute volume method. However, the relative proportions of the different materials are expressed by their absolute weight relative to the weight of cement. This makes the designing and batching process easier for the user. Consider the following example for the following mortar mix design:

Material	Relative Proportion by Weight
Cement	1
Top Sand (SSD)	4.851
LWA Composite	0.364
Water	0.607
Superplasticizer	0.0025
Total Mass	**6.2175**

The information provided by a mix design expressed in this format is that for each pound of cement, 4.851 lbs of sand, 0.364 lbs of LWA composite, 0.607 lbs of water, and 0.0025 lbs of superplasticizer should be added. The total absolute volume can be calculated by using the following formula:

$$\mathbf{U} = \frac{1}{\gamma_{cement}} + \frac{4.851}{\gamma_{sand}} + \frac{0.364}{\gamma_{Microlite}} + \frac{0.607}{\gamma_{water}} + \frac{0.0025}{\gamma_{superplasticizer}}$$

Where:

$\mathbf{U}$ = Compacted Volume of Mortar or Concrete
γ_{cement} = Density of the Cement
γ_{sand} = Density of the Top sand
γ_{LWA} = Density of the LWA Composite
γ_{water} = Density of the water
$\gamma_{superplasticizer}$ = Density of the superplasticizer

Thus, by knowing the total mass and the compacted volume of mortar or concrete, the unit weight of the mixture, and the weight proportions for the desired volume can be easily calculated. In the following paragraphs a description of the different behavior laws will be presented.

2.2.1.1 Abrams' Law

This behavior law relates the compressive strength of the mortar or concrete, as a function of its water-to-cement ratio at a specific age (Figure 2.2.1.1). It was demonstrated by Abrams that when having discrete data points the best function that represents the phenomenon has the form:

$$fc=\frac{K_1}{K_2^{w/c}}$$

Where:

fc = Compressive strength of the mortar or concrete,
K_1= Constant
K_2= Constant
w/c= water-cement ratio

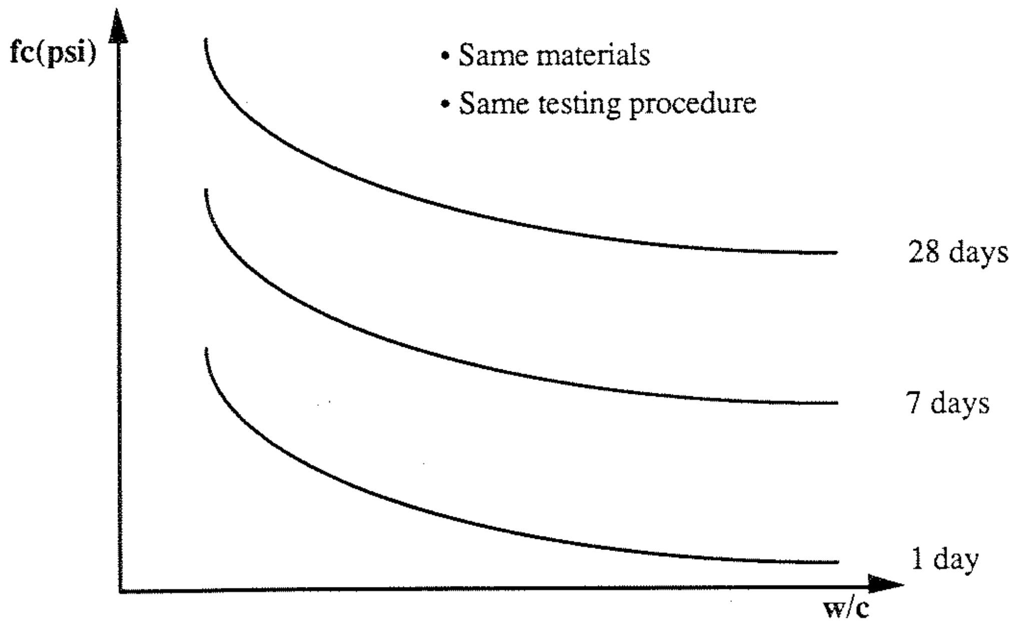


Figure 2.2.1.1 Abrams' Law.

Therefore, by calculating the values of K_1 and K_2, the behavior of the mortar can be established.

2.2.1.2- Lyse's Law

This law states that the ratio between the volume of water to the volume of mortar is constant for a given consistency. Assuming that the amount of water per unit volume remains constant for a given range of consistency (0-1" for example), different mixtures can be achieved by changing the cement content. Thus, the best curve fit to represent this law behavior (Figure 2.2.1.2.) is :

$$m = K_3 * \left[\frac{w}{c}\right] + K_4$$

Where:

m	Aggregates-Cement Ratio (by weight),
K_3	Constant which depends on the materials
K_4	Constant which depends on the materials used
w/c	Water-to-cement ratio (by weight).

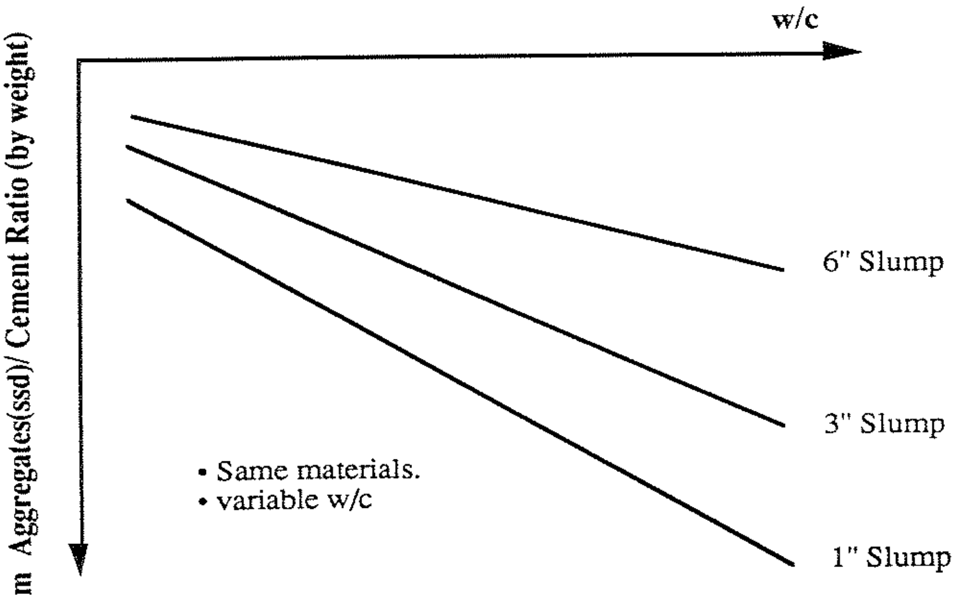


Figure 2.2.1.2 Lyse's Law

2.2.1.3 Molinari's Law

This law states that the cement content in a mix is inversely proportional to the aggregate-cement ratio (by weight) (Figure 2.2.1.3.). This behavior law can be represented by the hyperbolic function:

$$C = \frac{1000}{\left(K_5 * m + K_6\right)}$$

Where:

C Cement Content (lbs/yd^3),

K_5 Constant

K_6 Constant

m Aggregates to Cement Ratio (by weight).

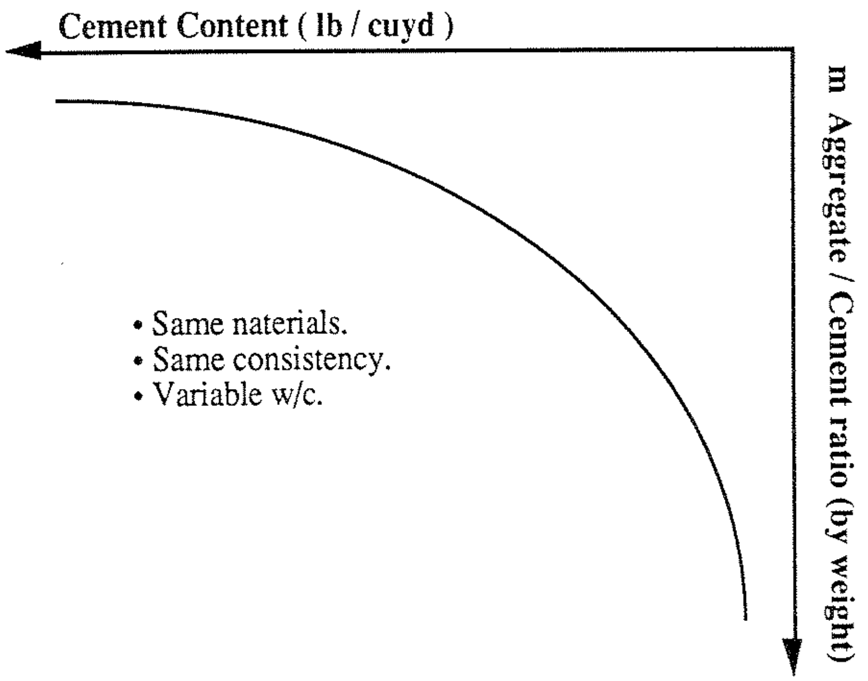


Figure 2.2.1.3 Molinari's Law

2.2.1.4 Cement Content's Law

This law correlates the cement content in the mixture with the compressive strength for a given age, consistency, and set of materials (Figure 2.2.1.4). The equation that best represents this law has the form:

$$C = \frac{1}{(K_7 * \log f_c + K_8)}$$

Where:

C Cement content in lb/yd^3 (as measured)
K_7 Constant
K_8 Constant
f_c Compressive strength at the given age.

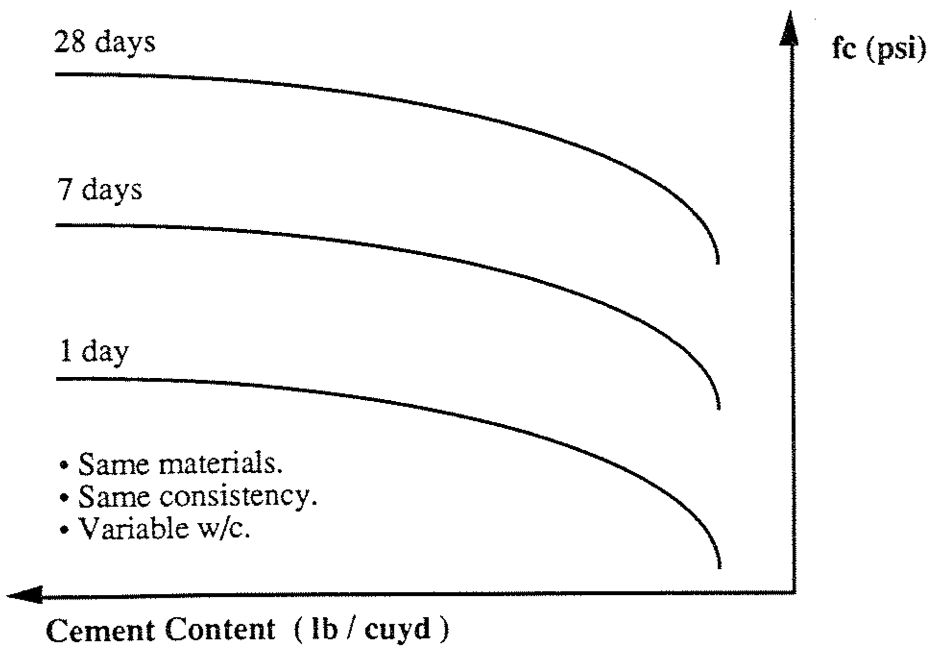


Figure 2.2.1.4 Cement Content Law.

Therefore, when this relationship is established based on a discrete set of data points from trial mixes, a quick estimation of the cement content can be obtained. It is important to point out that when working with mixes having the same consistency (slump), the increase in compressive strength corresponds to an increase in cement content. However, since the amount of water remains constant, it is the reduction in the water cementitious ratio that causes the increase in compressive strength, not the increase in cement content.

2.2.2 Mix Design Diagram

By combining the four behavior laws in a single diagram, a mix design diagram(4) can be developed (Figure 2.2.2.). As it can be seen from Figure 2.2.2, this type of diagram is a powerful mix design tool. For example, assume that the required mean compressive strength of the mortar or concrete at a specific age and the slump requirement are given as design criteria. With this, by entering the diagram in the first quadrant with the required f'c horizontally until it intersects the required age curve, the necessary water-to-cement ratio can be established. Then, by moving down vertically from this intersection point to the intersection of the required slump curve, the amount of aggregate can be determined. Lastly, by moving horizontally from this point until intersecting the cement content curve, the cement content per unit volume can be established. Multiplying the cement content by ***m***, the total amount of aggregate can be determined. Similarly, to obtain the water requirement, the cement content should be multiplied by the water-to-cement ratio. The usefulness of this type of design diagram can be increased by correlating other performance criteria with water-to-cement ratios. With this procedure, the compliance to the mix design performance criteria can easily and readily be assessed. Figure 2.2.2 on the following page gives a graphical procedure to perform the mix design process.

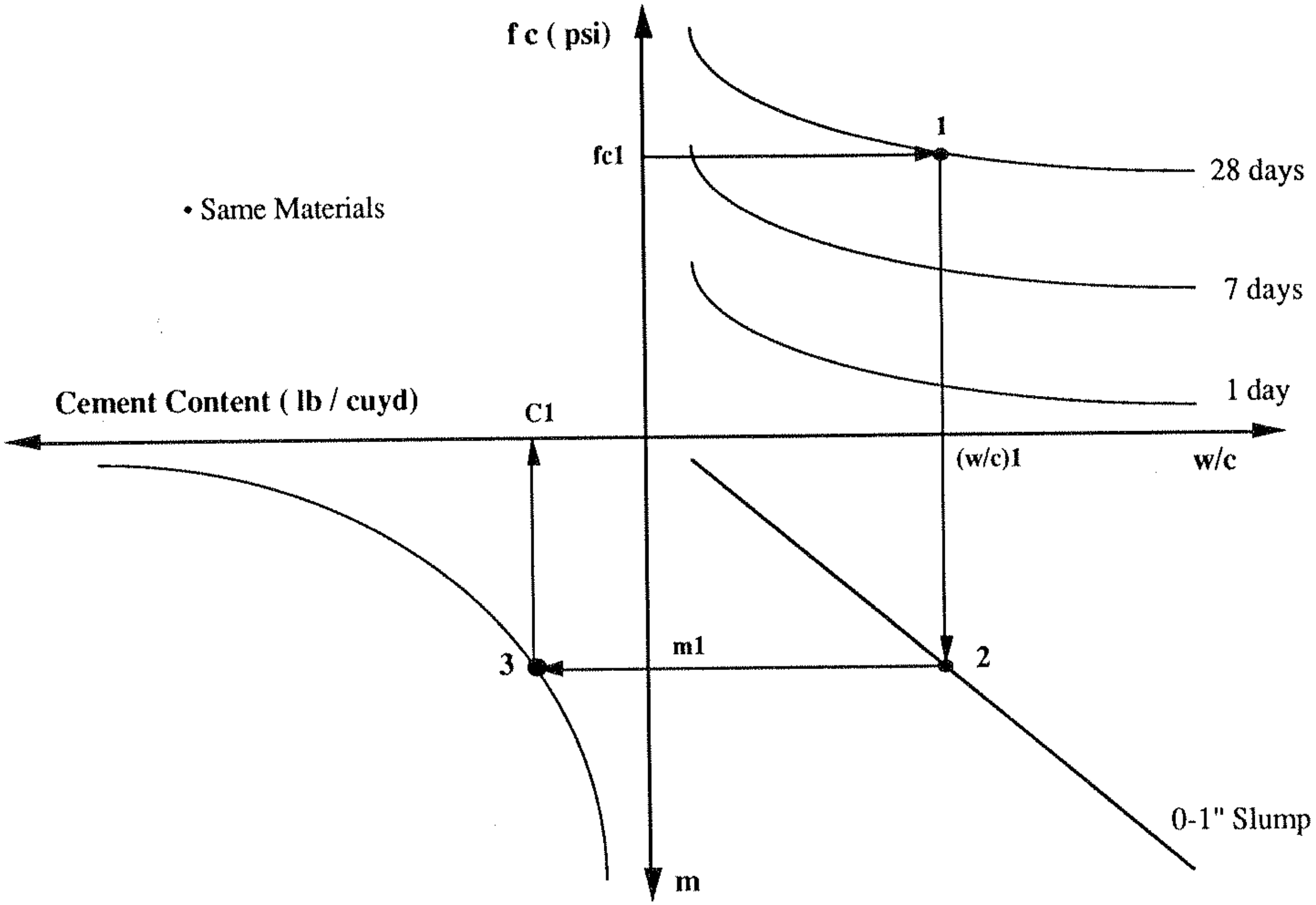


Figure 2.2.2 Mix Design Diagram

3.0 Experimental Study

This chapter will describe the research on mortars made with fine lightweight materials (LWA). It presents mix design parameters, fresh mortar characteristics, and hardened mortar properties.

3.1 Mortar Mix Design

Four mix design series were prepared to achieve the overall research objectives. To compare the performance of the different mix series, the following parameters are defined below:

- **Water Cement ratios:** To cover the standard range that is commonly used in practice, three different water cement ratio mortars were selected: 0.4, 0.55, and 0.6.
- **Aggregate Proportion:** Three aggregate-to-cement ratios of 3-3.5, 4.5-5.0, and 5.0-6.0 were used in the mix designs. It should be noted that the fine LWA was considered as part of the total amount of aggregate present in the mix and that all aggregates except the LWA were saturated surface dry (SSD).
- **Superplasticizer:** The superplasticizer added to the mortar mixes was 0.25% of the cement weight for all mix designs.
- **Amount of Fine LWA:** The total amount of LWA introduced in the mortar mixes was 16% of the cement content by weight except for mix series #4. In the case of mix series #4, where the LWA composite was used instead of the uncoated LWA, the amount of composite added was 36.4% of the cement content.
- **Workability:** All mixes were designed to have the same consistency, which was measured by its slump. The slump for all mixes was between zero and one inch.

- **Cement Content:** Three different cement contents were used for each mix series to represent the common use of structural mortars. The range of cement contents was between 450 lbs./yd^3 and 1000 lbs./yd^3.
- **Mix Series:** Four mix series with three different water-to-cement ratios were mixed and tested as follows:

  Series #1: control mix (sand, cement, and water)
  Series #2: with uncoated LWA
  Series #3: with uncoated LWA and Diatomite
  Series #4 with LWA Composite

3.2 Materials

All materials except the superplasticizer and sand were supplied and delivered to the Concrete Materials laboratory by Specrete-IP Inc. It should be noted that two different types of lightweight materials are being tested in this research; an uncoated LWA (aggregate) with no admixtures and a coated LWA combined with several admixtures (composite). The coated LWA with admixtures will be referred to as the LWA composite. The sand used had a specific gravity (SG) of 2.65, a fineness modulus (FM) of 3.09, and a gradation as shown in Figure 3.2.1 (ASTM C 136). The plasticizer used in the project was Sikament 86™ produced by Sika® Corporation. The admixture is characterized as an extended slump-life superplasticizing, water-reducing, non-air-entraining admixture and meets ASTM C494 Type A and F standards. The Sika® admixture has a SG of 1.24, contains 40% solids, and has a pH greater than 8.

The LWA materials are made by Specrete Inc. and registered by Microlite® denomination.

3.3 Mix Proportions and Fresh Mortar Characteristics

Tables 3.3.1 A through 3.3.4 A contain all the material proportions for the mortar mixtures tested in this phase of research. It should be noted that the reference to LWA in the tables refers to the uncoated LWA. The coated LWA and mineral admixture composition proportions and properties are presented in Tables 3.3.4 a and 3.3.4 b. Tables 3.3.1 B through 3.3.4 B contain fresh mortar properties in both U.S. and S.I. units. The slump was determined following ASTM C 143-78 and the unit weight was obtained following ASTM C 138-81. The mix designs and fresh mortar properties are as follows:

Table 3.3.1 a *Mix #1 Material Proportions (by weight)*

Material	Mix 1A	Mix 1B	Mix 1C
Cement	1.00	1.00	1.00
LWA	NONE	NONE	NONE
Top Sand (SSD)	3.191	4.756	5.250
Water	0.429	0.593	0.673
Admixture	0.0025	0.0025	0.0025

Table 3.3.1 b *Mix #1 Fresh Mortar Properties*

	MIX	Unit Weight	Consistency	Cement Content
U.S.	1A	142.9 lb /cu ft	0.5 in	834 lb /cu yd
Units	1B	140.0 lb /cu ft	0.5 in	594 lb /cu yd
	1C	139.5 lb /cu ft	0.75 in	543 lb /cu yd
S.I.	1A	2287 kg/cu m	12 mm	495 kg/cu m
Units	1B	2242 kg/cu m	12 mm	352 kg/cu m
	1C	2232 kg/cu m	19 mm	322 kg/cu m

Table 3.3.2 a *Mix #2 Material Proportions (by weight)*

Material	Mix 2A	Mix 2B	Mix 2C
Cement	1.00	1.00	1.00
LWA	0.16	0.16	0.16
Top Sand (SSD)	1.524	2.593	2.963
Water	0.463	0.570	0.638
Admixture	0.0025	0.0025	0.0025

Table 3.3.2 b *Mix #2 Fresh Mortar Properties*

	MIX	Unit Weight	Consistency	Cement Content
U.S.	2A	114.1 lb /cu ft	1.0 in	976 lb /cu yd
Units	2B	119.9 lb /cu ft	0.5 in	748 lb /cu yd
	2C	124.2 lb /cu ft	1.0 in	703 lb /cu yd
S.I.	2A	1825 kg/cu m	25 mm	579 kg/cu m
Units	2B	1919 kg/cu m	12 mm	444 kg/cu m
	2C	1988 kg/cu m	25 mm	417 kg/cu m

Table 3.3.3 a *Mix #3 Material Proportions (by weight)*

Material	Mix 3A	Mix 3B	Mix 3C
Cement	1.00	1.00	1.00
LWA Aggregate	0.16	0.16	0.16
Diatomite	0.027	0.027	0.027
Top Sand (SSD)	1.633	2.378	2.99
Water	0.461	0.556	0.646
Admixture	0.0025	0.0025	0.0025

Table 3.3.3 b *Mix #3 Fresh Mortar Properties*

	MIX	Unit Weight	Consistency	Cement Content
U.S.	3A	113.4 lb /cu ft	0.5 in	977 lb /cu yd
Units	3B	117.4 lb /cu ft	0.5 in	786 lb /cu yd
	3C	120.0 lb /cu ft	1.0 in	692 lb /cu yd
S.I.	3A	1814 kg/cu m	12 mm	579 kg/cu m
Units	3B	1879 kg/cu m	12 mm	466 kg/cu m
	3C	1919 kg/cu m	25 mm	410 kg/cu m

Table 3.3.4 a *Mix #4 Material Proportions (by weight)*

Material	Mix 4A	Mix 4B	Mix 4C
Cement	1.00	1.00	1.00
LWA Composite	0.364	0.364	0.364
Top Sand (SSD)	3.468	4.807	5.748
Water	0.487	0.651	0.752
Admixture	0.0025	0.0025	0.0025

Table 3.3.4 b *Mix #4 Fresh Mortar Properties*

	MIX	Unit Weight	Consistency	Cement Content
U.S. Units	4A	132.3 lb /cu ft	0.75 in	671 lb /cu yd
	4B	133.5 lb /cu ft	0.5 in	530 lb /cu yd
	4C	134.7 lb /cu ft	0.5 in	462 lb /cu yd
S.I. Units	4A	2117 kg/cu m	19 mm	398 kg/cu m
	4B	2148 kg/cu m	12 mm	315 kg/cu m
	4C	2155 kg/cu m	12 mm	274 kg/cu m

3.4 Properties of Hardened Mortar

3.4.1 Compressive, Flexural, and Splitting Tensile Strength

Compressive Strength of the 4" x 8" (diameter x height) mortar cylinders were determined following ASTM C 39. Splitting Tensile Strengths were determined following ASTM Standard C 496. These specimens also measured 4" in diameter and 8" in height. All specimens were kept moist until time of testing. Determination of flexural strength was according to ASTM C 78 (Third Point Loading Method). Concrete specimens were cast in 2"x2"x36" (*h x w x l*) molds. After curing and before testing, the specimens were cut to eight inch test lengths as required by the specifications.

3.4.2 Modulus of Elasticity, Poisson's Ratio, and Stress-Strain Curves

Modulus of Elasticity and Poisson's Ratio was determined according to ASTM C 469. The effective length of the longitudinal and radial linear variable differential transformer (LVDT) was 4" and 2" respectively. Stress-Strain curves were produced using a standard compression machine. The specimens were fitted in a compressometer with 4" longitudinal effective length. LVDT's were utilized to measure the longitudinal strain. The specimens were loaded at a rate which produced a constant strain rate of 7.2 minches per second throughout the test. Data was collected with an IBM AT computer and the UC Data Acquisition System.

3.4.3 Carbonation Depth

4" x 8" cylindrical specimens were cast and placed in the laboratory at room conditions. Carbonation testing was performed at 7, 28, and 91 days. At the specified times, specimens were split longitudinally using the apparatus for splitting tensile testing. After the specimens were split, a chemical solution was sprayed over the fractured surface. One fractured surface was treated with a phenolphthalein solution and the other with a thymolphthalein solution. The phenolphthalein solution has a pH of 9.6 at 25°C and consisted of 1 part phenolphthalein, 49 parts rubbing alcohol, and 50 parts water by mass. The thymolphthalein solution has a pH of 10.4 and consisted of 1 part thymolphthalein and 99 parts alcohol. Because the pH of normal concrete is approximately 12.6, when the solutions are placed on the fractured surface, the solution will change color if the pH of the concrete is more basic than the solution. Areas around the perimeter of the fractured surface are immediately observed after applying the solution. If a pinkish-bluish coloration is not evident around the perimeter, then the non-colored depth is the depth of carbonation. This depth is then measured and recorded with the type of solution used. Because the thymolphthalein solution has a higher pH than the Phenolphthalein solution, the thymolphthalein solution can detect smaller decreases in the pH than the Phenolphthalein solution.

3.4.4 Water Absorption

Water absorption of the mortar specimens was determined following ASTM C 642.

3.4.5 Chloride Permeability

Chloride permeability of the mortar specimens was determined using a modified AASHTO T 277 standard. Instead of the 3.75" diameter specimens required by the standard, 4" diameter samples were tested in the laboratory . It should be noted that the AASHTO standard states that the testing procedure is for aged, in place cored samples. Because of this, the samples are supposed to be prepared before permeability tests are performed. Once the samples tested for this project were cured at 100% relative humidity, it was not necessary to soak the samples in de-aerated water in a desiccator for 18 hours. All other testing procedures were followed. It should also be noted that because the specimens were cast instead of cored, the diameter of the specimen is larger than that recommended by the test standard. Correlation between the different specimen sizes has not been established but testing with 4" diameter specimens is common.

The properties of the hardened mortar mixtures are presented in Tables 3.4.1 through 3.4.4 on the following pages. Stress-Strain diagrams are presented in figures 3.1 through 3.12 for the twelve different mixes and directly follow table 3.4. The microstructure research and analysis are presented in Chapter 5.

Table 3.4.1 *Properties of Hardened Mortars, Mix Series #1*

Property	Age (days)	Units	Mix 1A	Mix 1B	Mix 1C
Compressive Strength	1	psi	3511	1679	1400
	3	psi	5216	3219	2439
	7	psi	6391	3723	3190
	28	psi	7095	4448	3830
	91	psi	7619	4720	4017
Splitting Tensile Strength	1	psi	405	204	194
	3	psi	432	307	319
	7	psi	600	439	370
	28	psi	644	444	415
	91	psi	660	495	435
Flexural Strength	28	psi	1089	931	715
Elastic Modulus	28	ksi	4320	3220	3090
Poisson's Ratio	28	***	0.19	0.2	0.18
Carbonation	28	mm	0	0	2
	91	mm	2	2	3
Chloride Permeability	28	Coul.	9406	14594	19993
	91	Coul.	8729	13900	16715

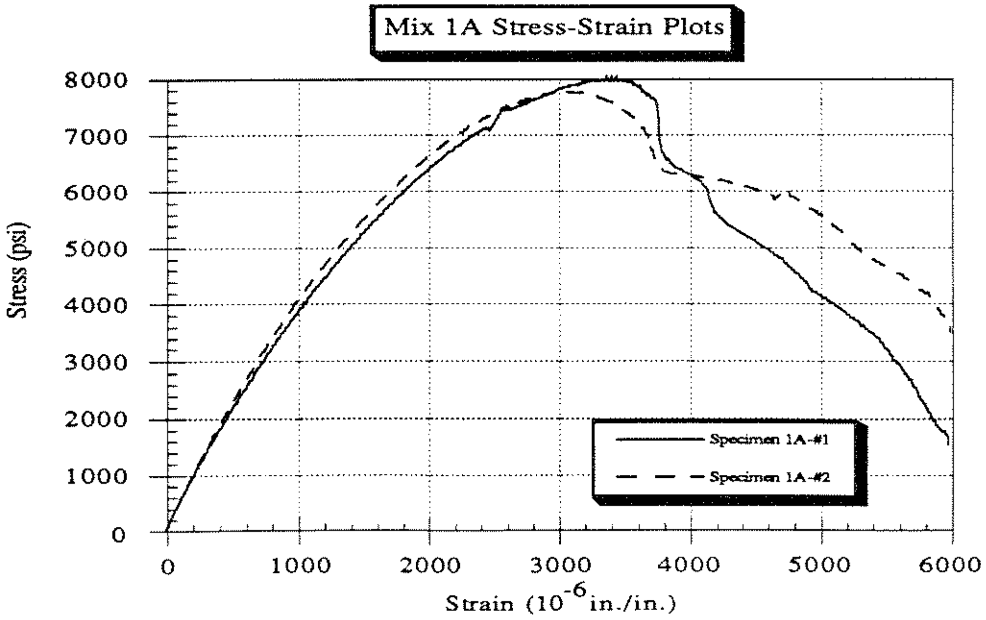


Figure 3.1 *Mix Series #1A Stress Strain Plots*

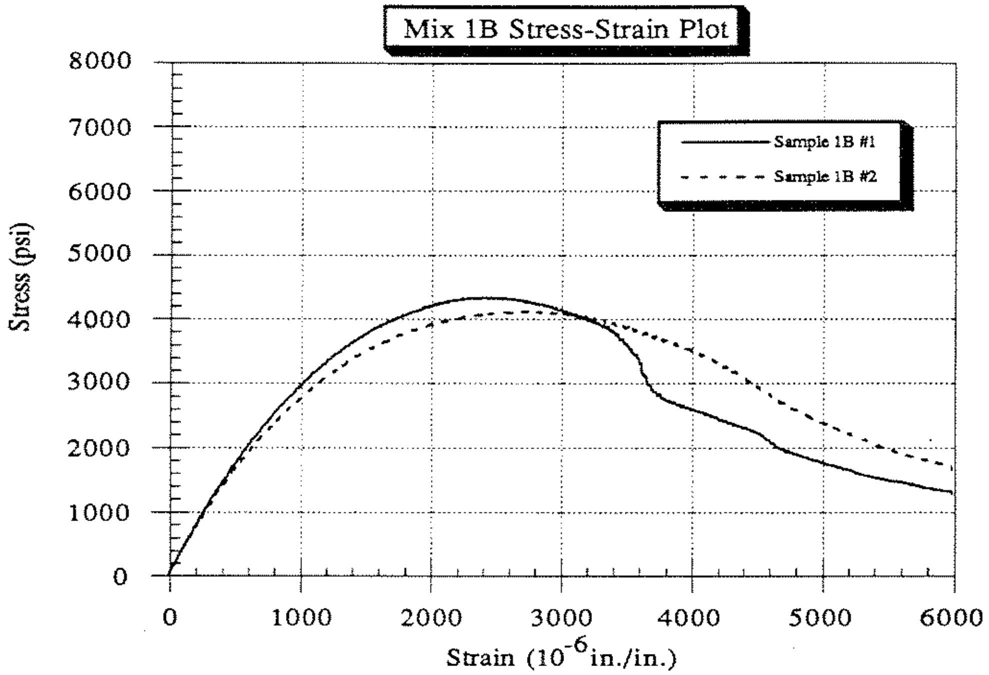


Figure 3.2 *Mix Series #1B Stress Strain Plots*

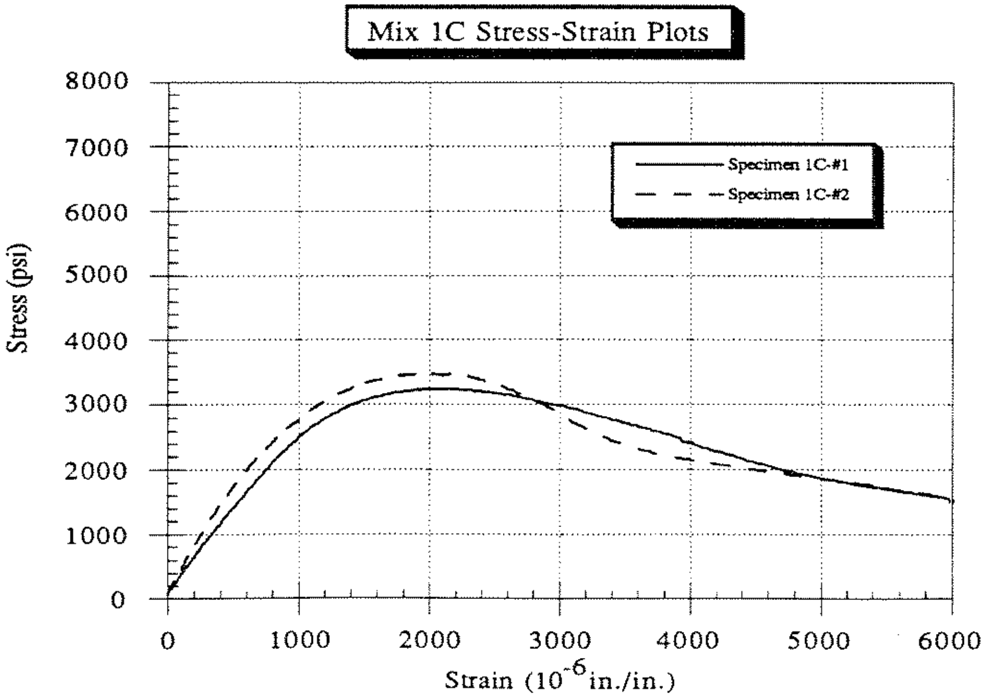


Figure 3.3 *Mix Series #1C Stress Strain Plots*

Table 3.4.2 *Properties of Hardened Mortars, Mix Series #2*

Property	Age (days)	Units	Mix 2A	Mix 2B	Mix 2C
	1	psi	3121	2061	1504
Compressive	3	psi	3805	3325	2644
Strength	7	psi	4169	4121	2975
	28	psi	4678	4690	3497
	91	psi	5202	5008	4074
	1	psi	340	257	211
Splitting	3	psi	466	364	312
Tensile	7	psi	488	421	377
Strength	28	psi	550	444	413
	91	psi	558	526	455
Flexural Strength	28	psi	766	745	653
Elastic Modulus	28	ksi	2280	2700	2200
Poisson's Ratio	28	***	0.21	0.21	0.21
Carbonation	28	mm	0	0	0
	91	mm	0	2	2
Chloride	28	Coul.	5459	11179	
Permeability	91	Coul.	2952	4301	7510

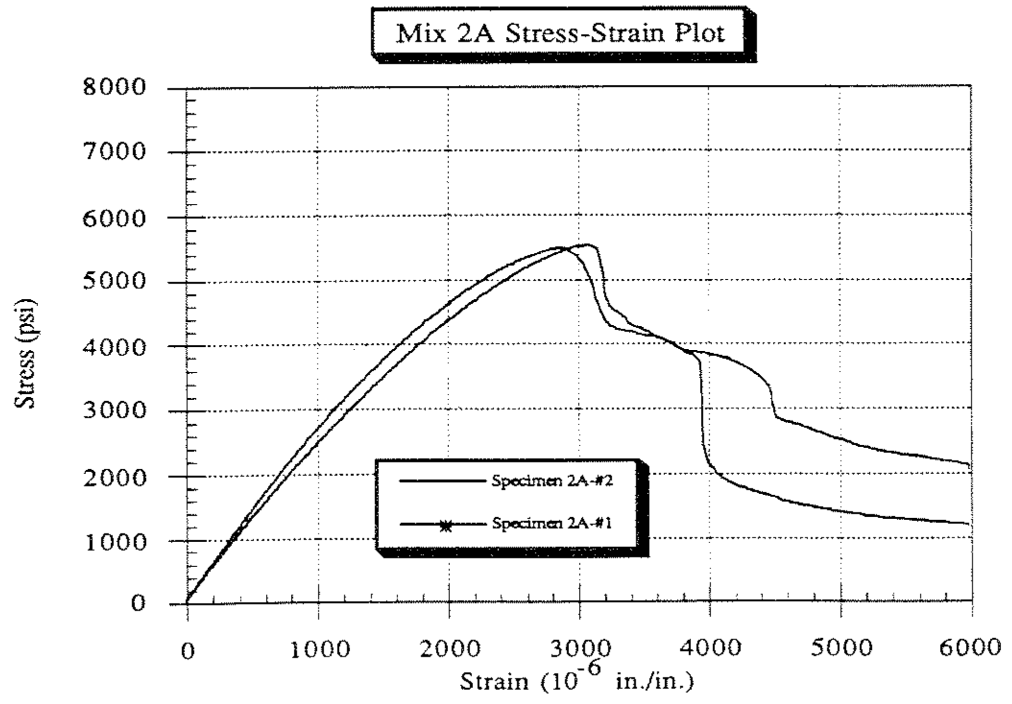


Figure 3.4 *Mix Series #2A Stress Strain Plots*

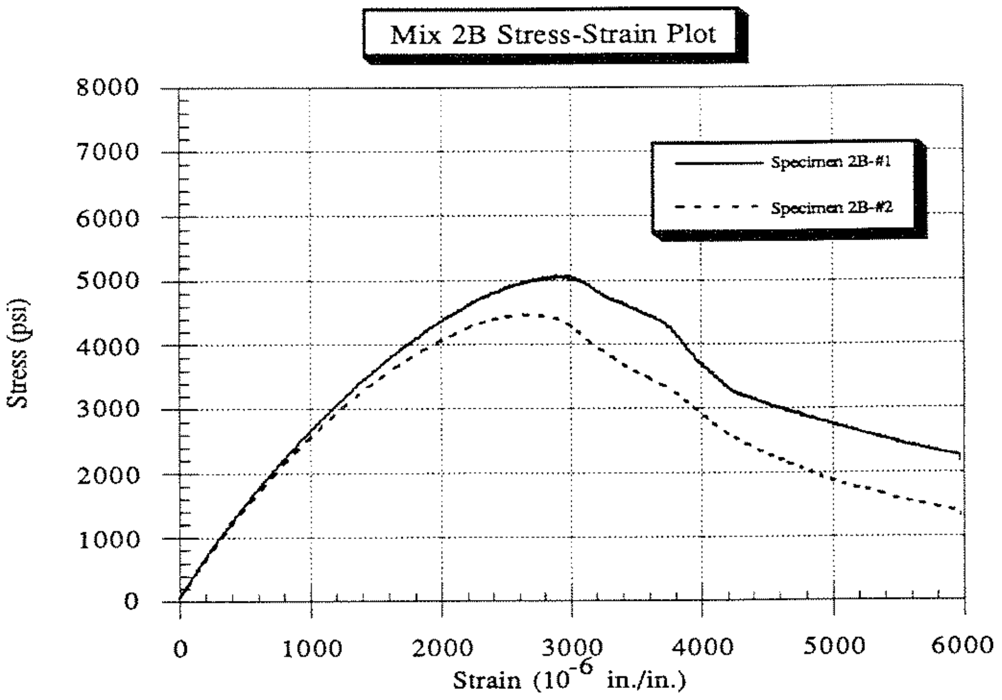


Figure 3.5 *Mix Series #2B Stress Strain Plots*

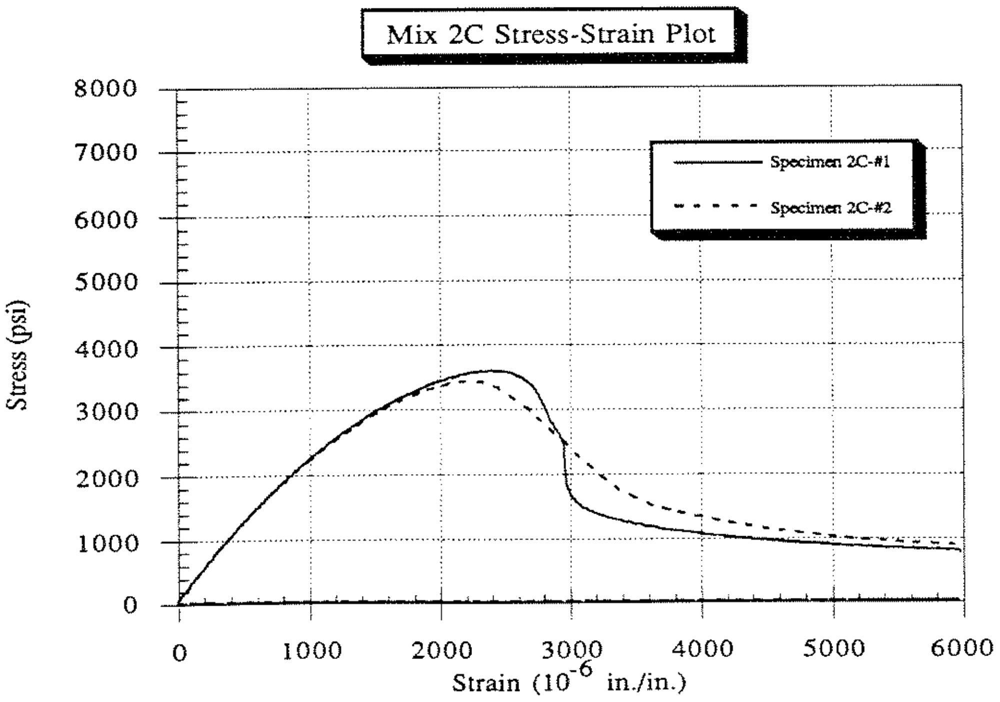


Figure 3.6 *Mix Series #2C Stress Strain Plots*

Table 3.4.3 *Properties of Hardened Mortars, Mix Series #3*

Property	Age (days)	Units	Mix 3A	Mix 3B	Mix 3C
Compressive Strength	1	psi	3384	1962	1641
	3	psi	3933	3296	2488
	7	psi	4532	4163	3042
	28	psi	5155	4988	3715
	91	psi	5698	5389	4083
Splitting Tensile Strength	1	psi	391	265	224
	3	psi	504	369	336
	7	psi	485	431	353
	28	psi	489	475	405
	91	psi	526	502	478
Flexural Strength	28	psi	786	714	630
Elastic Modulus	28	ksi	2410	2570	2310
Poisson's Ratio	28	***	0.22	0.22	0.22
Carbonation	28	mm	0	0	0
	91	mm	1	2	3
Chloride Permeability	28	Coul.	5070	7764	10860
	91	Coul.	2283	2952	6002

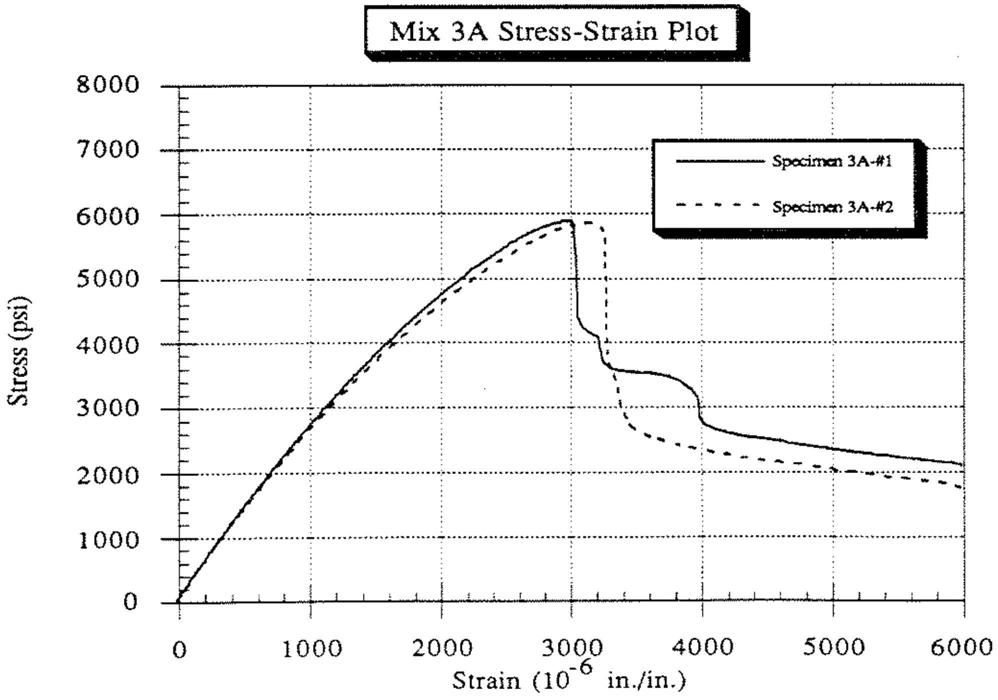


Figure 3.7 *Mix Series #3A Stress Strain Plots*

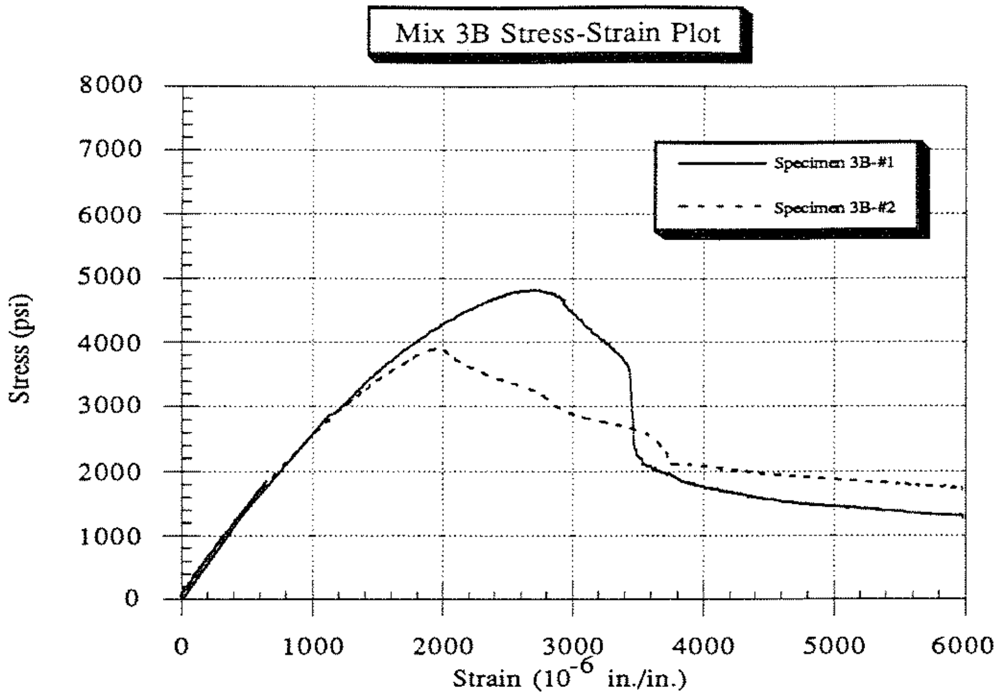


Figure 3.8 *Mix Series #3B Stress Strain Plots*

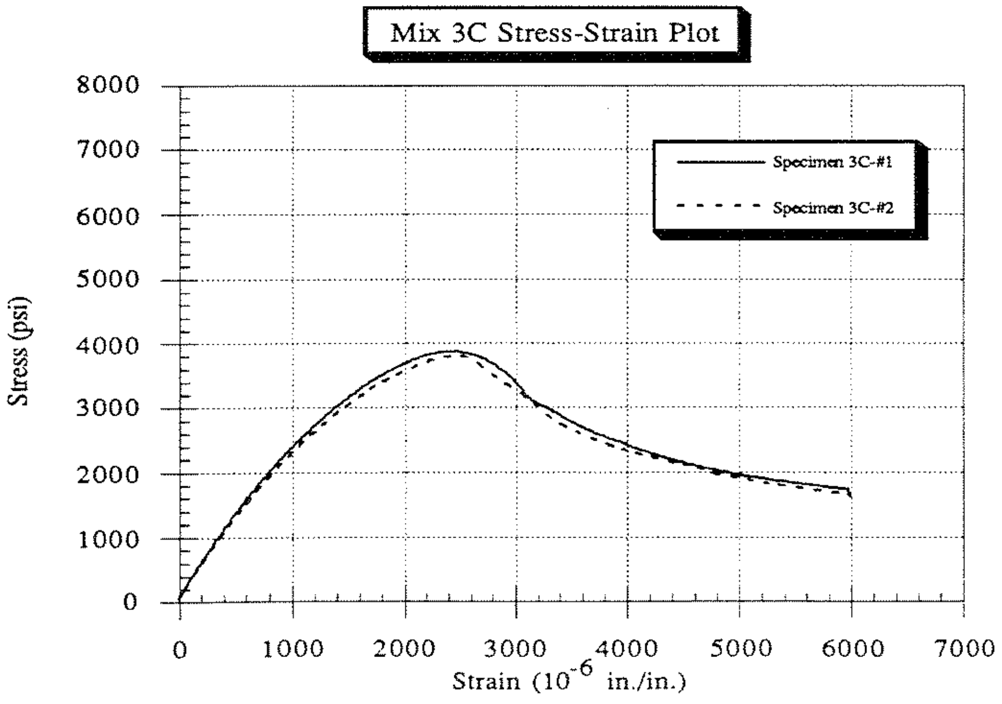


Figure 3.9 *Mix Series #3C Stress Strain Plots*

Table 3.4.4 *Properties of Hardened Mortars, Mix Series #4*

Property	Age (days)	Units	Mix 4A	Mix 4B	Mix 4C
	1	psi	2869	2034	1360
Compressive	3	psi	4256	2978	2347
Strength	7	psi	5396	4160	3243
	28	psi	7148	6040	4967
	91	psi	7518	6320	5166
	1	psi	330	266	179
Splitting	3	psi	438	367	290
Tensile	7	psi	518	487	373
Strength	28	psi	607	571	507
	91	psi	648	626	590
Flexural Strength	28	psi	1038	1021	943
Elastic Modulus	28	ksi	3570	3470	3090
Poisson's Ratio	28	***	0.21	0.21	0.19
Carbonation	28	mm	0	0	0
	91	mm	0	0	2
Chloride	28	Coul.	1267	2663	3127
Permeability	91	Coul.	656	1225	1635

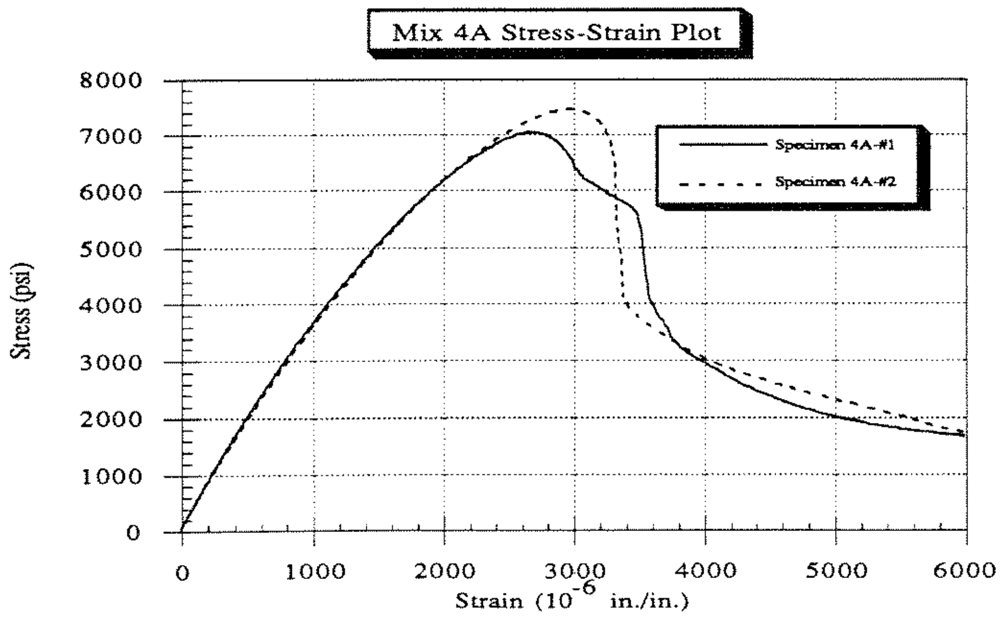


Figure 3.10 *Mix Series #4A Stress Strain Plots*

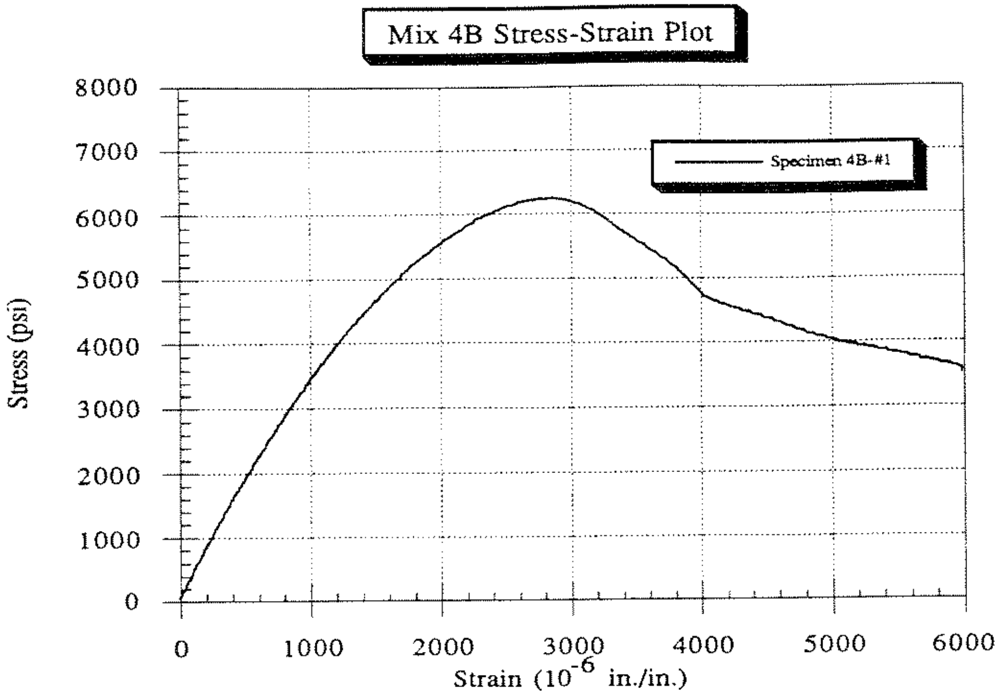


Figure 3.11 *Mix Series #4B Stress Strain Plots*

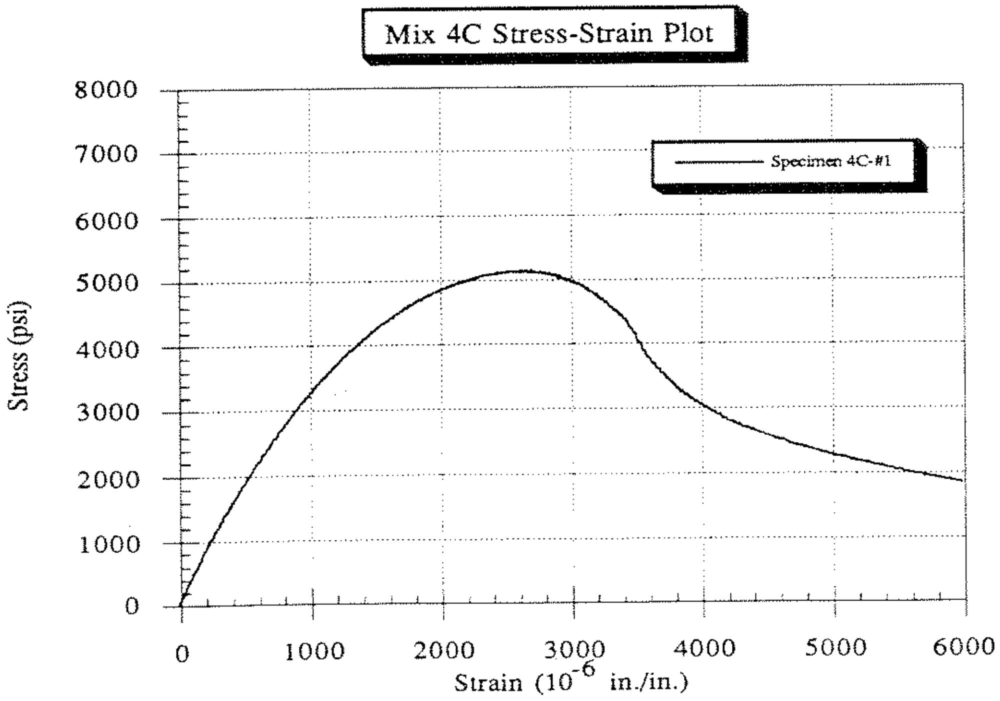


Figure 3.12 *Mix Series #4C Stress Strain Plots*

4.0 Analysis and Results

4.1 Introduction

This chapter presents the analysis of the experimental data obtained, as well as a behavior comparison of the different mix series for the established performance criteria. The experimental data was processed using regression analysis techniques to obtain different design charts. One of the most important design charts is the Mix Design Diagram already presented in a conceptual format in chapter 2. By using the information from the Mix Design Diagram, it is not only possible to design a mix that complies with the predefined performance criteria, but also to compare the performance of mixtures corresponding to different mix series. This chapter will first present the different Mix Design Diagrams obtained for each of the four mix series and then a comparison will be presented between the different mix series .

4.2 Mix Design Diagram

As was described in chapter 2, by combining the four different behavior laws in a single diagram, a Mix Design Diagram can be obtained. From this diagram, it is very simple to find the proportion of materials to satisfy the two basic design criteria, compressive strength and consistency of the mix. This approach can also be used for other properties such as permeability, flexural strength, modulus of elasticity, etc. By plotting the desired performance criteria versus the water-to-cement ratio, these relationships can be established. The following paragraphs will present the different Mix Design Diagrams and other properties of the hardened mortar, as well as a mix design example for each of the four mix series.

4.2.1 **Mix Series #1** (Control Mix)

The mix design diagram for mix series #1 is presented in Figure 4.2.1.a. By using this diagram, the mix proportions can easily be determined for a mortar that will have the required compressive strength at a given age. Noted that during this research phase, all mortars studied have a consistency of 0"-1" as measured by the standard slump test.

Consider the following example:

- Given a required fc = 6000 psi at 28 days, find the mix proportions and the expected values for the following properties of the mortar:
  * Compressive Strength at 1,3,7, and 91 days.
  * Splitting tensile strength at 1, and 28 days.
  * Flexural strength at 28 days.
  * Chloride permeability at 28, and 91 days.
  * Elastic Modulus (28 days).
  * Poisson's ratio (28 days)
  * Fresh mortar unit weight.

This problem can be solved by performing the following steps using the mix design diagram:

1- From Abram's law : fc = 6000 psi ---->w/c = 0.49

2- From Lyse's law : w/c = 0.49 ---->m = 3.78

3- From Molinari's law: m = 3.78 ---->C = 727 lb / yd^3

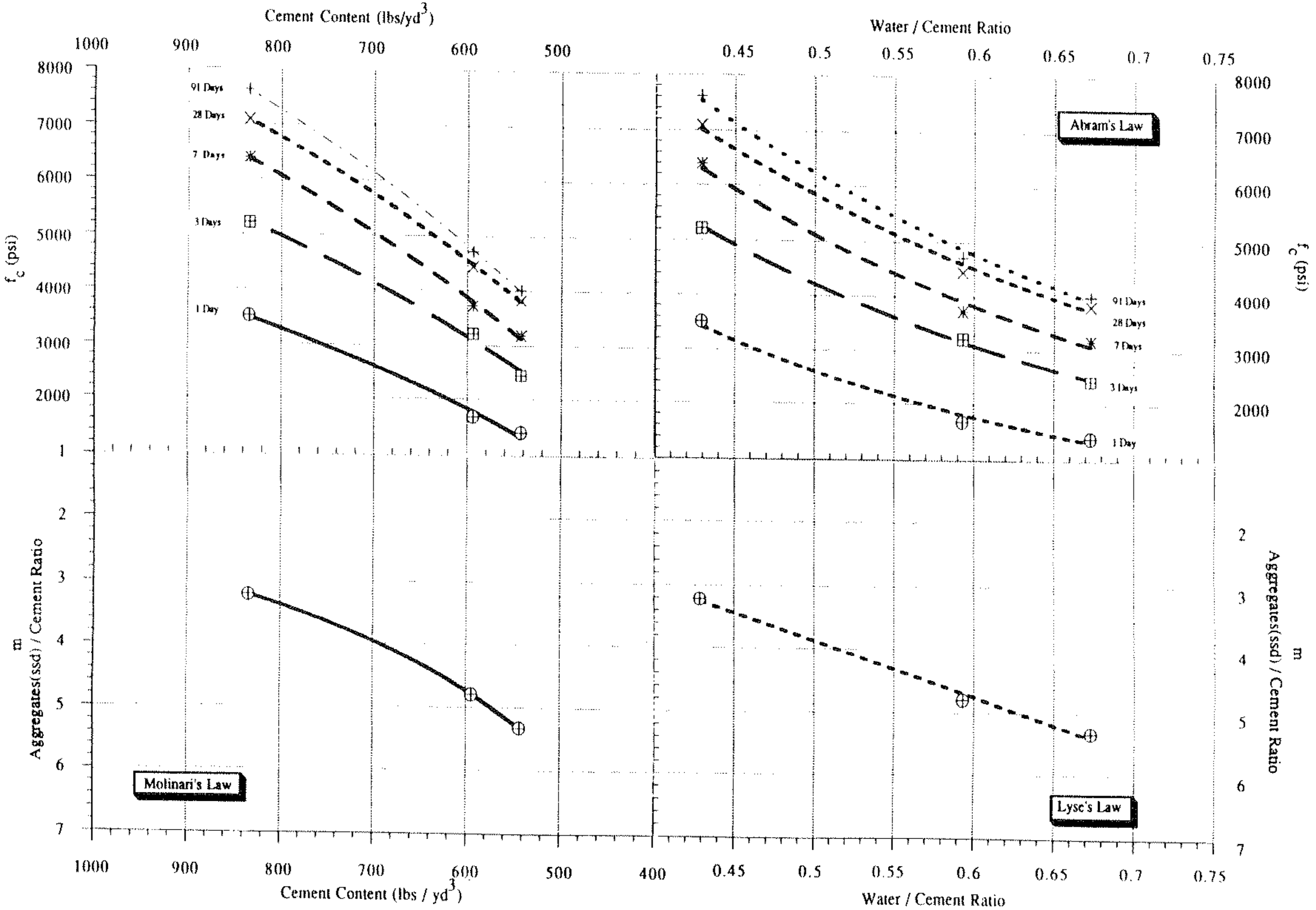
4- Also by knowing the w/c ratio, we can obtain the expected compressive strength values for other ages using Abram's law.

5- From figure 4.2.1b, and the w/c ratio obtained in step 1, the expected value for the splitting tensile strength at the ages of 1 and 28 days can be obtained.

6- From figure 4.2.1c, and the w/c ratio obtained in step 1, the expected value for the flexural strength at the age of 28 days can be obtained.

7- From figure 4.2.1d, and the w/c ratio obtained in step 1, the expected value for the chloride permeability at the ages of 28 and 91 days can be obtained.

Figure 4.2.1.a. Mix Series #1 Design Diagram



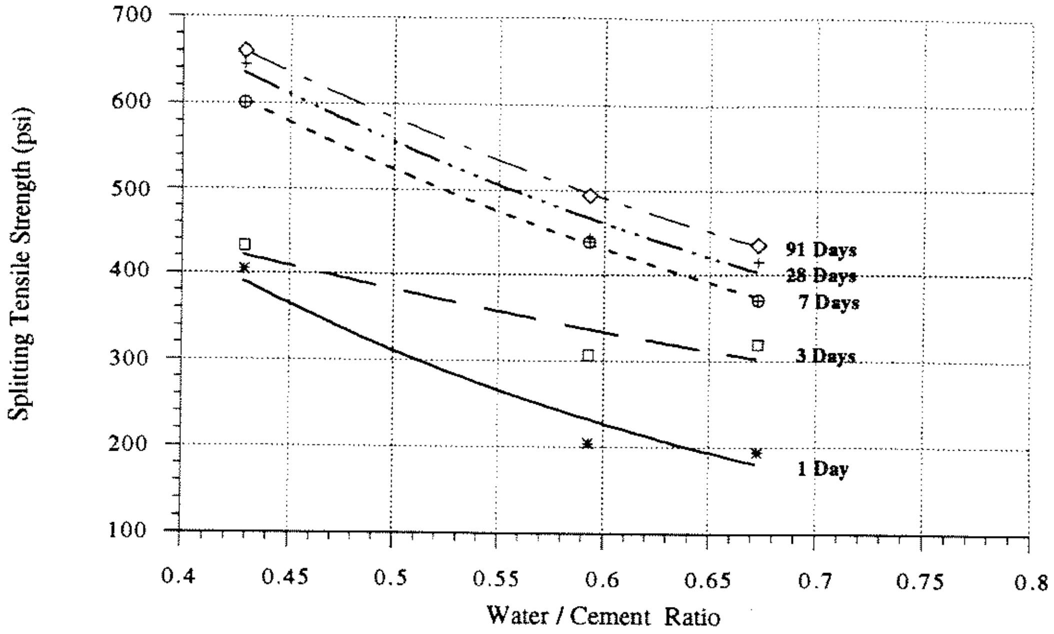


Figure 4.2.1b *Mix Series #1- Splitting Tensile Strength vs. Water/Cement Ratio.*

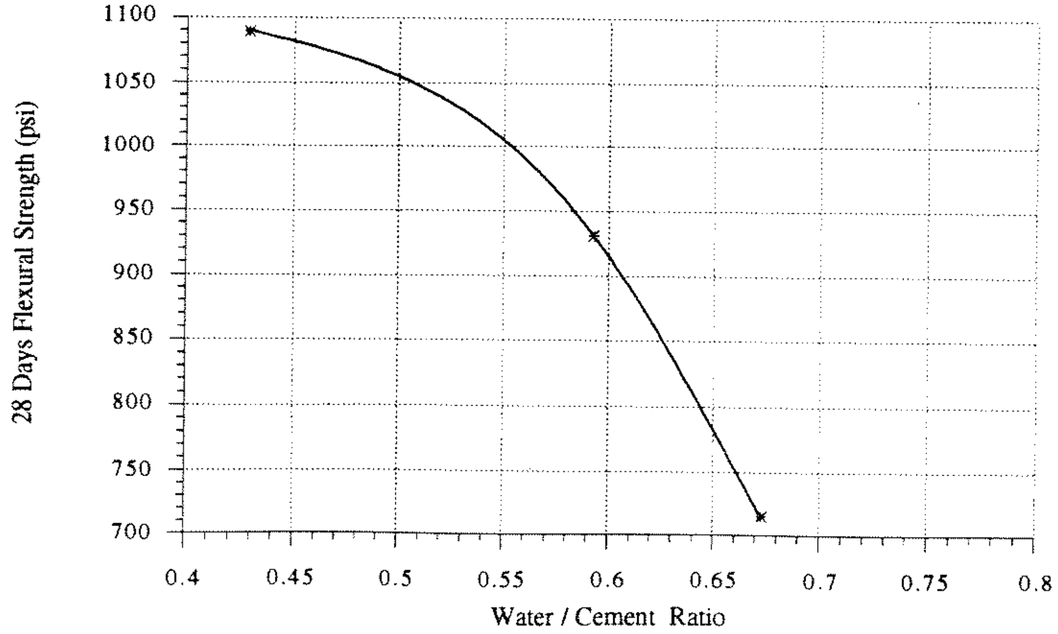


Figure 4.2.1c *Mix Series #1- Flexural Strength vs. Water -Cement Ratio*

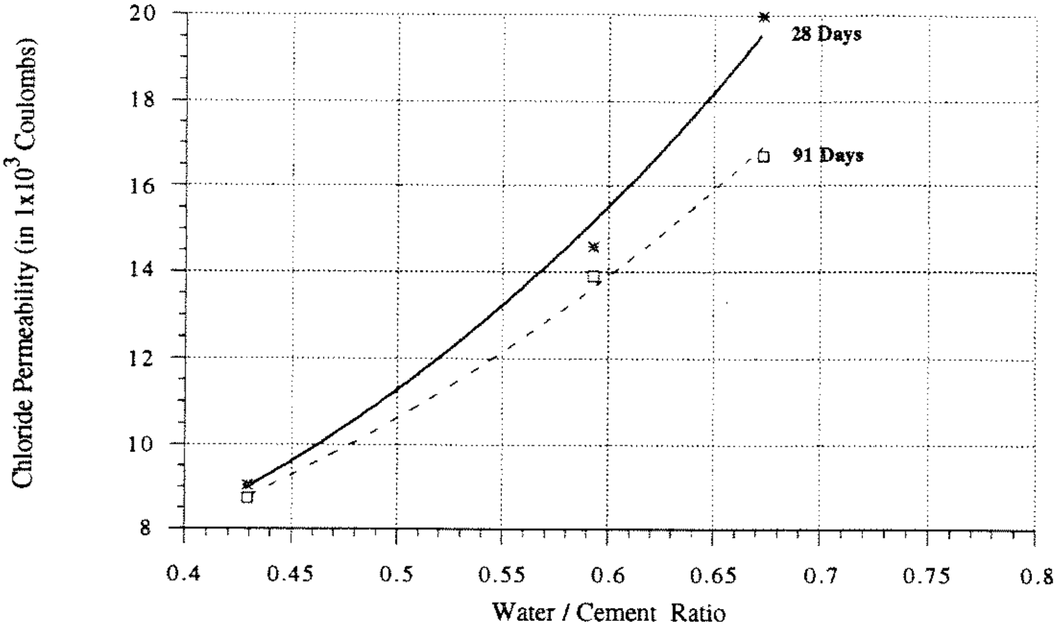


Figure 4.2.1d *Mix Series #1- Chloride Permeability vs. Water -Cement Ratio*

8- From figure 4.2.1e and the w/c ratio obtained in step 1, the expected value for the elastic modulus at the age of 28 days can be obtained.
9- From figure 4.2.1f and the w/c ratio obtained in step 1, the expected value for the Poisson's ratio can be obtained.
10- From figure 4.2.1g and the w/c ratio obtained in step 1, the expected value for the mortar unit weight can be obtained.

Thus, knowing the required w/c ratio, all the other properties of the hardened mortar can easily be determined as described above. The results for the mix design are shown on Table 4.2.1a and 4.2.1b.

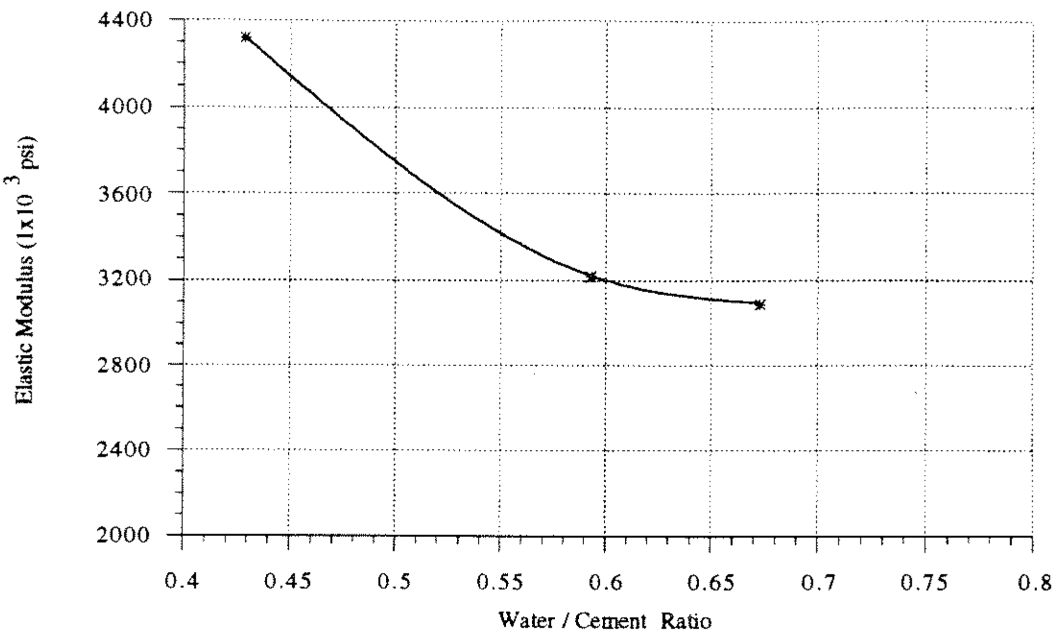


Figure 4.2.1e *Mix Series #1- 28 Days Elastic Modulus vs. Water -Cement Ratio.*

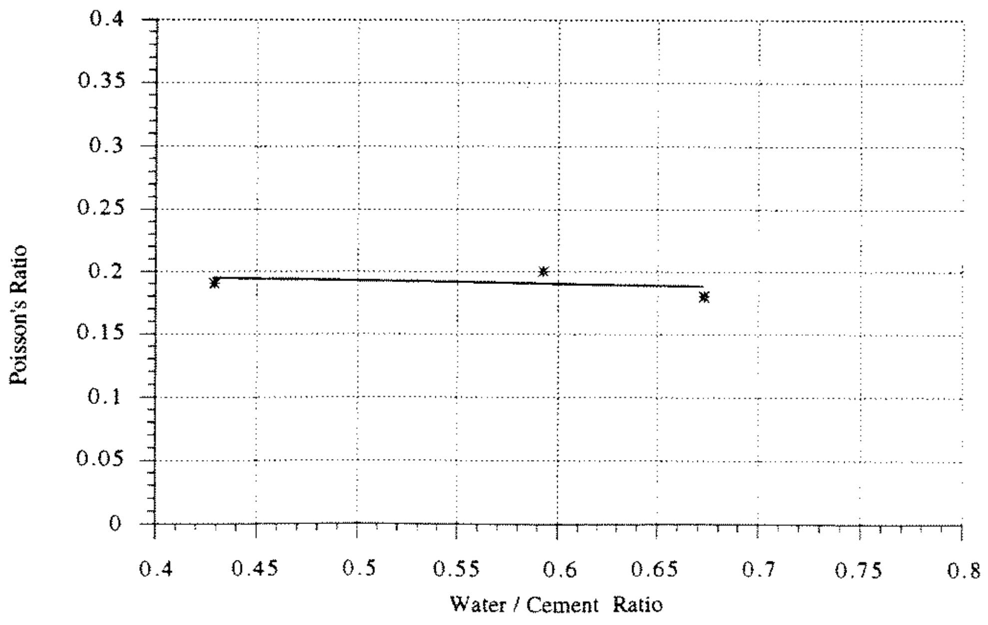


Figure 4.2.1f *Mix Series #1- 28 Days Poisson's Ratio vs. Water -Cement Ratio.*

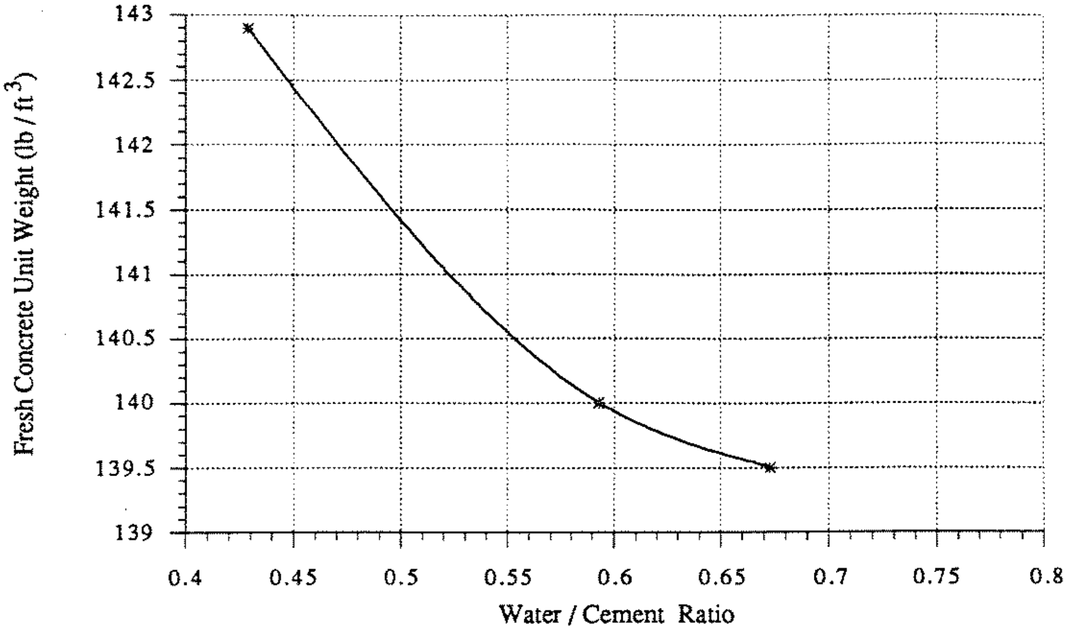


Figure 4.2.1g Mix Series #1- Fresh Mortar Unit Weight vs. Water -Cement Ratio.

Table 4.2.1a Mortar Mix Design - Series #1

Materials	Relative Proportions	Final Proportions (lb /yd^3)
Cement	1.00	727.00
Sand (SSD)	3.78	2748.00
Water	0.49	356.00
Superplasticizer	0.0025	1.82

πTable 4.2.1b Summary of Results for Mix Design Example Series #1

Mortar's Properties	**AGE**				
	1 Day	**3 Days**	**7 Days**	**28 Days**	**91 Days**
Compressive Strength (psi)	2690	4325	5264	**6000**	6413
Splitting Tensile Strength (psi)	319			564	
Flexural Strength (psi)				1059	
Chloride Permeability (Coul.)				10895	10300
Elastic Modulus ($1x10^3$ psi.)				3825	
Poisson's Ratio				0.194	

*Fresh Mortar Unit Weight (pcf) **141.6**

4.2.2- Mix Series #2 (Cement + Sand+Uncoated LWA)

The mix design diagram for mix series #2 is presented in Figure 4.2.2a. The uncoated LWA has been considered as a fixed percentage of the cement content (16% of the cement content by weight). Therefore, once the cement content is determined, the amount of LWA can be calculated by multiplying the cement content by 0.16. Consider the following example:

- Given a required fc = 4000 psi at 28 days, find the mix proportions and the expected values for the following properties of the mortar:
    * Compressive Strength at 1,3,7, and 91 days.
    * Splitting tensile strength at 1 and 28 days.
    * Flexural strength at 28 days.
    * Chloride permeability at 28 and 91 days.
    * Modulus of Elasticity(28 days).
    * Poisson's ratio.
    * Fresh mortar unit weight.

This problem can be solved by performing the following steps:

1- From Abram's law : fc = 4000 psi ---->w/c= 0.596

2- From Lyse's law : w/c = 0.596 ---->m= 2.716

3- From Molinari's law: m = 2.716 ---->C= 736 lb/yd^3

4- From 3, LWA uncoated content = C*0.16= 117.8 lb/yd^3

5- Also by knowing the w/c ratio, we can obtain the expected compressive strength values for other ages using again the Abram's law.

6- From figure 4.2.2b and the w/c ratio obtained in step 1, the expected value for the splitting tensile strength at the ages of 1 and 28 days is obtained.

7- From figure 4.2.2c and the w/c ratio obtained in step 1, the expected value for the flexural strength at the age of 28 days is obtained.

8- From figure 4.2.2d and the w/c ratio obtained in step 1, the expected value for the chloride permeability at the ages of 28 and 91 days is obtained.

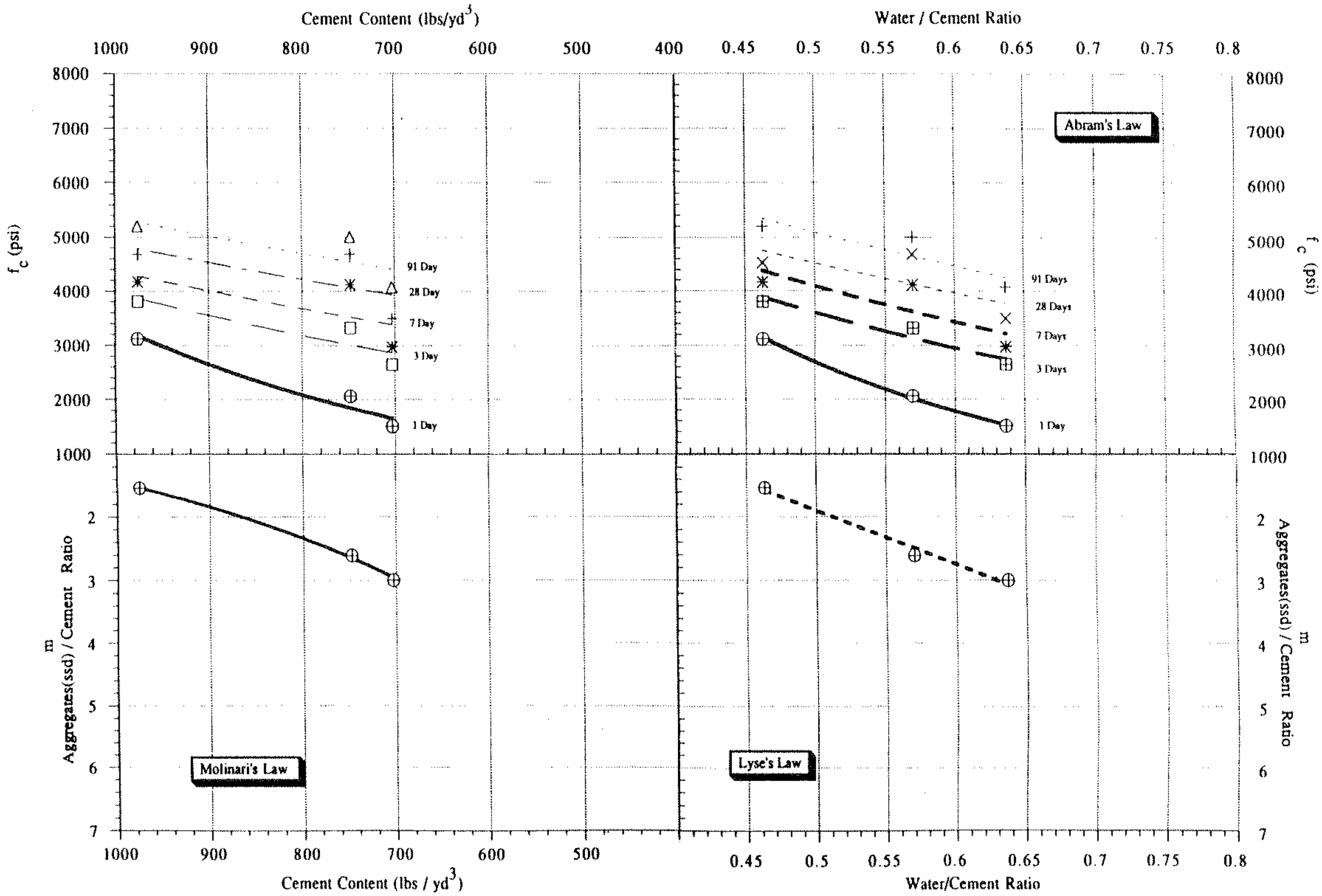
9- From figure 4.2.2e and the w/c ratio obtained in step 1, the expected value for the elastic modulus at the age of 28 days is obtained.

10- From figure 4.2.2f and the w/c ratio obtained in step 1, the expected value for the Poisson's Ratio is obtained.

11- From figure 4.2.2g and the w/c ratio obtained in step 1, the expected value for the mortar unit weight is obtained.

As it can be seen, by knowing the required w/c ratio, all the other properties of the hardened mortar can easily be determined by following the different steps presented above. The results for the mix design are shown on Table 4.2.2a and 4.2.2b.

Figure 4.2.2.a. Mix Series #2 Design Diagram



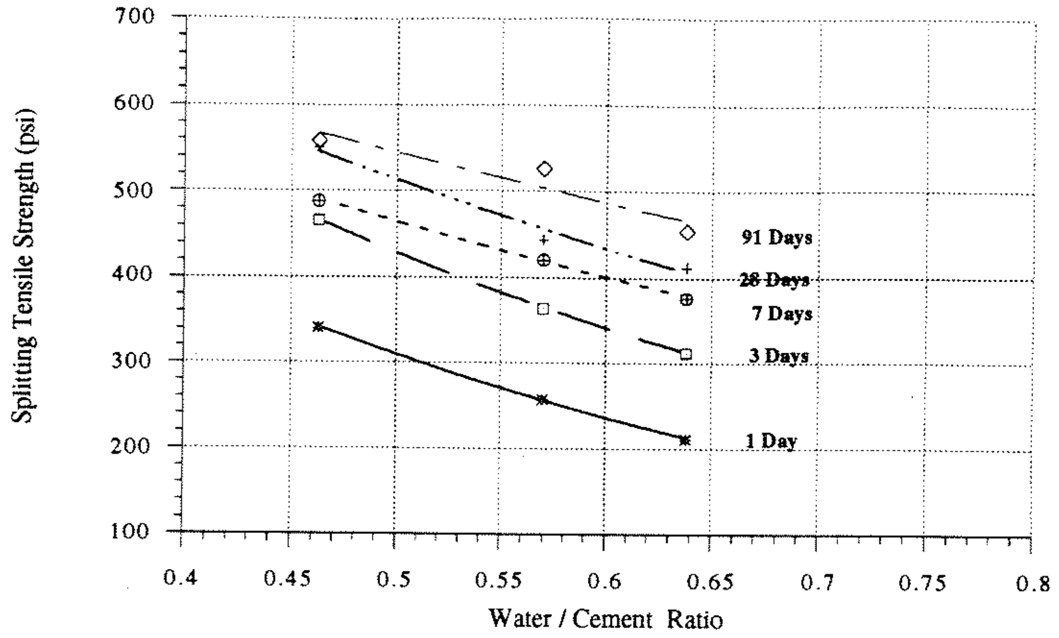


Figure 4.2.2b *Mix Series #2- Splitting Tensile Strength vs. Water-Cement Ratio.*

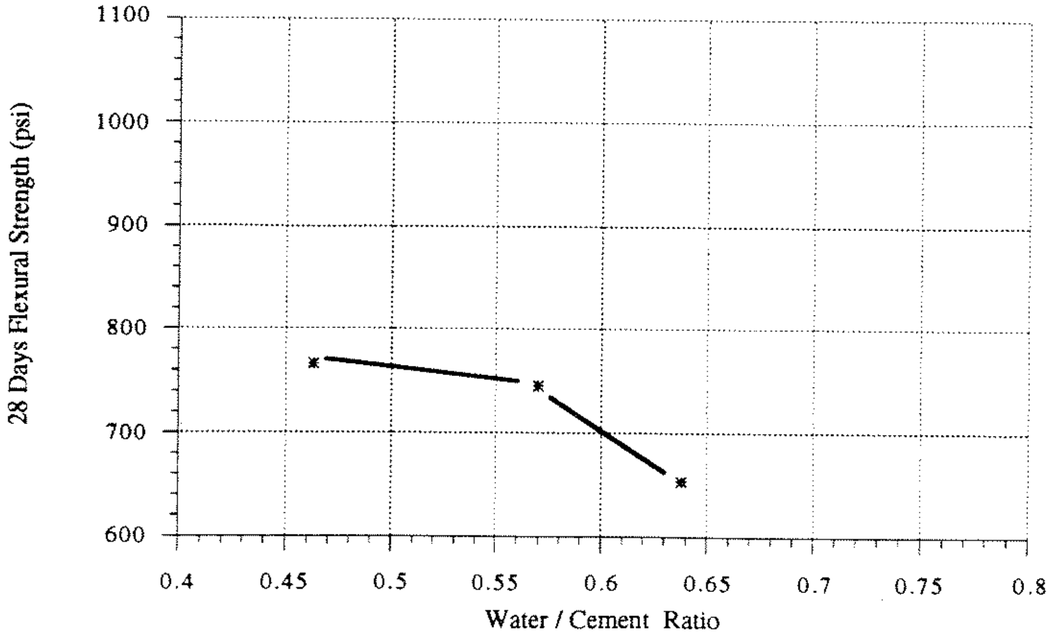


Figure 4.2.2c *Mix Series #2- Flexural Strength vs. Water -Cement Ratio*

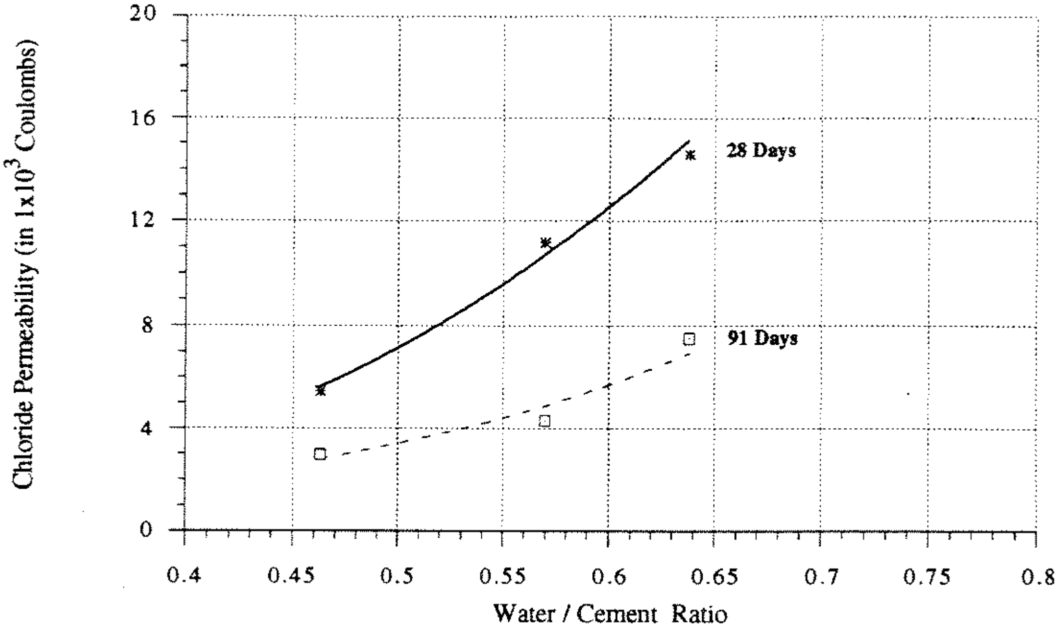


Figure 4.2.2d *Mix Series #2- Chloride Permeability vs. Water -Cement Ratio*

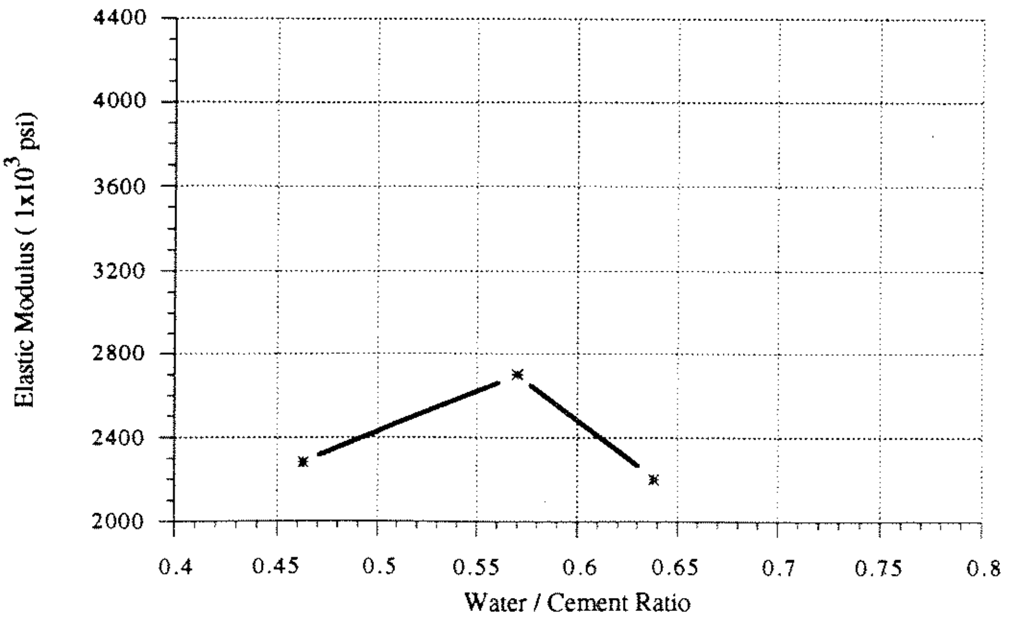


Figure 4.2.2e *Mix Series #2- 28 Days Elastic Modulus vs. Water -Cement Ratio.*

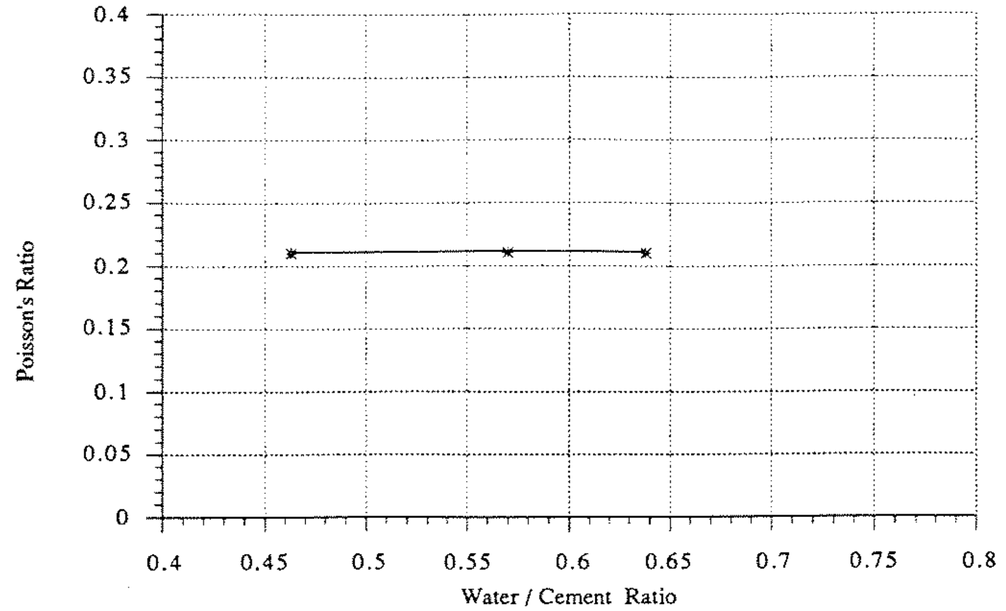


Figure 4.2.2f   Mix Series #2- 28 Days Poisson's Ratio vs. Water -Cement Ratio.

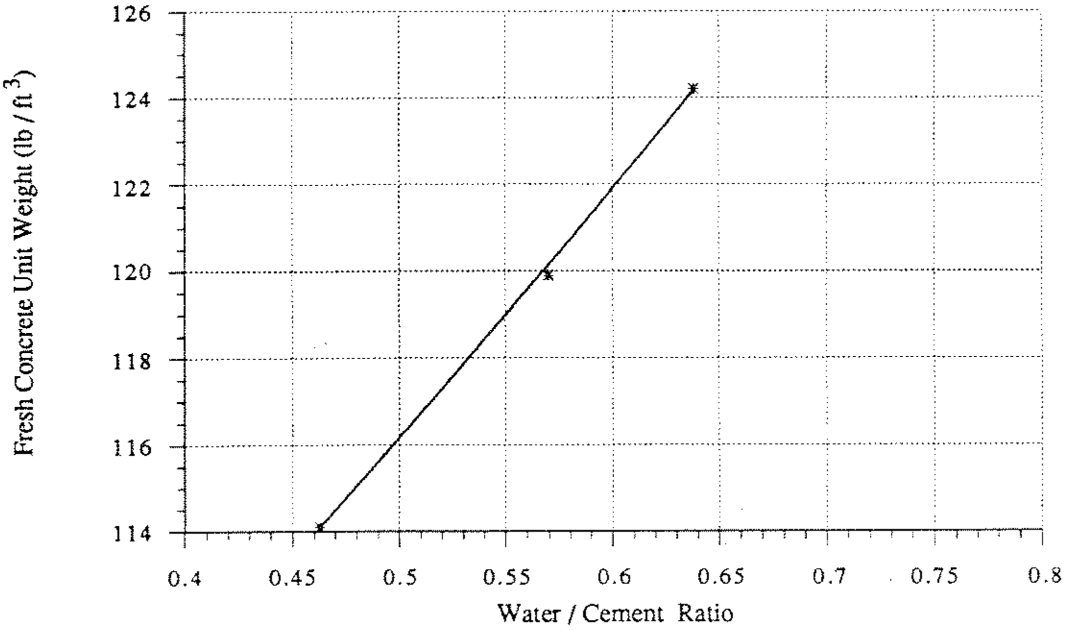


Figure 4.2.2g   Mix Series #2- Fresh Mortar Unit Weight vs. Water -Cement   Ratio.

Table 4.2.2a Mortar Mix Design - Series #2

Materials	Relative Proportions	Final Proportions (lb /yd^3)
Cement	1.000	736.00
Sand (ssd)	2.716	1999.00
Uncoated LWA	0.160	117.80
Water	0.596	438.70
Superplasticizer	0.0025	1.84

Table 4.2.2b Summary of Results for Mix Design Example Series #2

Mortar's Properties	AGE				
	1 Day	3 Days	7 Days	28 Days	91 Days
Compressive Strength (psi)	1821	2968	3490	**4000**	4500
Splitting Tensile Strength (psi)	239			436	
Flexural Strength (psi)				706	
Chloride Permeability (Coul.)				12290	5535
Elastic Modulus (1x10^3 psi.)				2510	
Poisson's Ratio				0.210	

*Fresh Mortar Unit Weight (pcf) **121.6**

4.2.3- Mix Series #3 (Cement+Sand+Uncoated LWA+Diatomite)

The mix design diagram for mix series #3 is presented in Figure 4.2.3.a. This design diagram has the proportion of fine LWA and diatomite already considered as a portion of the cement content. Even though the diatomite is a pozzolanic admixture and usually would be considered as part of the cementitious material, the diagram has been constructed for simplicity considering only the water-cement ratio. With this, the calculations of the relative proportions are simplified. Consider the following example:

- Given a required fc = 4000 psi at 28 days, find the mix proportions and the expected values for the following properties of the mortar:
  - * Compressive Strength at 1,3,7, and 91 days.
  - * Splitting tensile strength at 1 and 28 days.
  - * Flexural strength at 28 days.
  - * Chloride permeability at 28 and 91 days.
  - * Modulus of Elasticity(28 days).
  - * Poisson's ratio.
  - * Fresh mortar unit weight.

This problem can be solved by performing the following steps:

1- From Abram's law : fc = 4000 psi ---->w/c= 0.629

2- From Lyse's law : w/c = 0.629 ---->m= 2.904

3- From Molinari's law: m = 2.904 ---->C= 704 lb/yd^3

4- From 3, LWA uncoated content = C*0.16= 112.64 lb/yd^3

5- From 3, diatomite content = C*0.027= 19.01 lb/yd^3

6- With the w/c ratio, we can obtain the compressive strengths for other ages using Abram's law.

7- From figure 4.2.3b and the w/c ratio obtained in step 1, the expected value for the splitting tensile strength at the age of 1 and 28 days can be obtained.

8- From figure 4.2.3c and the w/c ratio obtained in step 1, the expected value for the flexural strength at the age of 28 days can be obtained.

9- From figure 4.2.3d and the w/c ratio obtained in step 1, the expected value for the chloride permeability at the age of 28 and 91 days can be obtained.

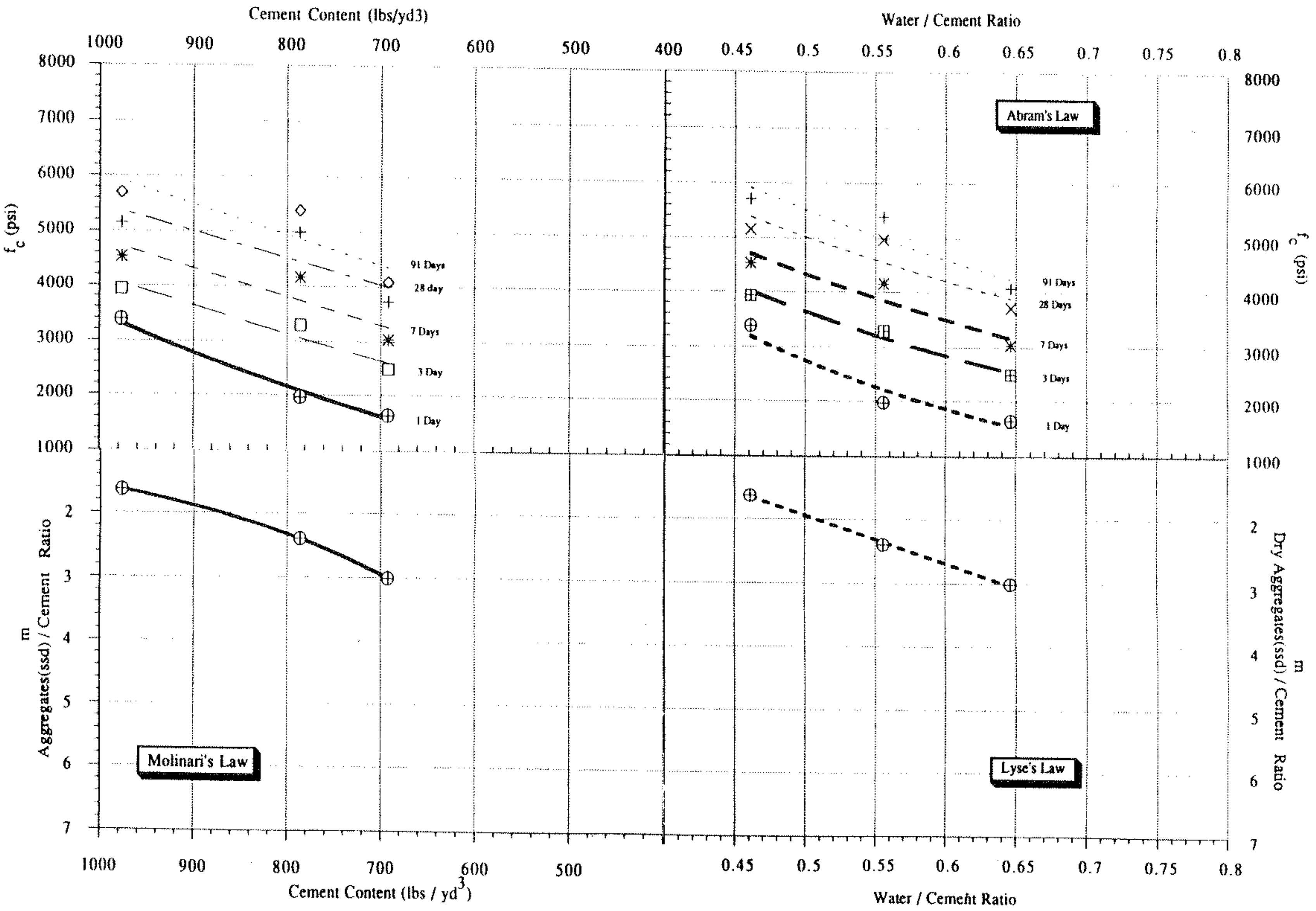
10- From figure 4.2.3e and the w/c ratio obtained in step 1, the expected value for the elastic modulus at the age of 28 days can be obtained.

11- From figure 4.2.3f and the w/c ratio obtained in step 1, the expected value for the Poisson's ratio can be obtained.

12- From figure 4.2.3g and the w/c ratio obtained in step 1, the expected value for the mortar unit weight can be obtained.

The results for the mix design are shown on Table 4.2.3a., and 4.2.3b.

Figure 4.2.3.a. Mix Series #3 Design Diagram



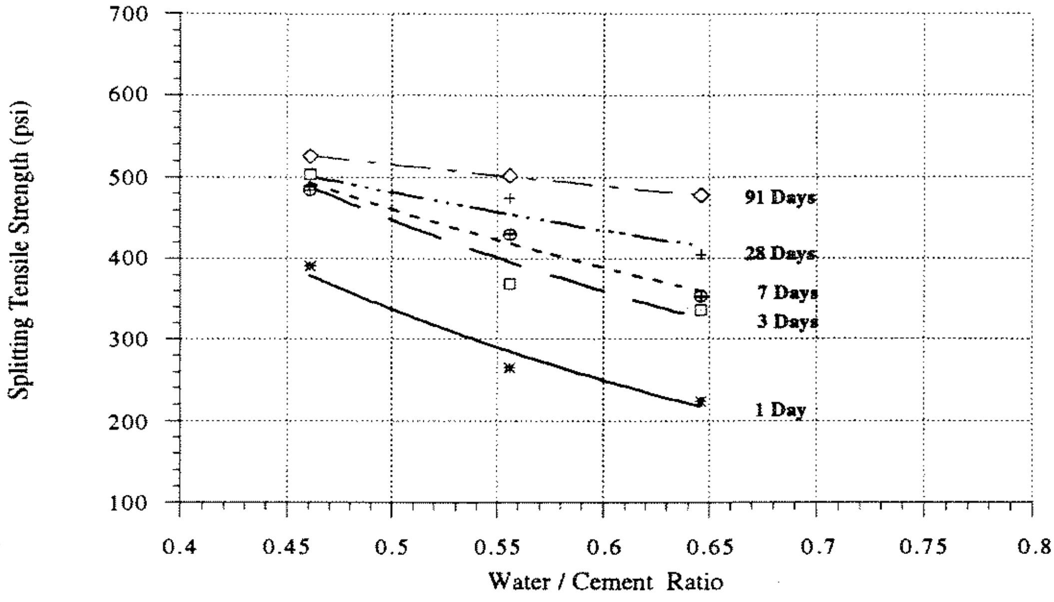


***Figure 4.2.3b.** Mix Series #3- Splitting Tensile Strength vs. Water-Cement Ratio.*

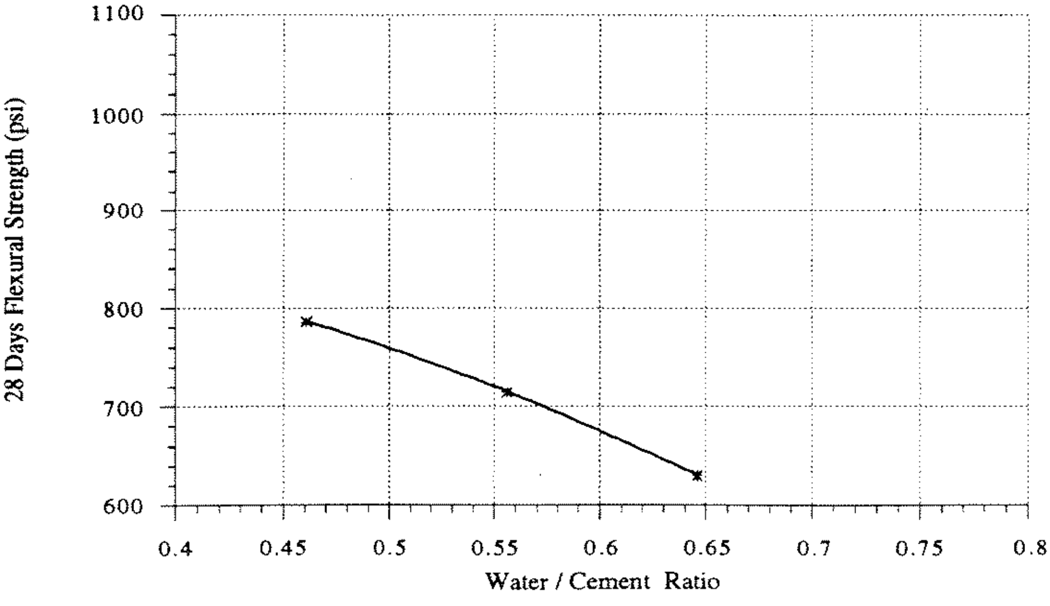


***Figure 4.2.3c** Mix Series #3- Flexural Strength vs. Water -Cement Ratio*

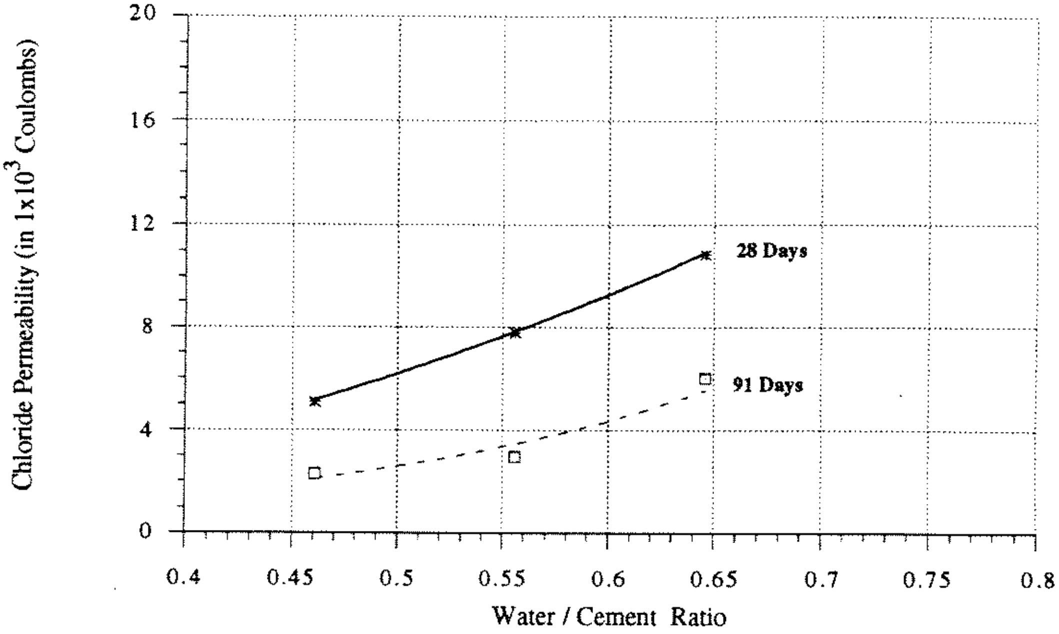


Figure 4.2.3d *Mix Series #3- Chloride Permeability vs. Water -Cement Ratio*

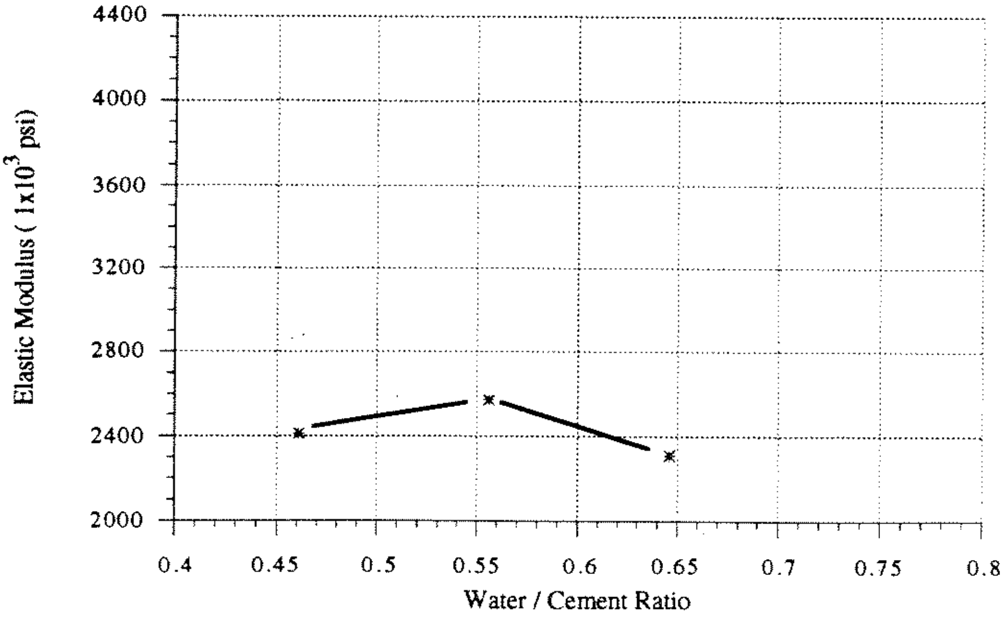


Figure 4.2.3e *Mix Series #3- 28 Days Elastic Modulus vs. Water -Cement Ratio.*

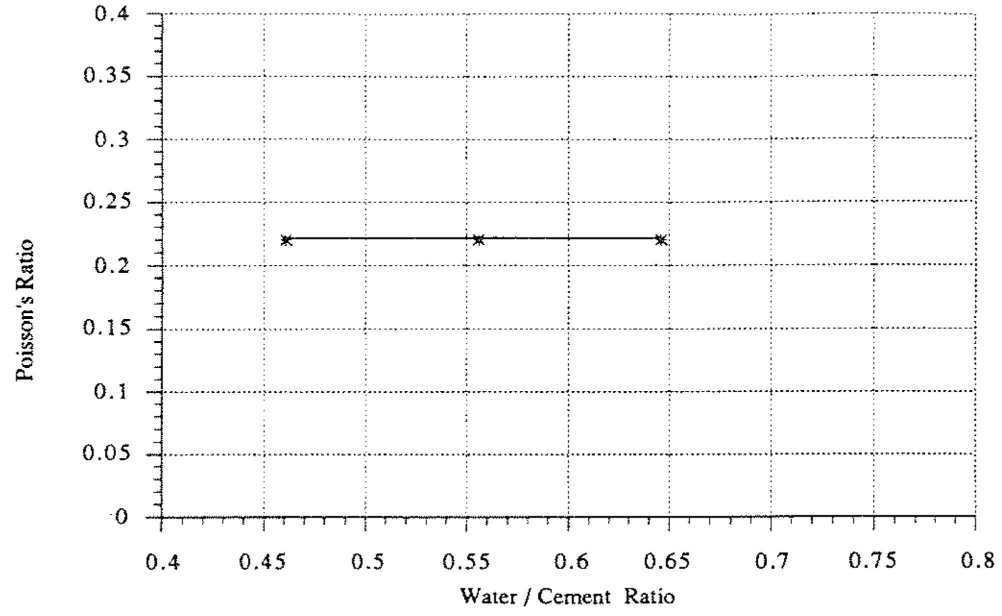


Figure 4.2.3f *Mix Series #3- 28 Days Poisson's Ratio vs. Water -Cement Ratio.*

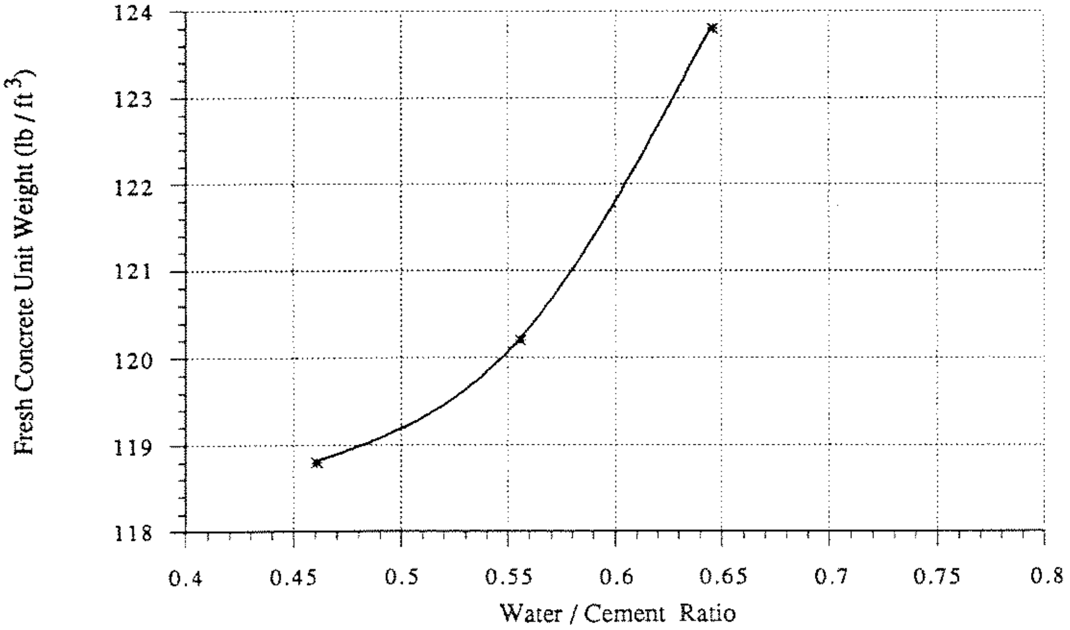


Figure 4.2.3g *Mix Series #3- Fresh Mortar Unit Weight vs. Water -Cement Ratio.*

Table 4.2.3a   Mortar Mix Design - Series #3

Materials	Relative Proportions	Final Proportions (lb/yd^3)
Cement	1.000	704.00
Diatomite	0.027	19.01
Sand (ssd)	2.904	2044.42
Fine lightweight aggregate	0.160	112.64
(uncoated)	0.629	442.82
Water	0.0025	1.76
Superplasticizer		

Table 4.2.3b   Summary of Results for Mix Design Example Series #3

Mortar's Properties	AGE				
	1 Day	3 Days	7 Days	28 Days	91 Days
Compressive Strength (psi)	1646	2620	3317	**4000**	4360
Splitting Tensile Strength (psi)	227			421	
Flexural Strength (psi)				645	
Chloride Permeability (Coul.)				10305	5040
Elastic Modulus (psi.)				2363	
Poisson's Modulus				0.220	

*Fresh Mortar Unit Weight (pcf)   **123.1**

4.2.4- Mix Series #4 (Cement + Sand + LWA composite)

The mix design diagram for mix series #4 is presented in Figure 4.2.4.a. Similar to mix series #2 and #3, the mix design diagram for mix series #4 has two important considerations that should be pointed out. First, the amount of fine LWA composite was designed as a fixed percentage of the cement content (36.4%). The second consideration is that the pozzolanic admixtures and free water in the composite have not been considered in the calculation of the water-cement ratio. The main reason for this is that both the amount of pozzolanic material and free water contained by the composite are kept proportionally constant by weight of Fine LWA composite. A similar reasoning was made with the amount of fine LWA aggregate contained in the composite. With this, the mix design is considerably simplified.

Consider the following example:

• Given a required fc = 6000 psi at 28 days, find the mix proportions and the expected values for the following properties of the mortar:

* Compressive Strength at 1,3,7, and 91 days.
* Splitting tensile strength at 1, and 28 days.
* Flexural strength at 28 days.
* Chloride permeability at 28, and 91 days.
* Modulus of Elasticity(28 days).
* Poisson's ratio.
* Fresh mortar unit weight.

This problem can be solved by performing the following steps:

1- From Abram's law : fc = 6000 psi ---->w/c = 0.628

2- From Lyse's law : w/c = 0.628 ---->m = 4.665

3- From Molinari's law: m = 4.665 ---->C = 543 lb/yd^3

4- From step 3, LWA composite = 0.364*C= 197.65 lb/yd^3

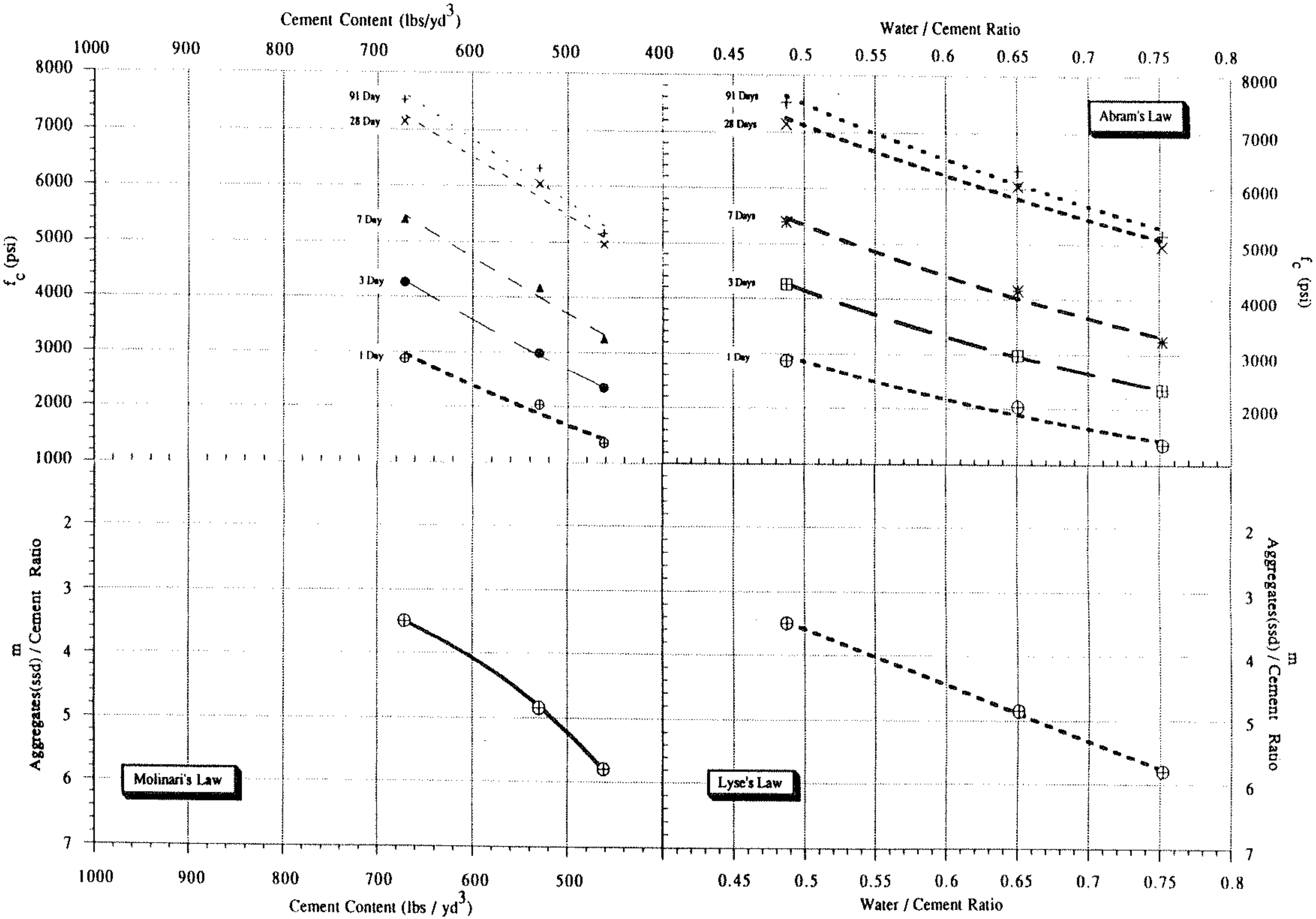
5- In the same way, by knowing the w/c ratio we can obtain the expected compressive strength values for other ages using again the Abram's law.

6- From figure 4.2.4b and the w/c ratio obtained in step 1, the expected value for the splitting tensile strength at the ages of 1 and 28 days can be obtained.

7- From figure 4.2.4c and the w/c ratio obtained in step 1, the expected value for the flexural strength at the age of 28 days can be obtained.

8- From figure 4.2.4d and the w/c ratio obtained in step 1, the expected value for the chloride permeability at the ages of 28 and 91 days can be obtained.

Figure 4.2.4.a. Mix Series #4 Design Diagram



9- From figure 4.2.4e., and the w/c ratio obtained in step 1, the expected value for the elastic modulus at the age of 28 days can be obtained.

10- From figure 4.2.4f and the w/c ratio obtained in step 1, the expected value for the Poisson's ratio can be obtained.

11- From figure 4.2.4g and the w/c ratio obtained in step 1, the expected value for the mortar unit weight can be obtained.

The results for the mix design are shown on Table 4.2.4a and 4.2.4b.

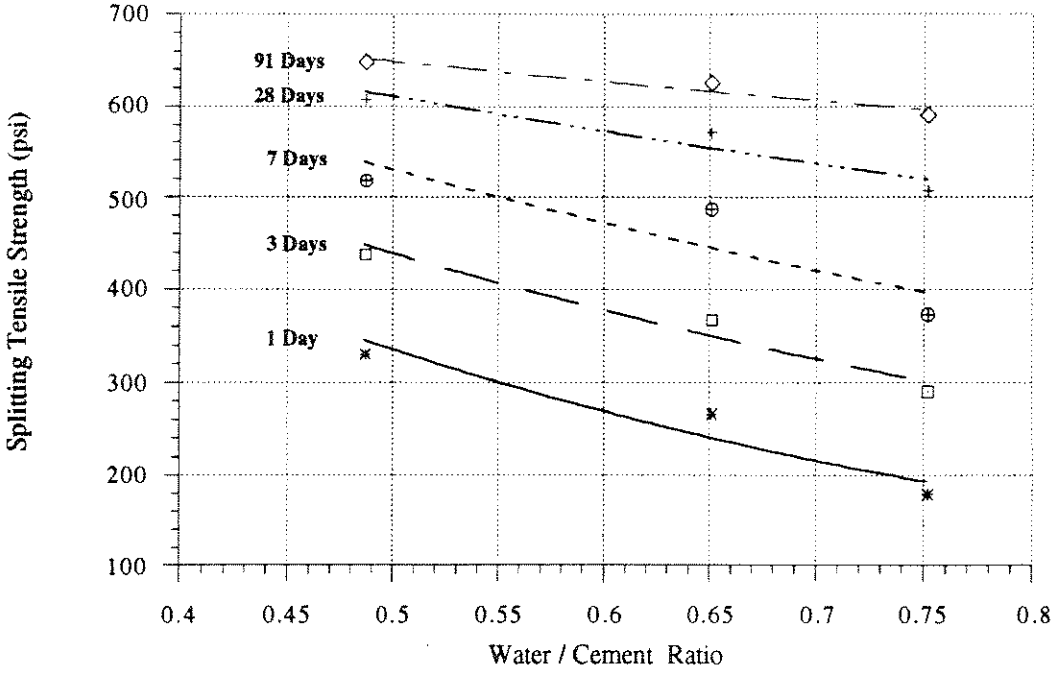


__Figure 4.2.4b__ Mix Series #4- Splitting Tensile Strength vs. Water-Cement Ratio.

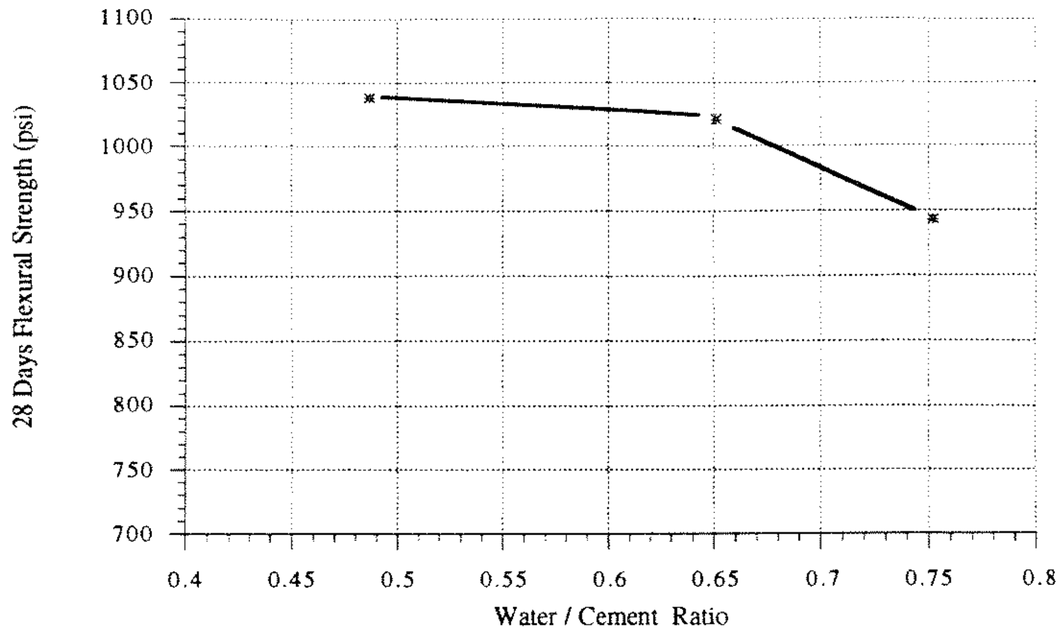


Figure 4.2.4c *Mix Series #4- Flexural Strength vs. Water -Cement Ratio.*

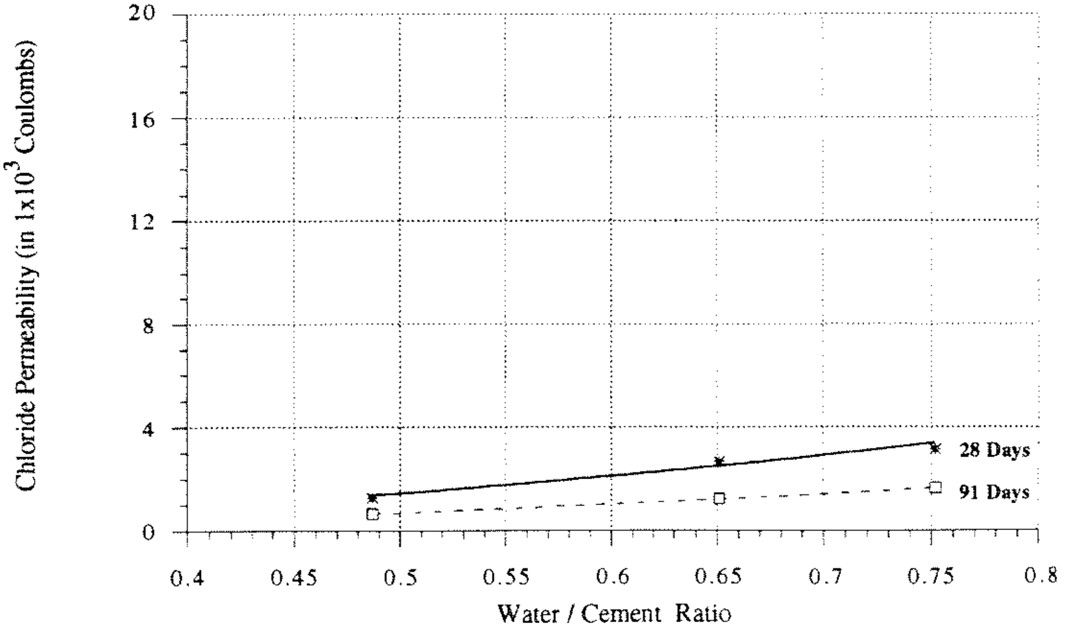


Figure 4.2.4d *Mix Series #4- Chloride Permeability vs. Water -Cement Ratio*

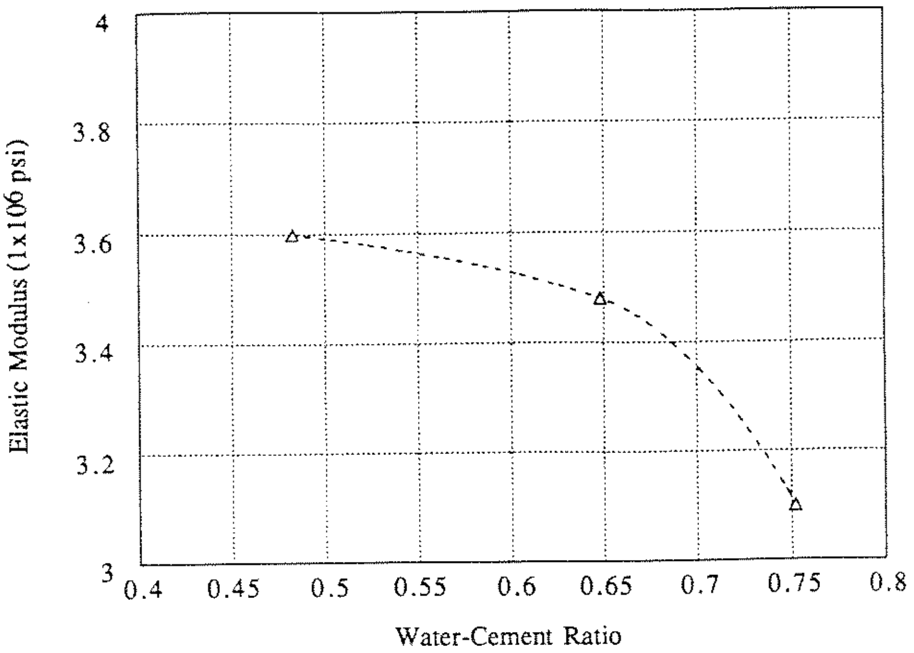


Figure 4.2.4e *Mix Series #4- 28 Days Elastic Modulus vs. Water -Cement Ratio.*

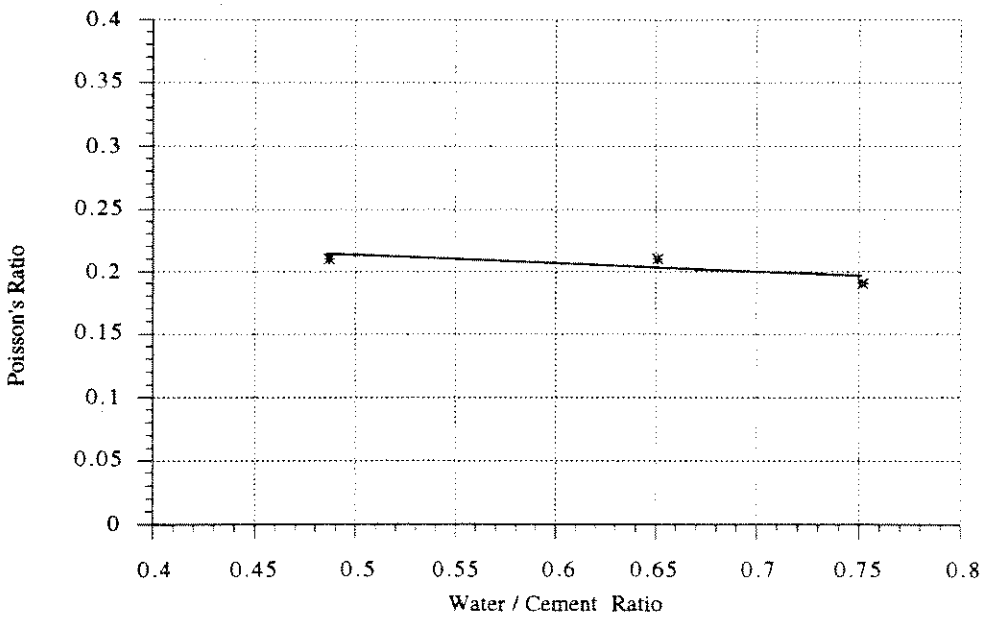


Figure 4.2.4f *Mix Series #4- 28 Days Poisson's Ratio vs. Water -Cement Ratio.*

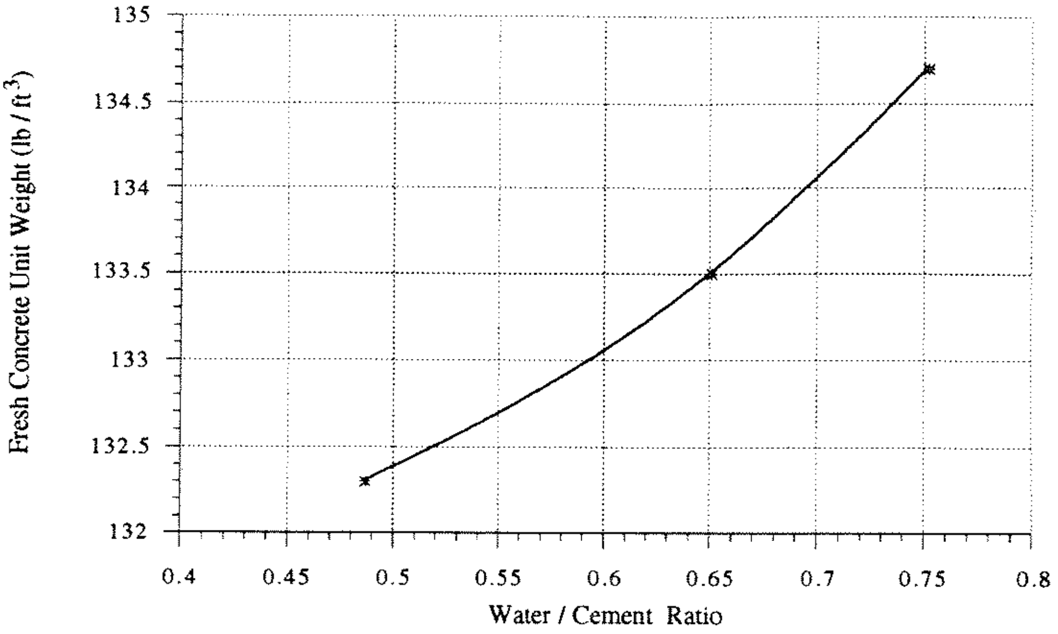


Figure 4.2.4g *Mix Series #4- Fresh Mortar Unit Weight vs. Water -Cement Ratio.*

Table 4.2.4a *Mortar Mix Design - Series #4*

Materials	**Relative Proportions**	**Final Proportions (lb/yd^3)**
Cement	1.000	543.00
LWA Composite	0.364	197.65
Sand (ssd)	4.665	2533.10
Water	0.628	341.00
Superplasticizer	0.0025	1.36

Table 4.2.4b *Summary of Results for Mix Design Example Series #4*

Mortar's Properties	**AGE**				
	1 Day	**3 Days**	**7 Days**	**28 Days**	**91 Days**
Compressive Strength (psi)	1995	3074	4152	**6000**	6275
Splitting Tensile Strength (psi)	251			561	
Flexural Strength (psi)				1023	
Chloride Permeability (Coul.)				2260	1127
Elastic Modulus (psi.)				3478	
Poisson's Modulus				0.203	

*Fresh Mortar Unit Weight (pcf) **133.3**

4.3 Comparison Between Different Mix Series

4.3.1 Mortar Unit Weight

Figure 4.3.1 shows the variation of the mortar unit weight for each mix series as a function of its compressive strength at 28 days. As it can be seen, mix series #4 provides an appreciable lower unit weight for a given compressive strength than mix series #1 (control mix). In addition, it can be observed that the higher the required compressive strength, the larger the reduction in unit weight. This is because an increase in compressive strength corresponds to a reduction in w/c ratio; thus, a higher cement content is required to provide a mix with the same amount of water per unit volume to maintain a constant consistency. Once the amount of LWA composite is a fixed percentage of the cement content in mix series #4, the change in unit weight for an increase in compressive strength is negative, while for mix series #1 it is positive. This results in mix series #4 showing a unit weight reduction as the compressive strength increases, while mix series #1 displays the opposite behavior.

The same behavior can be observed when comparing mix series #2 and #3 with the control mix. The only difference is that for mix series #2 and #3 the compressive strength is lower than that of mix series #4. The higher compressive strength and unit weight of mix series #4 are due to the additional pozzolanic material contained in LWA composite. Similarly, the difference in the behavior between mix series #2 and #3 can be attributed to the addition of diatomite in mix series #3, which causes not only a pozzolanic reaction and consequently higher compressive strengths, but also an increase in unit weight.

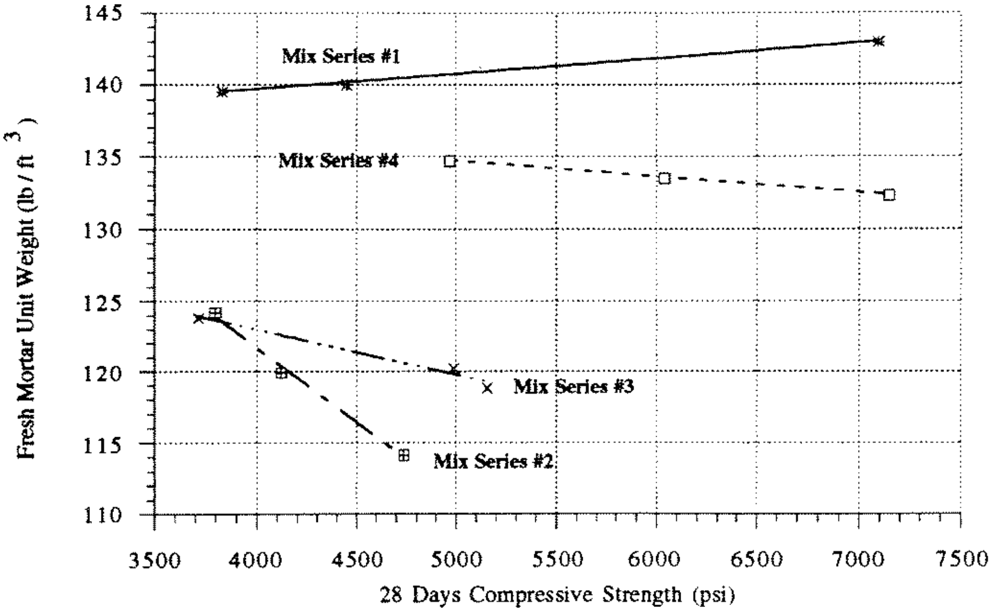


Figure 4.3.1 Fresh Mortar Unit Weight vs. 28 Days Compressive Strength.

4.3.2 Cement Savings

The cement content of a mixture is usually regarded as the largest economic issue or cost indicator for a proposed mixture. Even though this type of reasoning is very common among professionals, it is important to point out that this may not always true and its validity must be studied for each particular case and application. In this report it is assumed that low cement contents are a desirable way to achieve economical mixtures. Because of this, a comparison of the required cement contents required for each mix series to achieve certain performance criteria will be presented below. Figure 4.3.2a through Figure 4.3.2e presents the relationships between cement content and compressive strengths for different curing times, for each of the four studied mix series. It is important to point out that all the mixtures being compared have the same consistency . Therefore it can be assumed that each can be used for the same application. As it can be seen from figure 4.3.2a through 4.3.2e, mix series #4 shows a much lower cement requirement than the other three studied mixtures to achieve the required compressive strength at any given age . However, it should be noted that the gain in compressive strength is different for each of the four mixes. While mix series #1 has a faster rate of compressive strength gain between 1 and 7 days, mix series #4 has a rapid increase between 7 and 28 days. In the same way, mix series #2 and #3 have a rapid gain in compressive strength between 1 and 7 days when

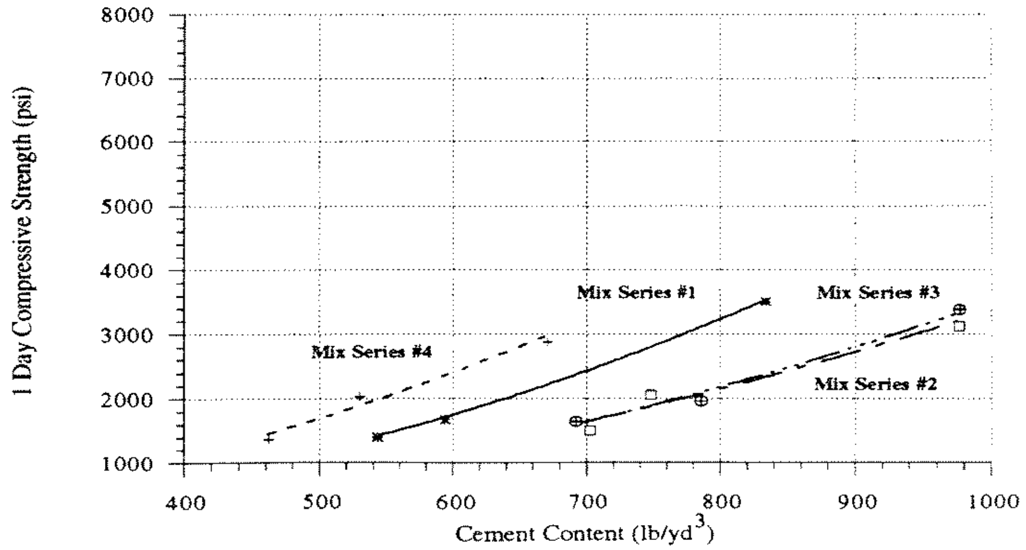


Figure 4.3.2a *1 Day Compressive Strength vs Cement Content.*

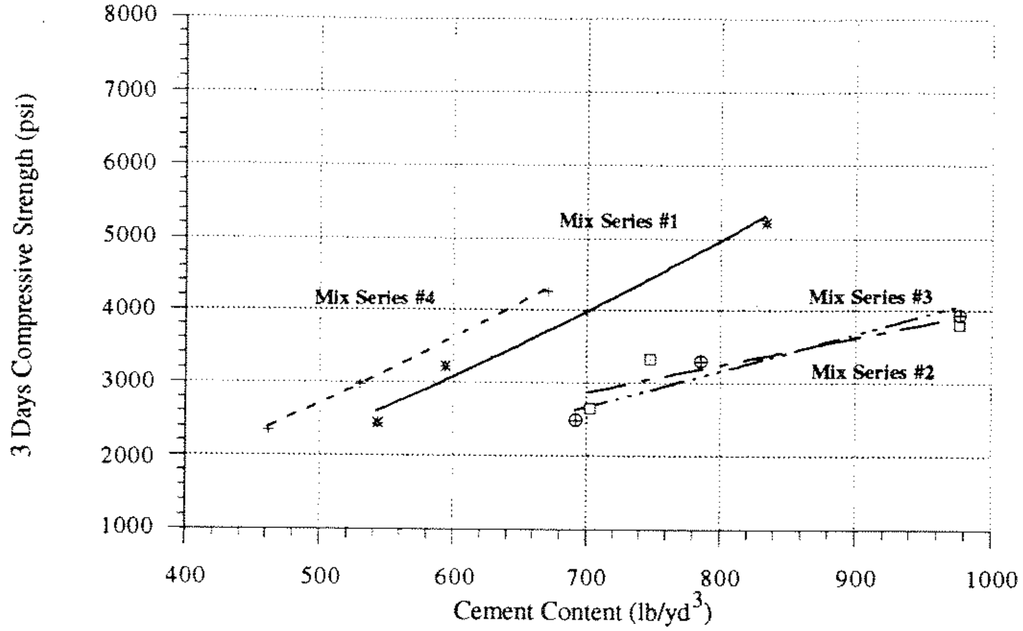


Figure 4.3.2b *3 Days Compressive Strength vs Cement Content.*

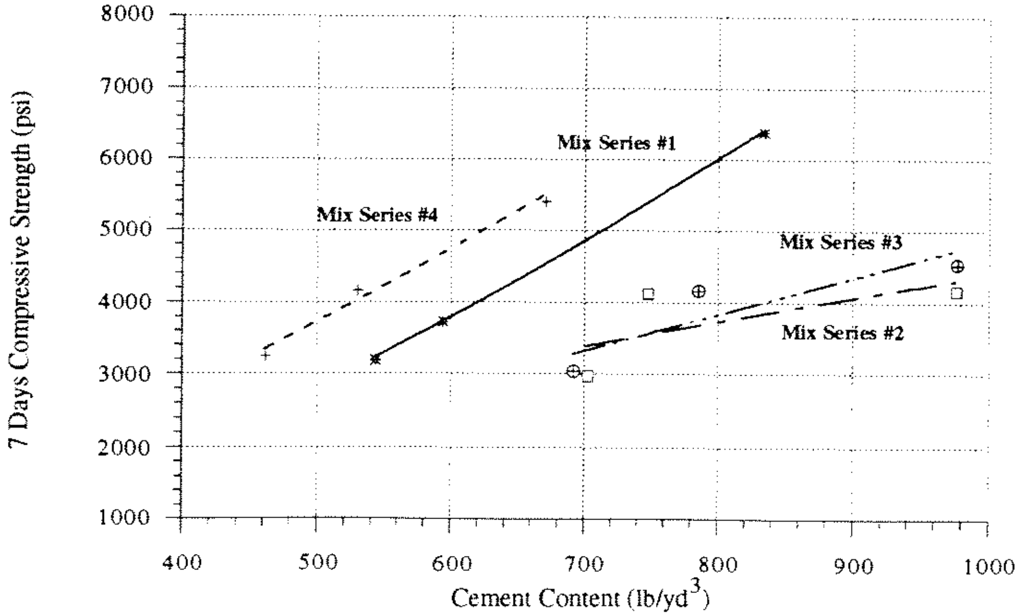


Figure 4.3.2c *7 Days Compressive Strength vs Cement Content.*

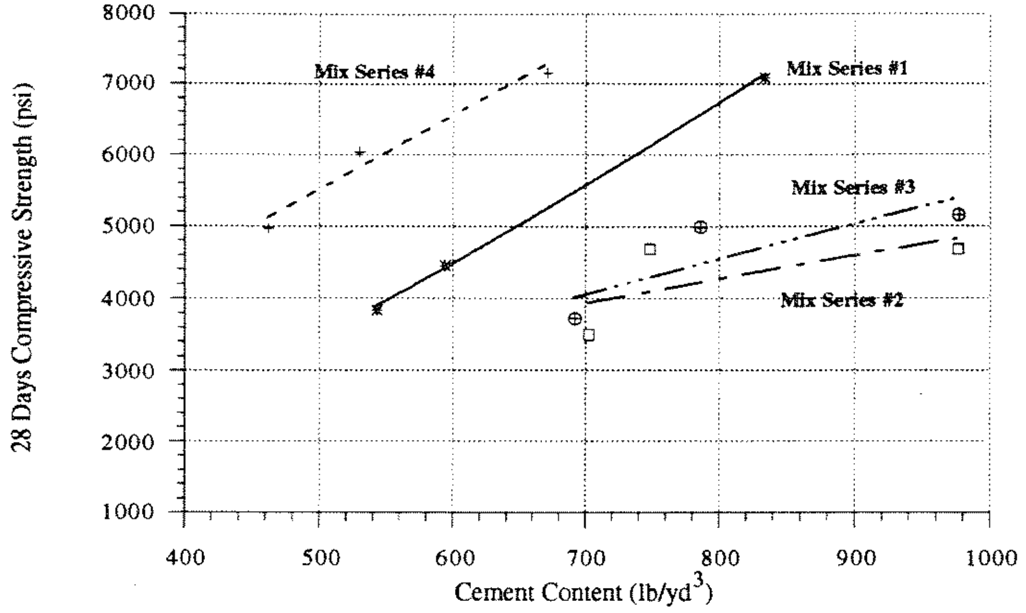


Figure 4.3.2d *28 Days Compressive Strength vs Cement Content.*

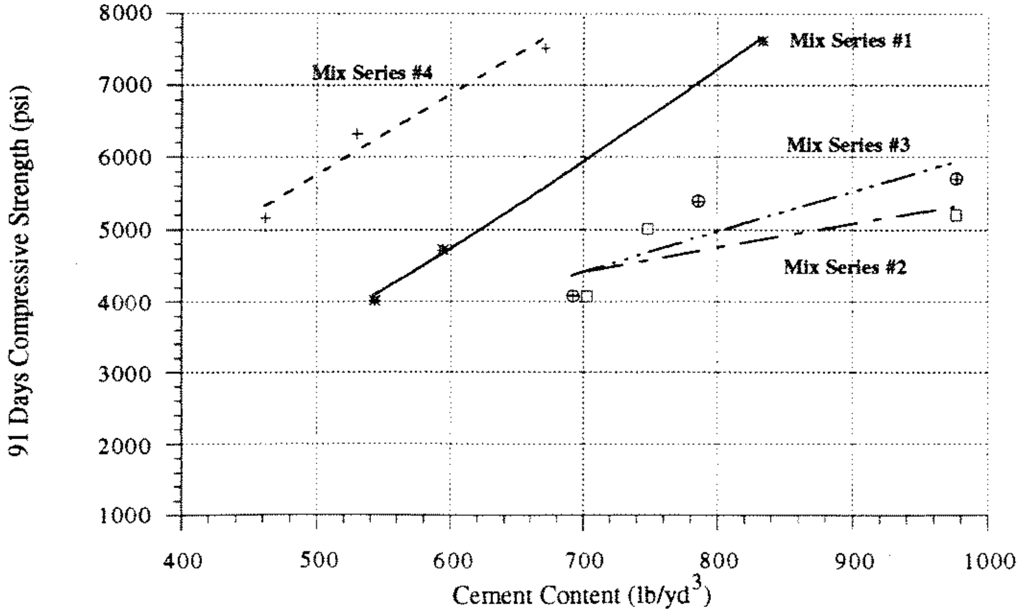


Figure 4.3.2e *91 Days Compressive Strength vs Cement Content.*

compared to its 28 and 91 days compressive strength rate. The behavior observed for mix series #4 may be caused by the slower reaction rate of some of the pozzolanic admixtures (silica fume and fly ash) present in the LWA composite. On the other hand, the rapid rate of increase for mix series #3 when compared to mix series #2 suggests that a rapid reaction of the diatomite may be occurring.

Figure 4.3.2f through Figure 4.3.2j presents the relationship between the cement contents and the splitting tensile strength for different curing times. As it can be seen from figure 4.3.2f through 4.3.2j, mix series #4 has a lower cement requirement to achieve the same required splitting tensile strength than the other three studied mixtures. However, it can be observed that mix series #2 and #3 show a rapid increase in the splitting tensile strength between 1 and 7 days, and a very low rate of increase between 7 and 91 days. While mix series #4 exhibits a moderate rate of increase in its splitting tensile strength between 1 and 7 days, and a more rapid rate of increase between 7 and 91 days. It is important to point out the consistency of the results for mix series #2, #3, and #4; between the behavior for the splitting tensile strength and the compressive strength.

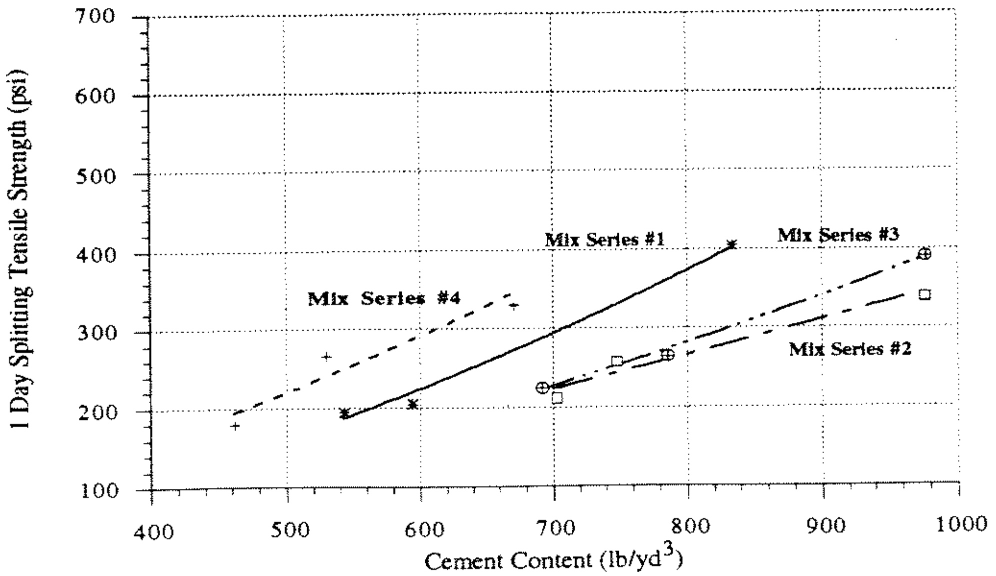


Figure 4.3.2f *1 Day Splitting Tensile Strength Vs Cement Content.*

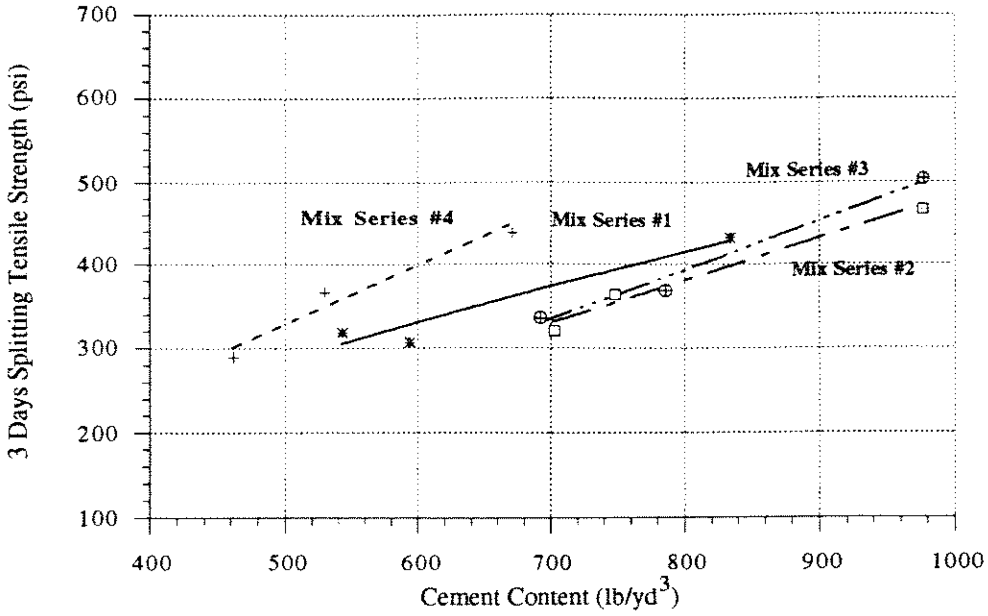


Figure 4.3.2g   *3 Days Splitting Tensile Strength Vs Cement Content.*

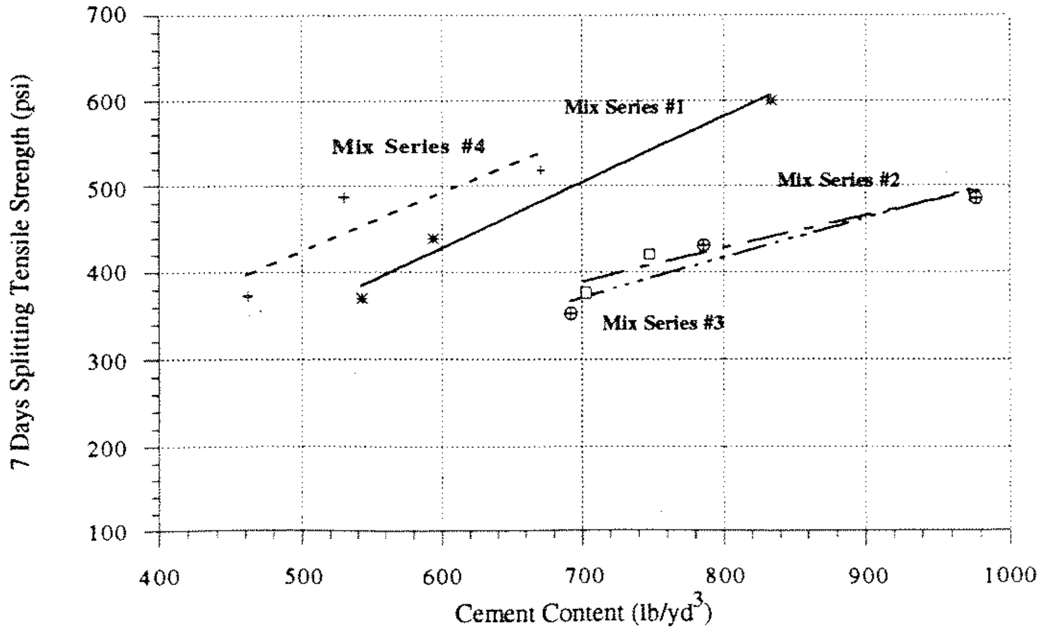


Figure 4.3.2h   *7 Days Splitting Tensile Strength Vs Cement Content.*

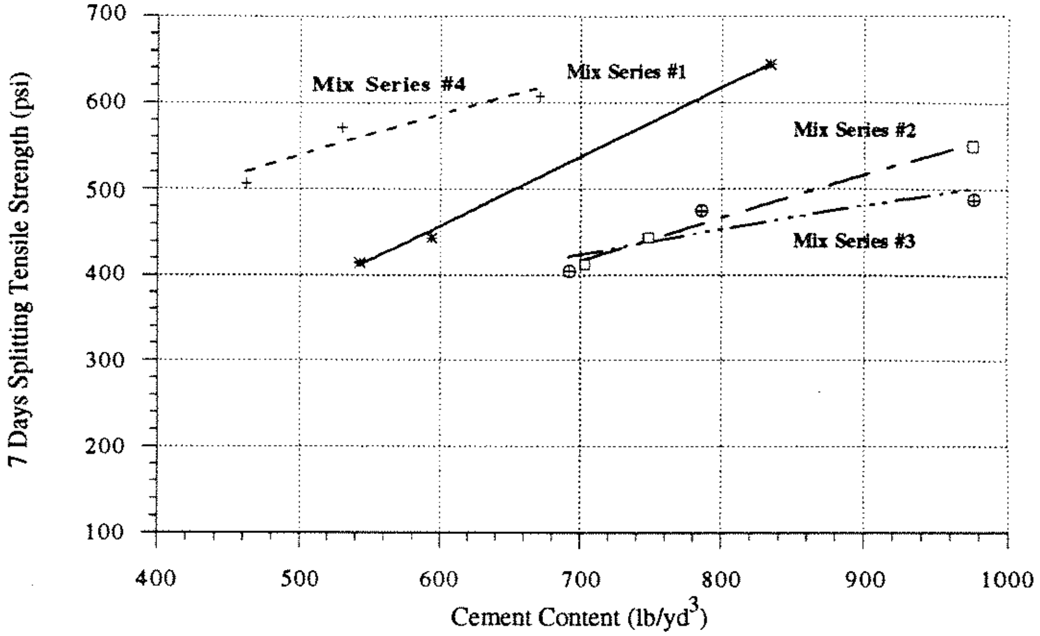


Figure 4.3.2i *28 Days Splitting Tensile Strength Vs Cement Content.*

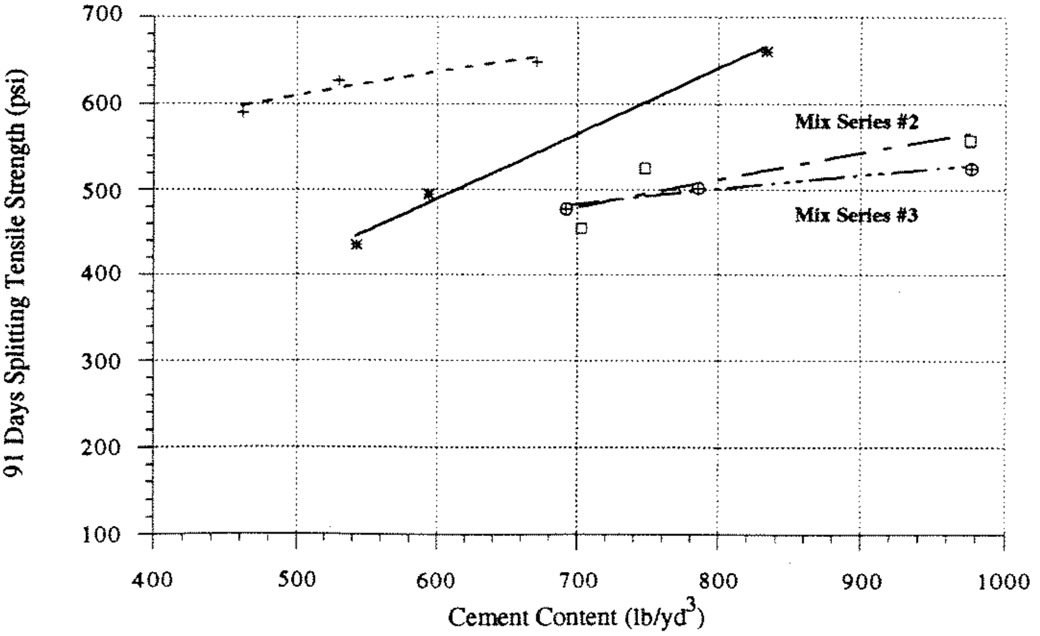


Figure 4.3.2j *91 Days Splitting Tensile Strength Vs Cement Content.*

Another characteristic which should be noted is the ultimate level of strength achieved by each of the mix series. It can be seen that at 91 days, mix series #4 exhibited a good splitting tensile strength (between 600 and 650 psi) and shows very small variations between mixtures with different cement contents. The same type of behavior can be observed for mix series #2 and #3. However, the level of splitting tensile strength (between 475 and 550 psi) for each of these two mixes is lower than that of mix series #4. Finally, Figures 4.3.2k and 4.3.2l show the relationship between the cement content and the chloride permeability for the four mix series. It can be seen that there is a large difference in chloride permeability between mix series #4 and the other three mix series. Also, there is a big improvement in impermeability between 28 and 91 days in the case of mix series #2 and #3.

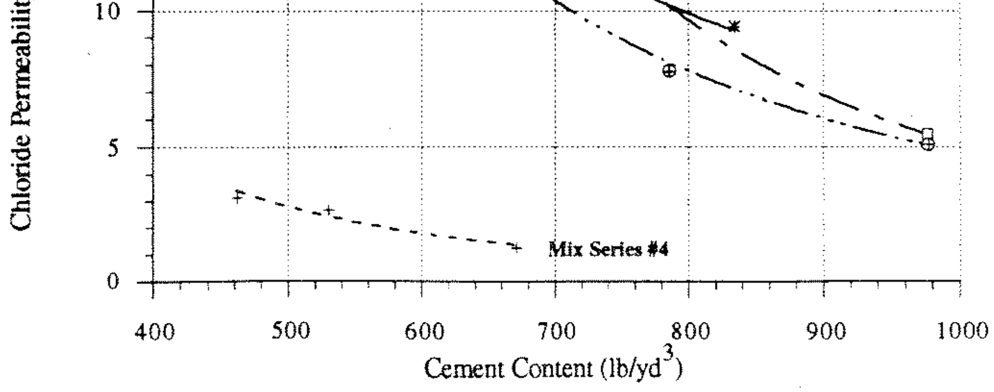


Figure 4.3.2k *28 Days Chloride Permeability vs. Cement Content.*

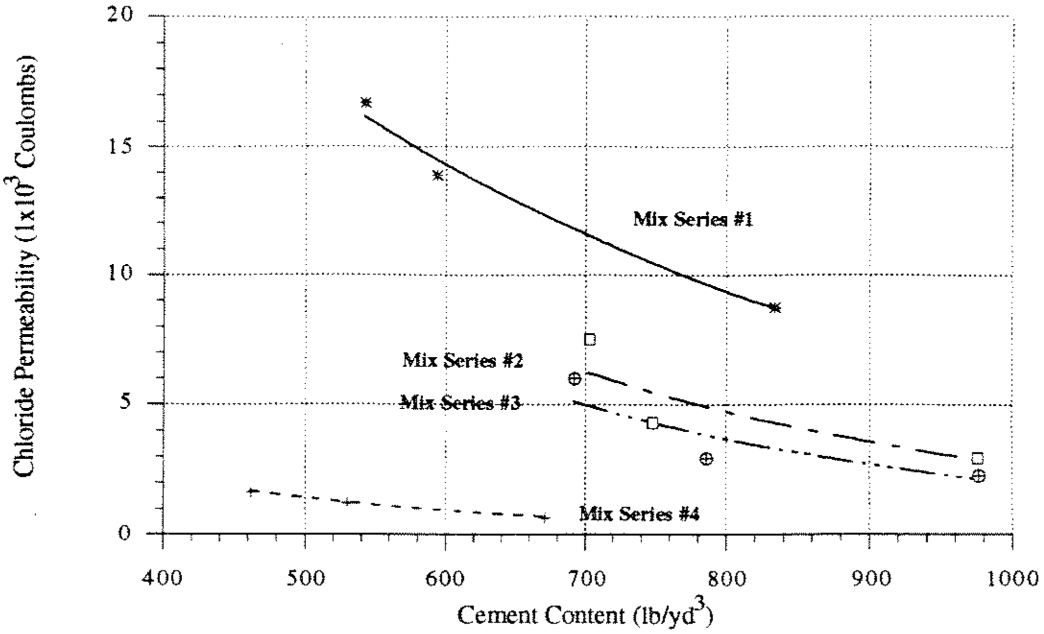


Figure 4.3.2l *91 Days Chloride Permeability vs. Cement Content.*

4.3.3 Strength Comparison

The previous section presented a comparison between various properties for the four mix series studied, while the cement content was the independent variable. In this section the same performance criteria will be selected, but the independent variable will be the water-to-cement ratio. Therefore, given a w/c ratio, the cement content for each mix series will be different to obtain a constant consistency of 0-1".

Figures 4.3.3a through 4.3.3e, show a comparison of the compressive strength versus the w/c ratio. It can be observed that the compressive strength for any given age of mix series #4 is greater than those of the other mix series.

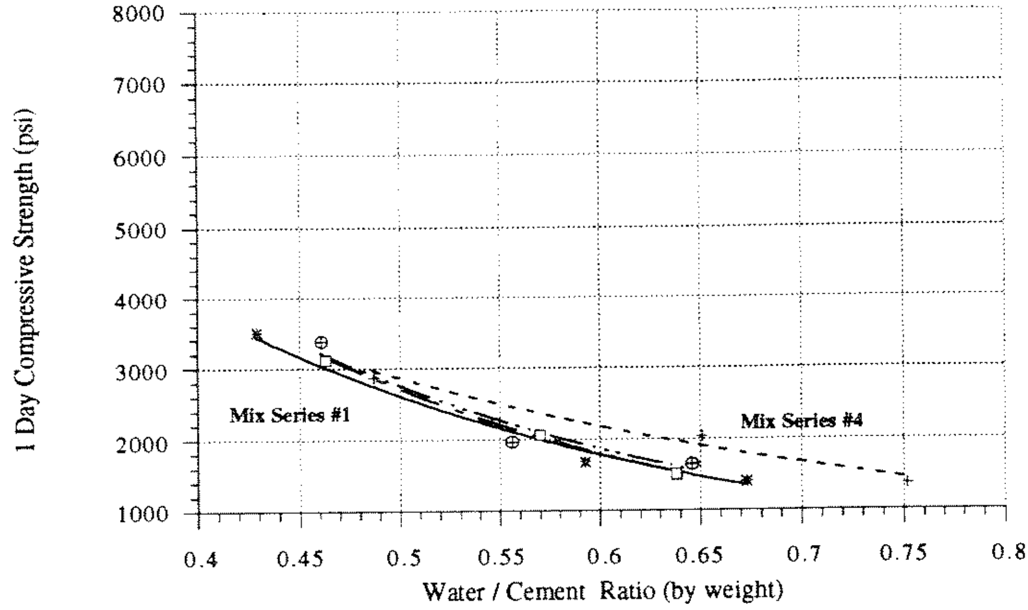


Figure 4.3.3a *1 Day Compressive Strength vs. Water-Cement ratio.*

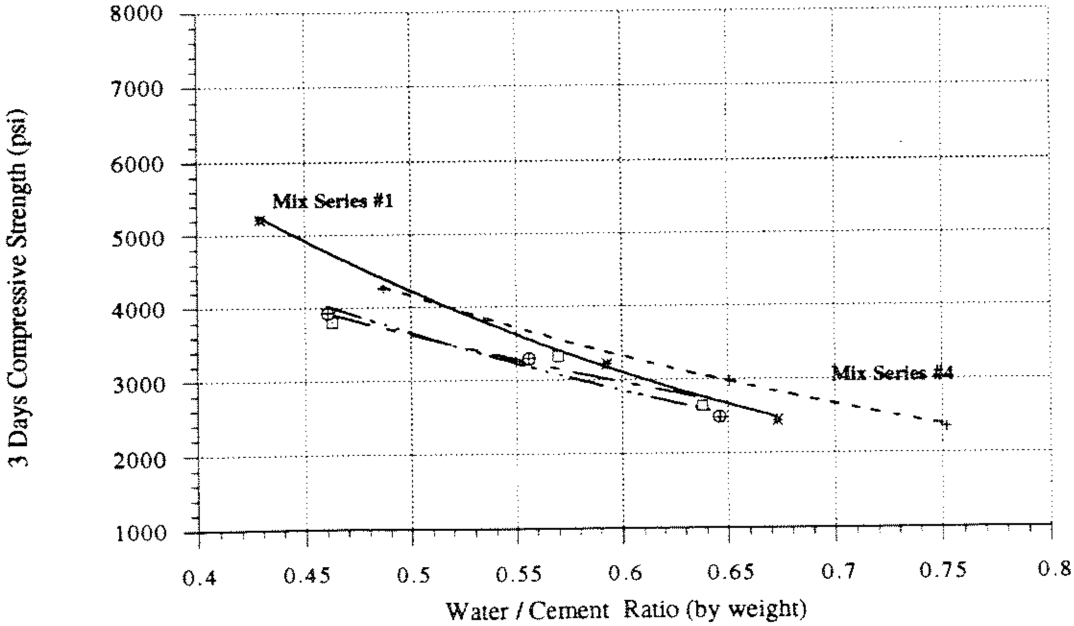


Figure 4.3.3b *3 Days Compressive Strength vs. Water-Cement ratio.*

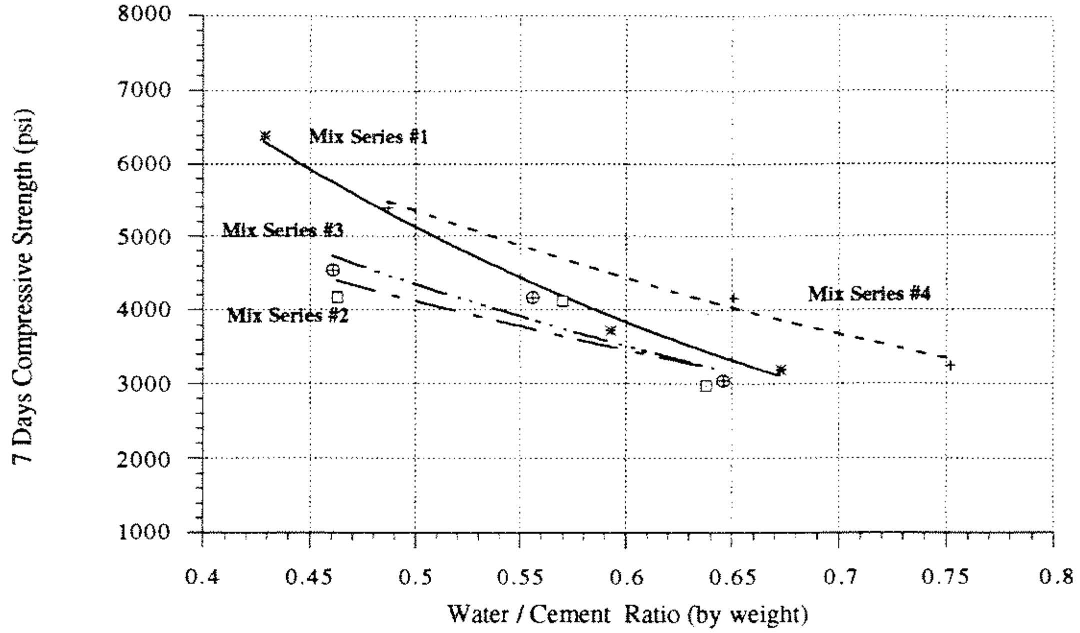


Figure 4.3.3c 7 Days Compressive Strength vs. Water-Cement ratio.

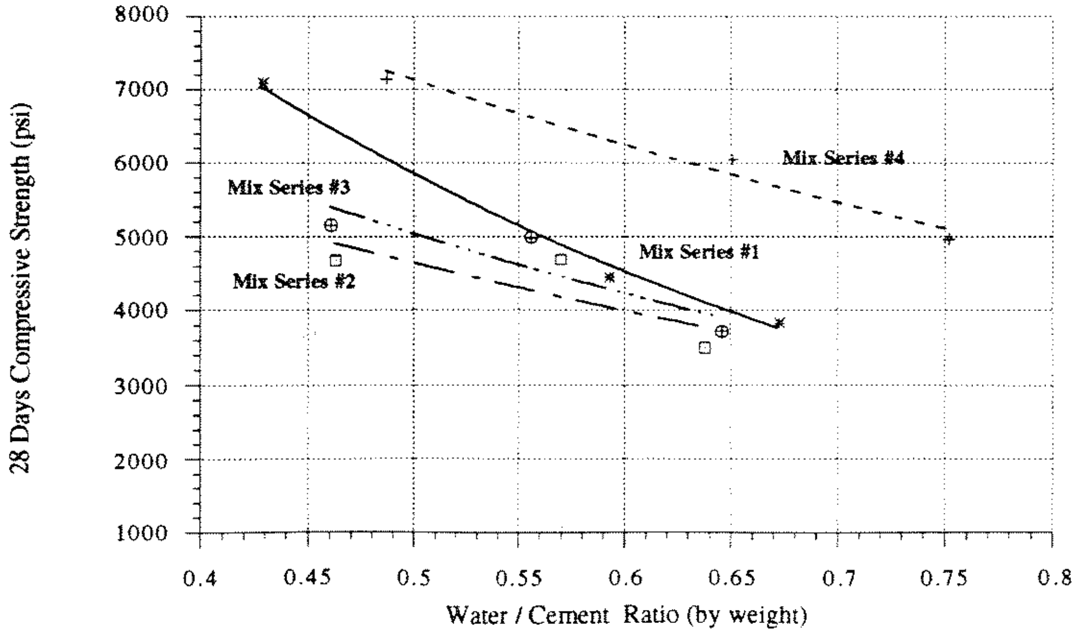


Figure 4.3.3d 28 Days Compressive Strength vs. Water-Cement ratio.

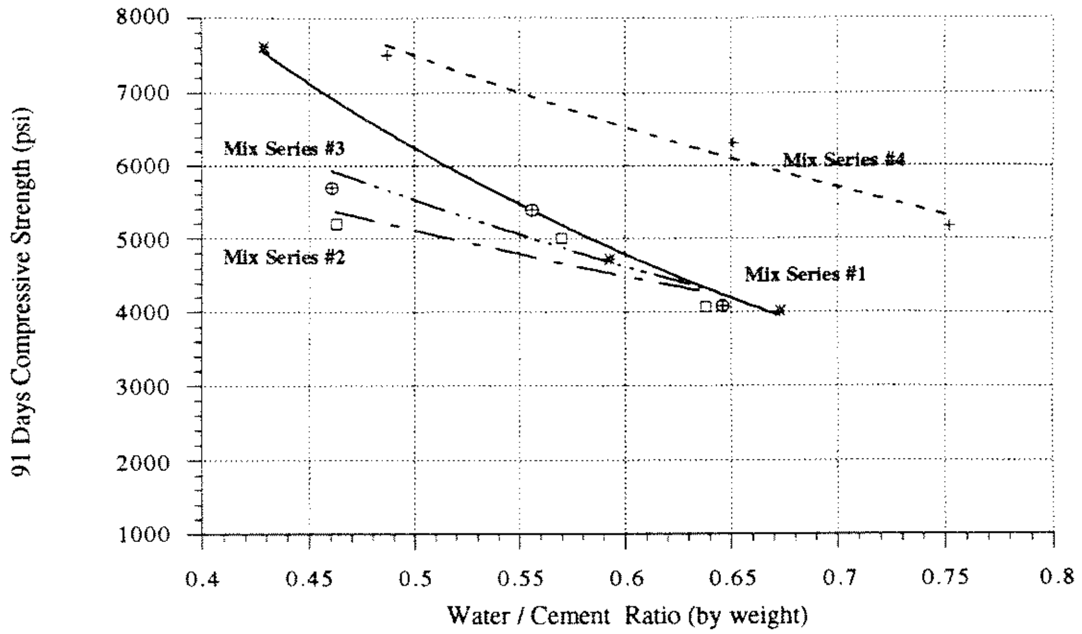


Figure 4.3.3e *91 Days Compressive Strength vs. Water-Cement ratio.*

Also, when comparing the behavior of mix series #2 and #3 with the behavior of mix series #1 it can be seen that for the same w/c ratio, after 1 day, mix series #1 has a higher compressive strength than mix series #2 and #3. Therefore, the uncoated fine LWA alone does not increase the compressive strength of the mortar. It should be noted that the compressive strength behavior curves for mix series #4 are almost parallel to those corresponding to mix series #2 and #3. This characteristic is consistent with the observations presented above for mix series #2 and #3. This indicates that the higher compressive strength observed in mix series #4 may be a consequence of the improvement in the quality of the cement paste because of the pozzolanic admixtures present in the LWA composite used in mix series #4.

Figures 4.3.3f through 4.3.3j show a comparison of the splitting tensile strength versus the w/c ratio. Mix series #4 shows a higher splitting tensile strength than mix series

#1 for all combinations of age and w/c ratios. Other important comparisons are between mix series #2, #3, and mix series #1. Mix series #2 and #3 not only have a larger rate of splitting tensile strength increase than mix series #1 up to 3 days of age, but also have higher strengths for the same w/c ratio than mix series #1. After 3 days, the rate of the strength increase for mix series #2 and #3 is low and the splitting tensile strength is lower than for mix series #1. Similar to the behavior observed for the compressive strength, the splitting tensile strength curves for mix series #2 and #3 are almost parallel to those corresponding to mix series #4.

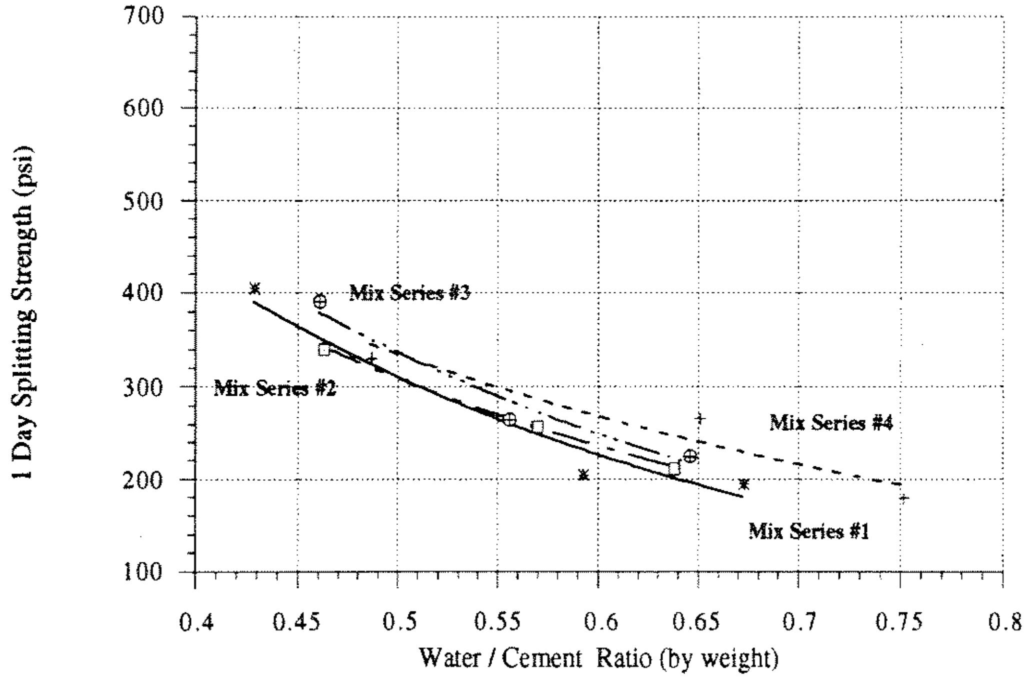


Figure 4.3.3f *1 Day Splitting Tensile Strength vs. Water-Cement ratio.*

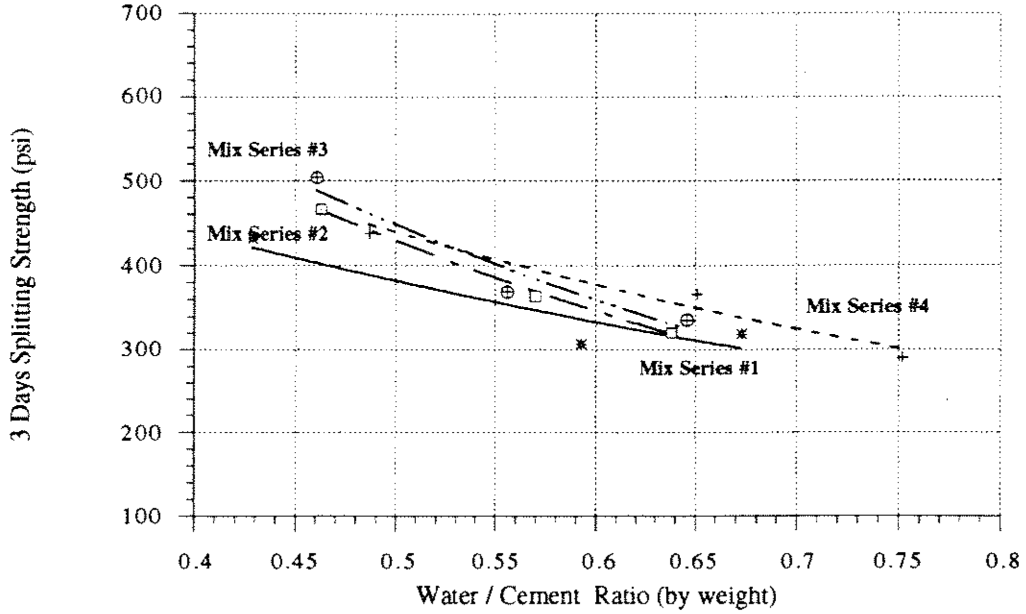


Figure 4.3.3g *3 Days Splitting Tensile Strength vs. Water-Cement ratio.*

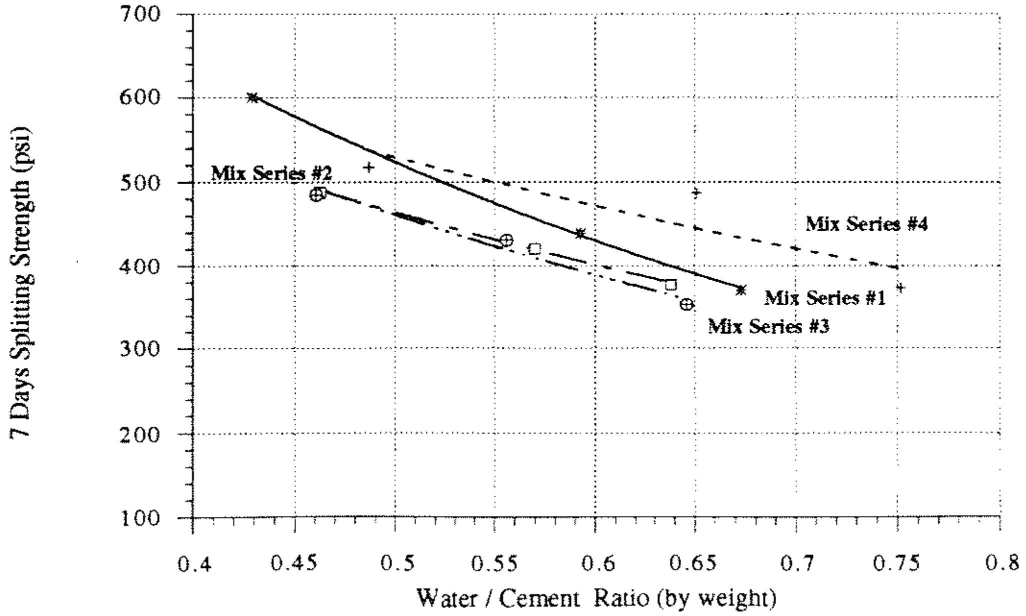


Figure 4.3.3h *7 Days Splitting Tensile Strength vs. Water-Cement ratio.*

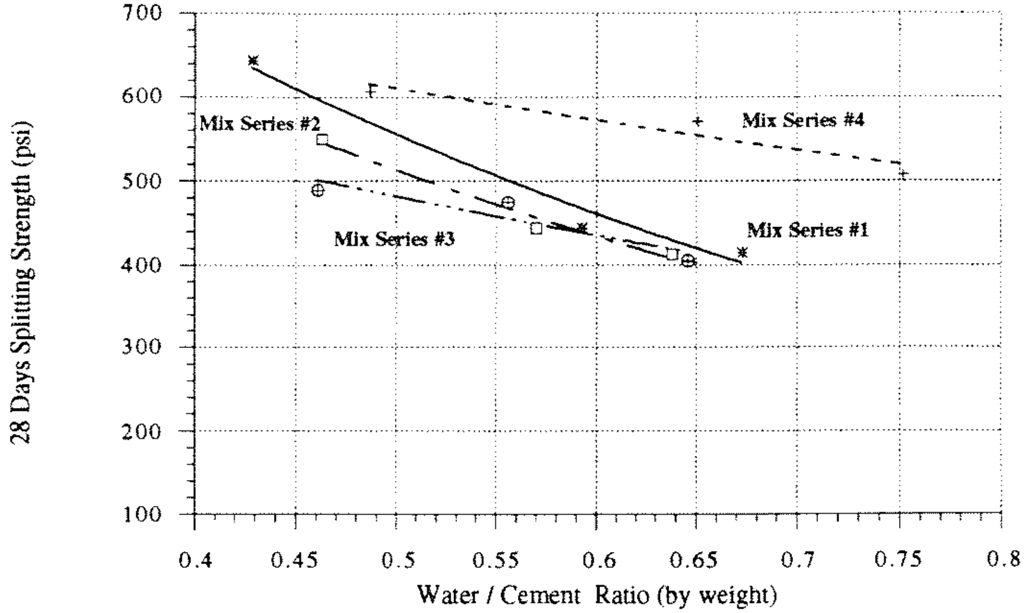


Figure 4.3.3i *28 Days Splitting Tensile Strength Vs. Water-Cement ratio.*

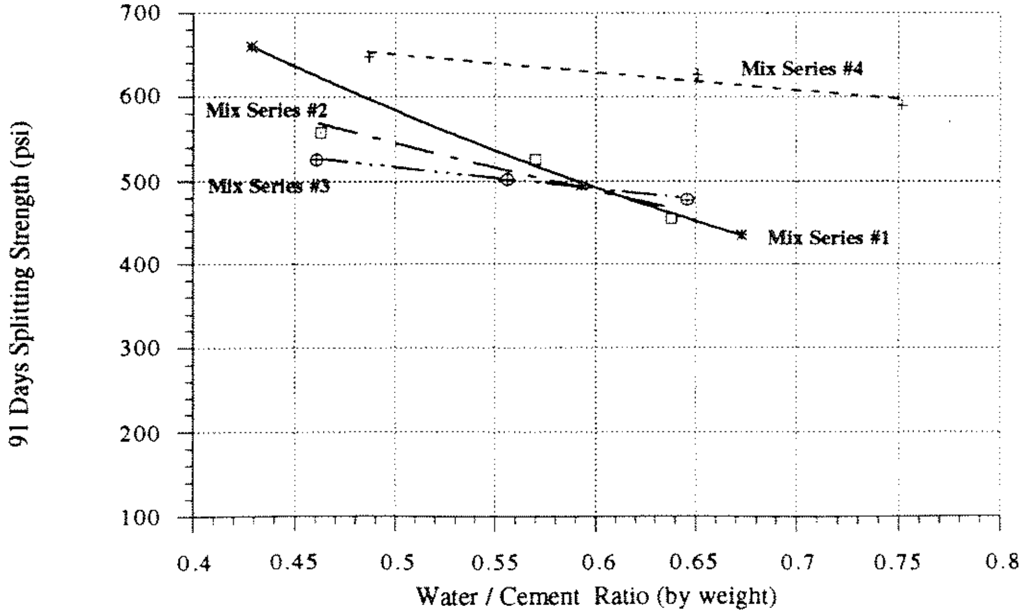


Figure 4.3.3j *91 Days Splitting Tensile Strength Vs. Water-Cement ratio.*

4.3.4- Durability

Durability is usually defined as the ability of the material to resist weathering action from the environment. The ability of a mortar or concrete to resist this weathering action depends mainly on two characteristics: permeability and volumetric stability of the mixture. Since this phase of the research did not include the study of the volumetric stability, chloride permeability will be presented as an indicator of the durability. However, it should be pointed out that this is only a partial measure, and until the study on volumetric stability is completed, a complete characterization can not be determined.

Figure 4.3.4a and 4.3.4b compares the four mix series for the chloride permeability versus the w/c ratio. Mix series #4 presents a much better behavior than the other three mix series, showing low chloride permeability values.

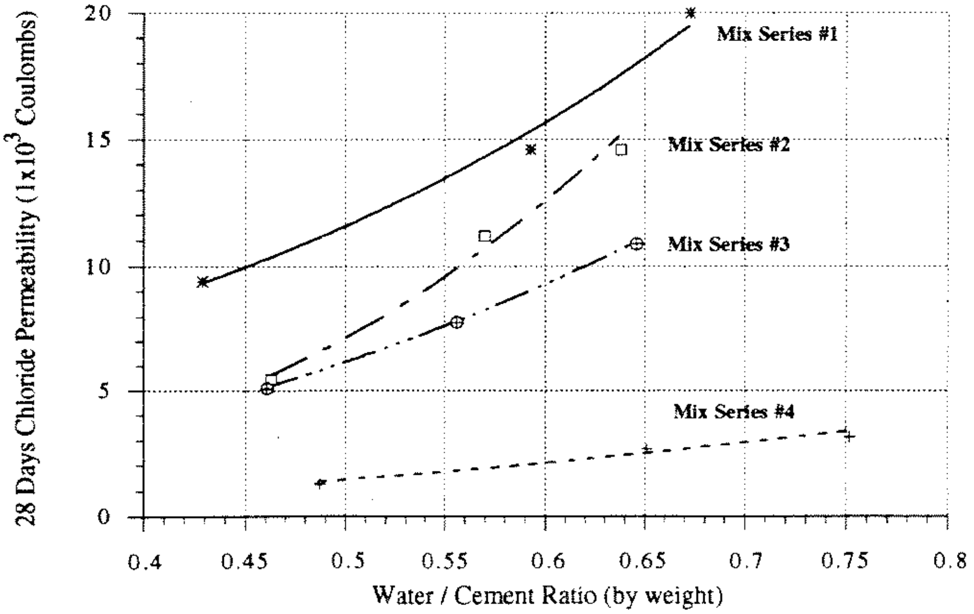


Figure 4.3.4a *28 Days Chloride Permeability vs. Water -Cement ratio.*

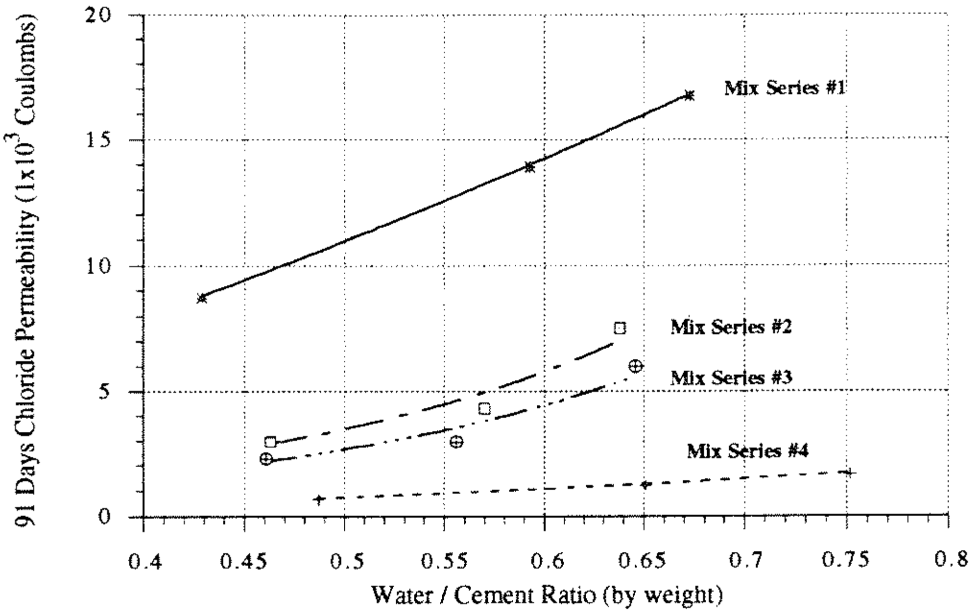


Figure 4.3.4b *91 Days Chloride Permeability vs. Water -Cement ratio.*

It is also important to point out the beneficial influence the fine LWA has on the chloride permeability of mix series #2, and #3. There is a large improvement in the permeability values of both mix series between 28 and 91 days. These values show a reduction of almost 50% of the 28-days permeability. Therefore, it can be said that the LWA composite and the fine LWA are beneficial for the durability of the mortar. This is probably a result of improving the quality of the cement paste-aggregate interface.

4.3.5- Deformability

Figure 4.3.5a. shows a comparison of the elastic modulus versus the 28 day compressive strengths for each of the four mix series. When comparing mixtures having the same 28-day compressive strength, mix series #1 shows a larger elastic modulus than any of the other three mix series studied.

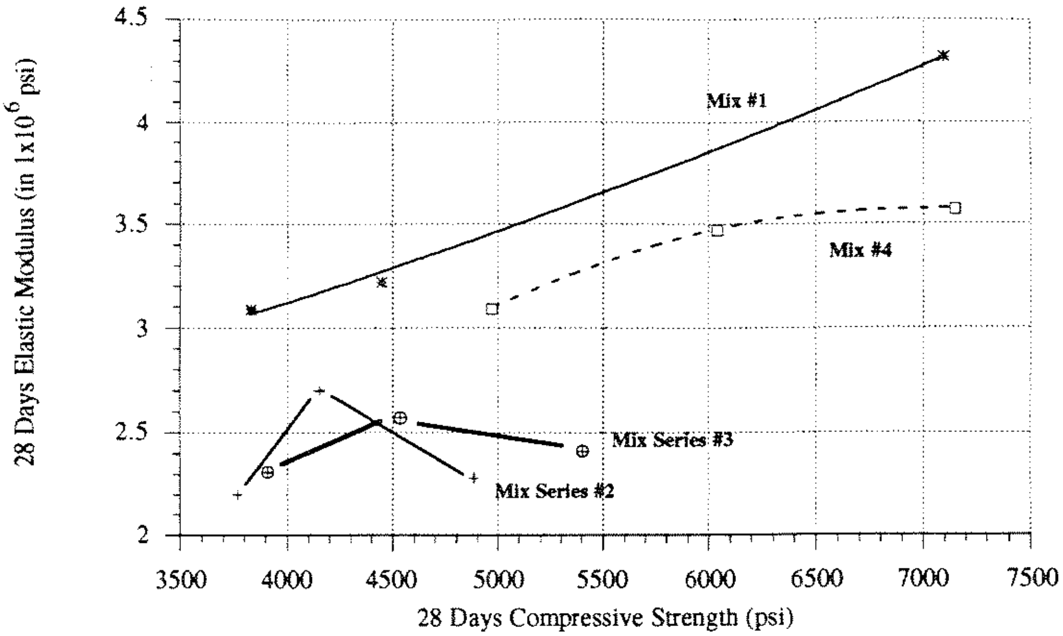


Figure 4.3.5a *Elastic Modulus vs. 28 Days Compressive Strength.*

It is also important to note that other differences in the behavior of mix series #2, #3, and #4 than those observed for mix series #1. While mix series #1 shows a continuous rate of increase in the elastic modulus with the increase in compressive strength, mix series #4 shows the same behavior only up to a compressive strength value of 6000 psi. After 6000 psi is exceeded, the rate of increase for the elastic modulus decreases (figure 4.3.5a). The behavior observed for mix series #4 is consistent with the behavior observed for mix series #2 and #3. From Figure 4.3.5a, mix #2 and #3 show a continuous crescent curve for the elastic modulus up to a certain value of compressive strength. After this point is surpassed the behavior changes, and the elastic modulus decreases. Hence, in the case of mix series #2 and #3, the same value for the elastic modulus can be achieved with two different mixtures. Note that the mixture corresponding to the point of higher elastic modulus for mix series #2 and #3 has the characteristic of having an approximate concentration of uncoated LWA of about 17-19% by volume. After this concentration of LWA is exceeded, the elastic modulus decreases (figure 5.3.5b). This can be explained by the fine LWA having a lower elastic modulus than the natural sands used in the mixtures and by the large cement contents required by the mixtures containing more than 17% fine LWA.

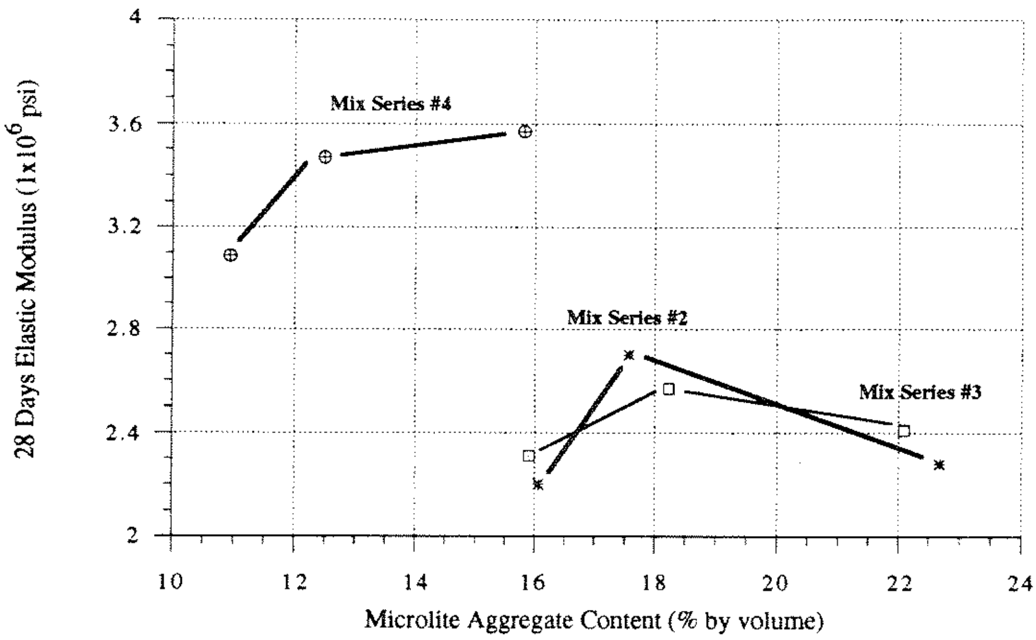


Figure 4.3.5b *Elastic Modulus vs. LWA Content (% by volume).*

Another important factor that should be considered when evaluating the deformability of a mortar or concrete mixture is its capacity of energy absorption. This capacity to absorb energy can be determined from the stress-strain curves obtained. Figure 4.3.5c shows the relationship between the energy absorbed up to a value of strain corresponding to maximum stress and the maximum stress achieved. There is no appreciable difference between the energy absorption behavior among the four studied mix series. Hence, the addition of LWA (aggregate and composite) seems to have almost no impact on the energy absorption values up to a strain corresponding to the maximum stress.

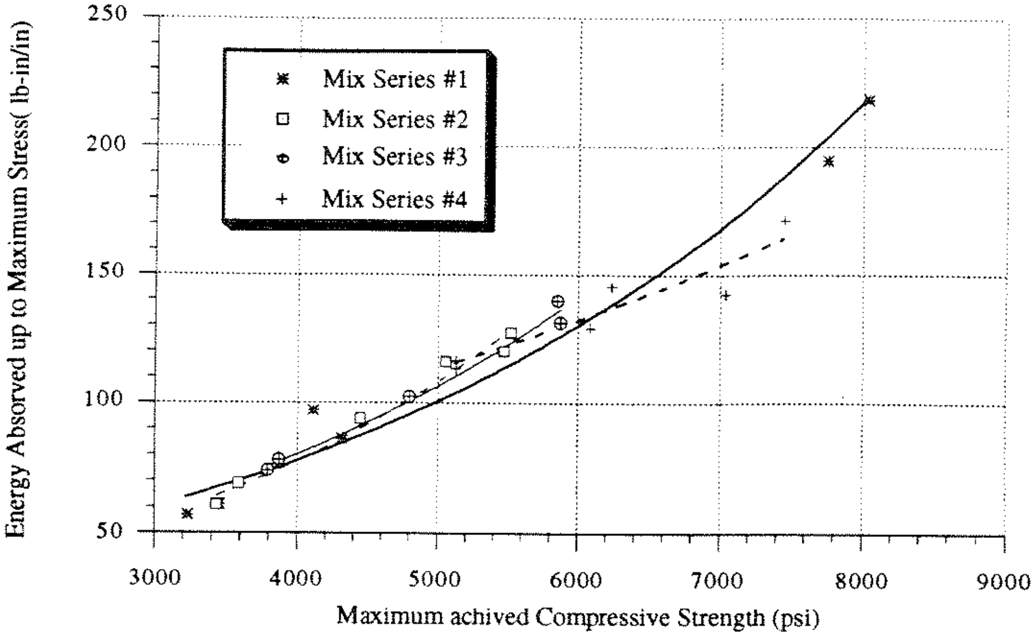


Figure 4.3.5c *Energy Absorption up to Maximum Stress vs. Maximum achieved Compressive Strength.*

By calculating the total energy absorption under the complete stress-strain curve, one can obtain a parameter to compare the plastic behavior of the different mixtures. Figure 4.3.5d shows the relationship between the total energy absorbed under the stress-strain curve and the maximum compressive strength achieved by the mix. There are some small differences between the values obtained for the mixtures containing the lightweight aggregate and composite with the values obtained for the control mix. It is important to point out that there are many factors that affect the experimental values. With this, it is difficult to assess if a difference in behavior exists or not. Even so, it can be said that in all the mix series, mixtures containing high cement contents and low w/c ratios show a more brittle behavior than in the case of low and medium cement contents. This fact can be observed from the stress-strain curves presented in section 3.

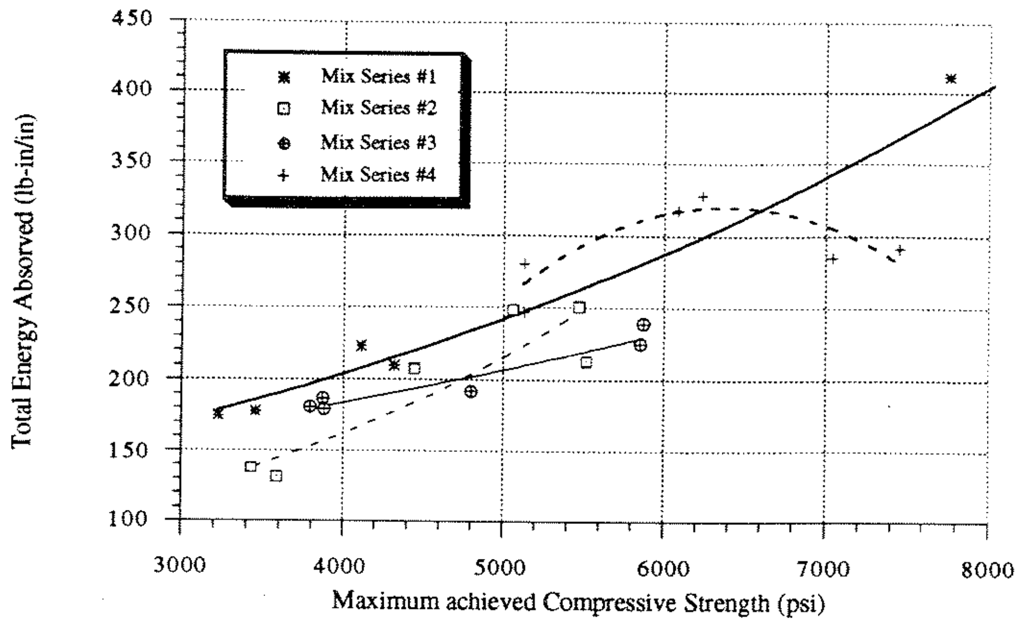


Figure 4.3.5d *Total Energy Absorbed Vs. Maximum achieved Compressive Strength.*

5.0 Microstructural Analysis

5.1- Introduction

By performing compressive strength, permeability, and modulus of elasticity tests, the engineering properties of a construction material can be determined. However, to understand the behavior of the material, it is necessary to perform a comprehensive study of its microstructure. Moreover, the microstructural study of the material provides information about how the mechanical properties can be improved.

The most important phase in mortar or concrete is the transition zone between the aggregate and the cement paste. There are many factors which affect the characteristics of the transition zone; mineral admixtures and mix proportioning having the most impact.

During this research a scanning electron microscope (SEM) was used to perform the microstructural analysis of the LWA, pure diatomite, and mortar specimens. The following sections will present a detailed description of this study.

5.2 Specimen Preparation

Two types of electron image microscopy, secondary electron image (SEI) and backscattered electron image (BEI), were used in the present research. Both images are generated utilizing the SEM. SEI is very useful to display the topography of the material and makes it possible to observe the size and shape of the crystals present in the material. On the other hand, BEI is more adequate to display the distribution and the interface between the different phases of the material.

The samples to be used in each case must be carefully prepared. For the SEI, the specimen must be crushed into smaller pieces until the desired size and shape is obtained. Following the crushing process, the selected sample is coated with gold in order to increase the conductivity. The specimens required for BEI observation must be very well polished in order to obtain a good definition of the different phases. Because of this, the sample is initially soaked in epoxy to prevent the loss of material during the cutting and polishing process. After the epoxy sets, the sample can be cut into small pieces of approximately 1" in diameter and 0.25" in thickness. These samples are then sequentially polished by using decreasing grit sizes until an adequate polishing is achieved with a 0.25 micron diamond paste. Finally, the polished specimens are coated with carbon. Table 5.2a shows a summary of the different specimens prepared to conduct the microscopic analysis.

Table 5.2a Summary of Mortar Samples Studied.

Specimen	**w/c**	**Description**
Mix 1B	0.55	Cement + Sand + Water.
Mix 2B	0.546	Cement + Sand + Water + LWA
Mix 3B	0.534	Cement + Sand + Water + LWA + Diatomite.
Mix 4B	0.607	Cement + Sand + Water + LWA Composite.

***Note:** Age of testing is 28 Days. All specimens prepared at The University of California at Berkeley.

5.3 Results from SEM Observations

5.3.1 Fine LWA Particles

Fine LWA particles were observed to determine the size, shape, surface texture, and internal cell structure. These factors have a large impact on the workability of the mix and in turn affect the transition zone between the aggregate and the cement paste. It can be observed from Photo 1 and Photo 2 that the particles are well rounded and have a smooth surface with some openings on the surface. Photo 3 is a close up of the openings on the surface of a LWA particle. The opening shows many crystals which tend to make the open areas rougher than the closed areas. These rougher areas and openings provide better mechanical bonding with the cement paste than do smooth areas. Photo 4 shows a LWA particle as having more open than closed areas on its surface. Photo 5 shows the cross section of a LWA particle. It can be seen that the internal cell structure is a honeycomb structure. This structure is responsible for the high absorption values of the material.

5.3.2 Pure Diatomite

Photo 6 shows the microstructure of a pure diatomite particle. Even though many small skeletal shells can be observed in the photo of pure unreacted diatomite, when observing 28 days mortar specimens with diatomite the skeletal structure was not evident. This may be caused by two reasons: first, the total amount of diatomite is small (2.7% of the cement content) and skeletal can not be found or the reaction of the diatomite might be faster than 28 days.

5.3.3 Mortar Specimens

The objective, when observing the mortar specimens, was to identify the distribution of the LWA particles, hydration products (especially calcium hydroxide), the characteristics of the transition zone, and the presence of voids and cracks in the mortar specimens.

Photo 7 shows the specimen from mix 2B under SEI. It can be seen that many LWA particles are broken. This is an indication that the bond strength between most of the LWA particles and the cement paste is stronger than the LWA particle. Only a few unbroken particles were found when observing mortar specimens from mix 2B and 3B (Photo 8). Photo 9 shows a specimen from mix 2B as observed under BEI. It can be seen that the LWA particles are well distributed within the mix. Photo 10 shows a large concentration of calcium hydroxide in mix 1B. Such a massive concentration of calcium hydroxide could not be found in specimens corresponding to mix 2B, 3B, and 4B. BEI observations verified large amounts of calcium hydroxide in the specimen from mix 1B (Photo 11). Photo 12 displays a large amount of small spheres in mix 4B. These spheres are probably unhydrated fly ash particles that usually have a slower rate of hydration under normal conditions. Photo 13 shows the transition zone between sand (gray), and cement paste (white), present in the specimen from mix 2B. The transition zone between the sand and cement paste can be observed as the non-continuous region (dark area) between these materials.

The transition zone between the LWA and the cement paste is shown in Photo 14. There is very little non-continuous region in the interface. Although, some non-continuous region exists, the transition zone between the LWA and the cement paste is generally smaller than that around the sand particles. There are several reasons that cause the LWA particles to achieve a better bond with the cement paste than sand:

1- The small size and the internal cell structure in the LWA particles tend to reduce the bleed water at the interface between the particles and the cement paste
2- The probable pozzolanic reaction from the LWA tends to improve the characteristics of the transition zone.

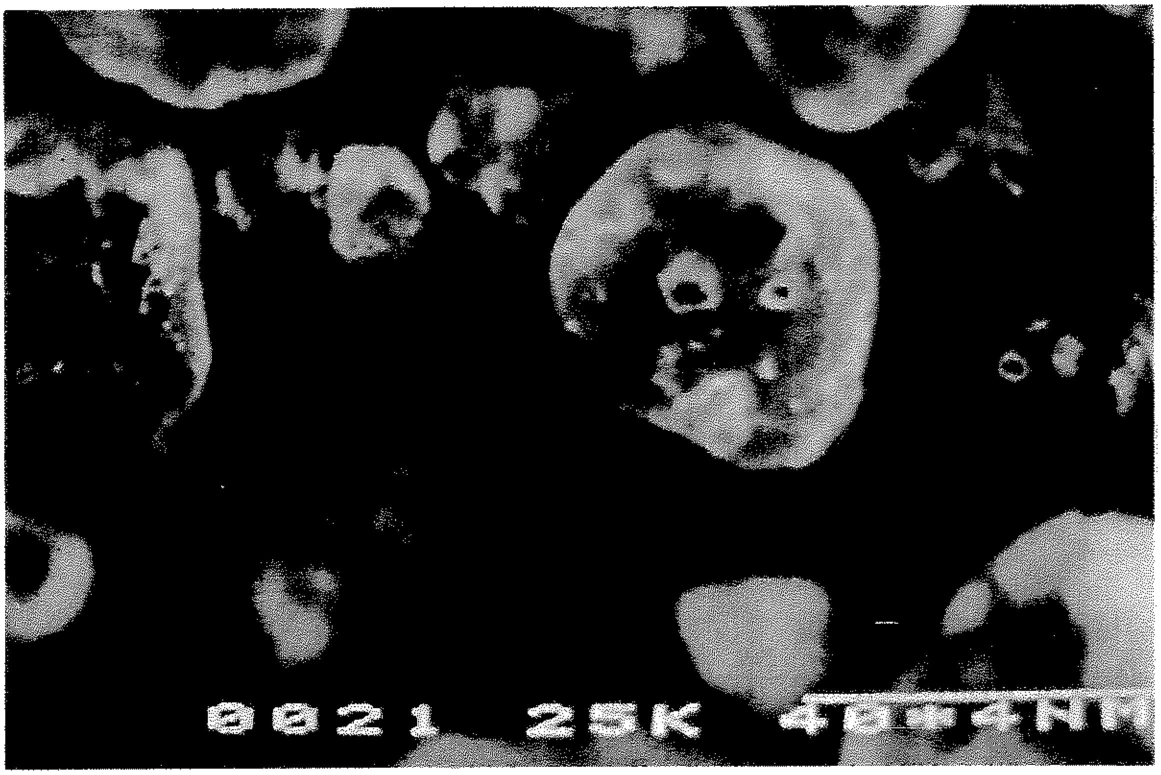


Figure 5.3.1a *Scanning Electron Image of Light Weight Aggregate Particle.*

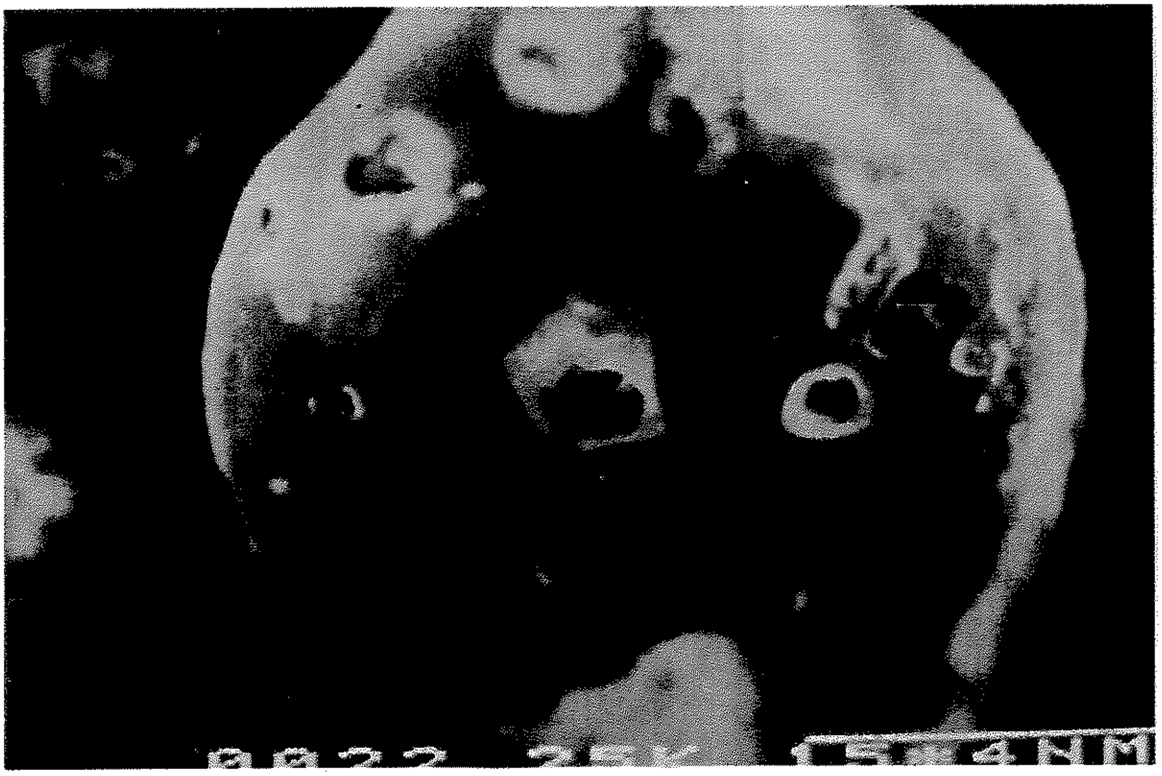


Figure 5.3.1b *Scanning Electron Image of Light Weight Aggregate Particle.*

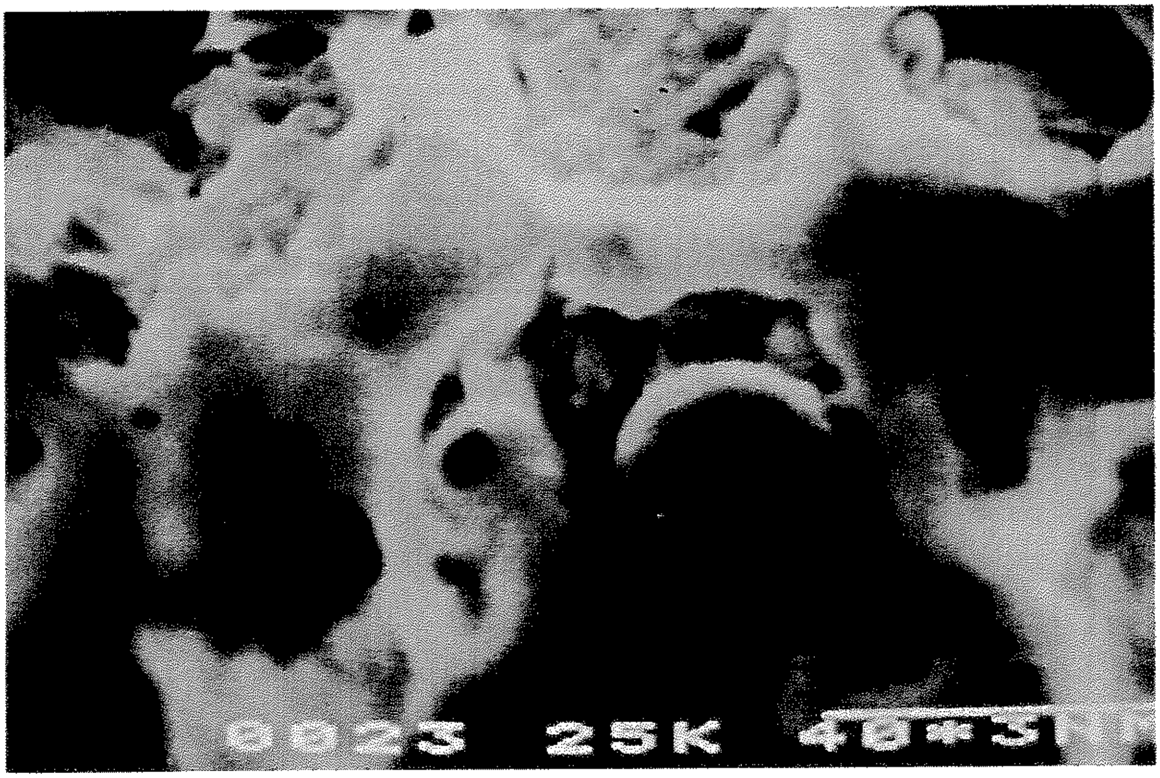


Figure 5.3.1c *S.E.I. Magnification of a Light Weight Aggregate Particle.*

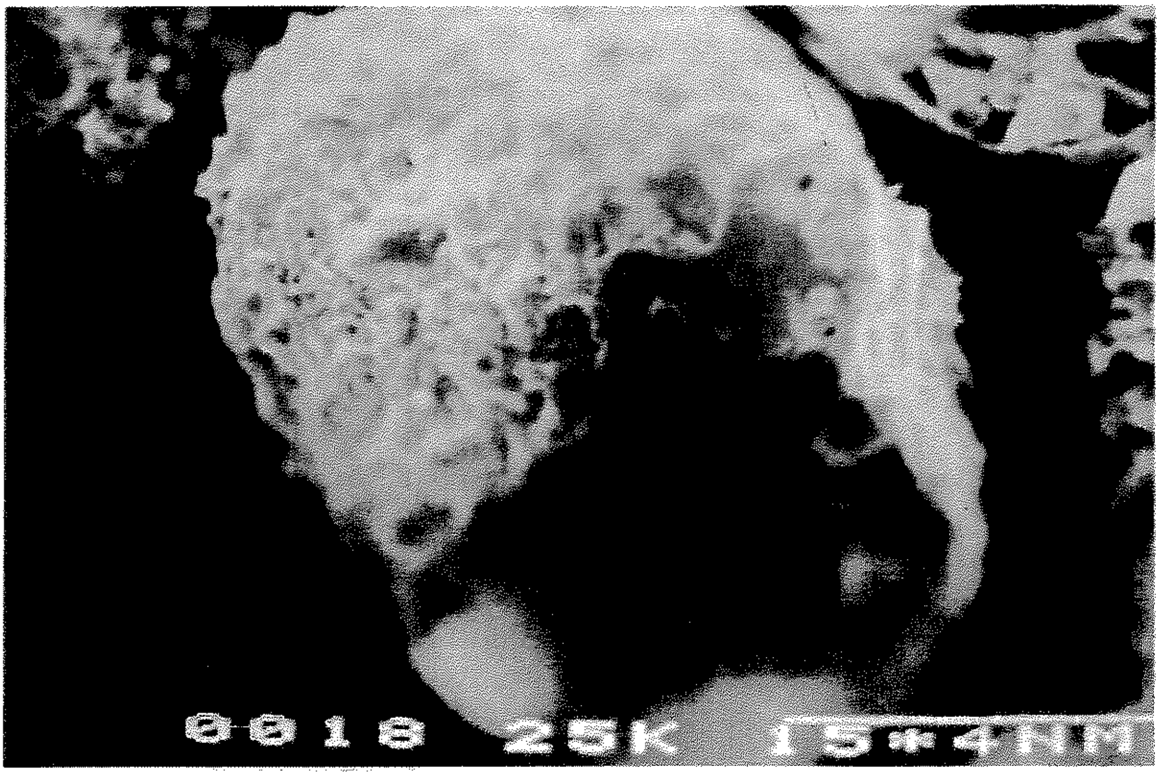


Figure 5.3.1d *S.E.I. Magnification of a Light Weight Aggregate Particle.*

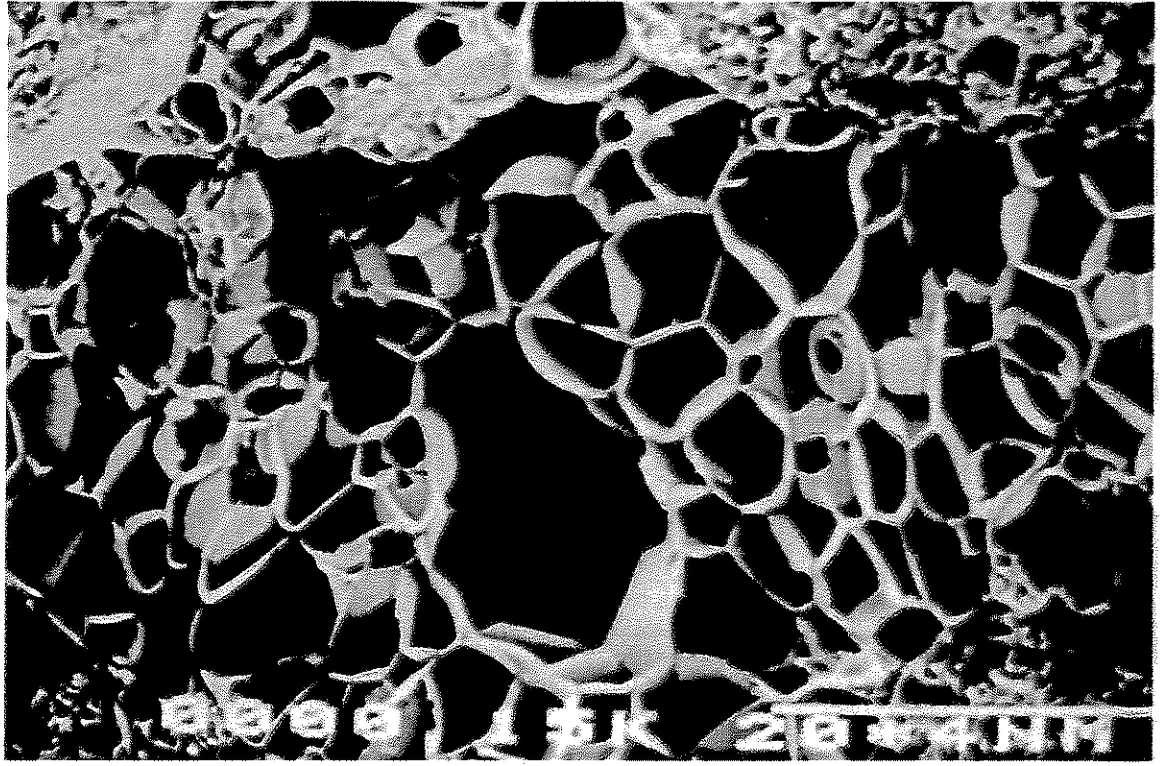


Figure 5.3.1e *B.E.I. of a Light Weight Aggregate Particle Cross Section.*

Figure 5.3.2a Microstructure of a Pure Diatomite Particle.

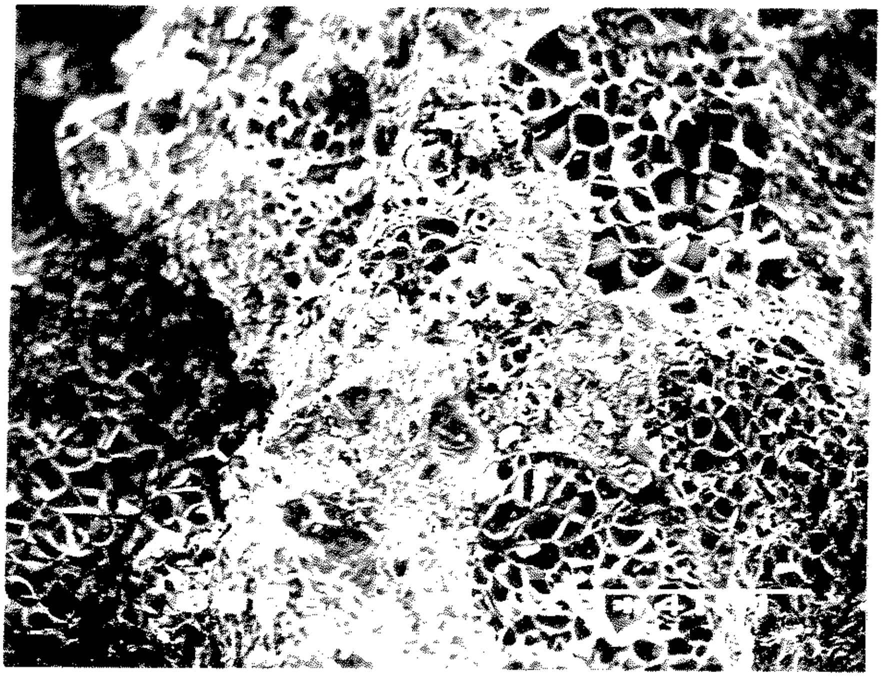


Figure 5.3.3a S.E.I. *of Specimen from Mix Series 2B.*

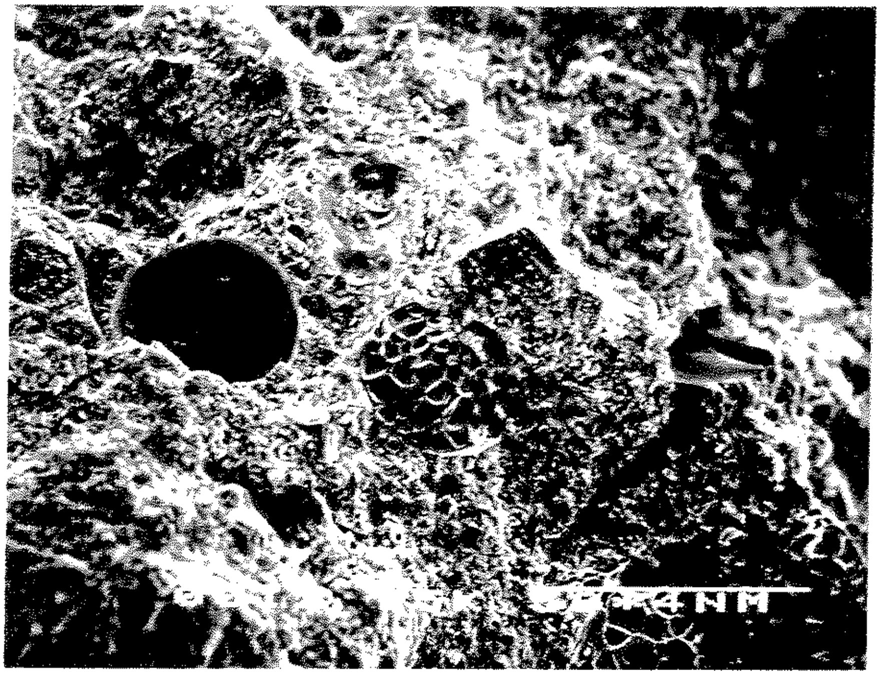


Figure 5.3.3b S.E.I. *of Specimen from Mix Series 3B.*

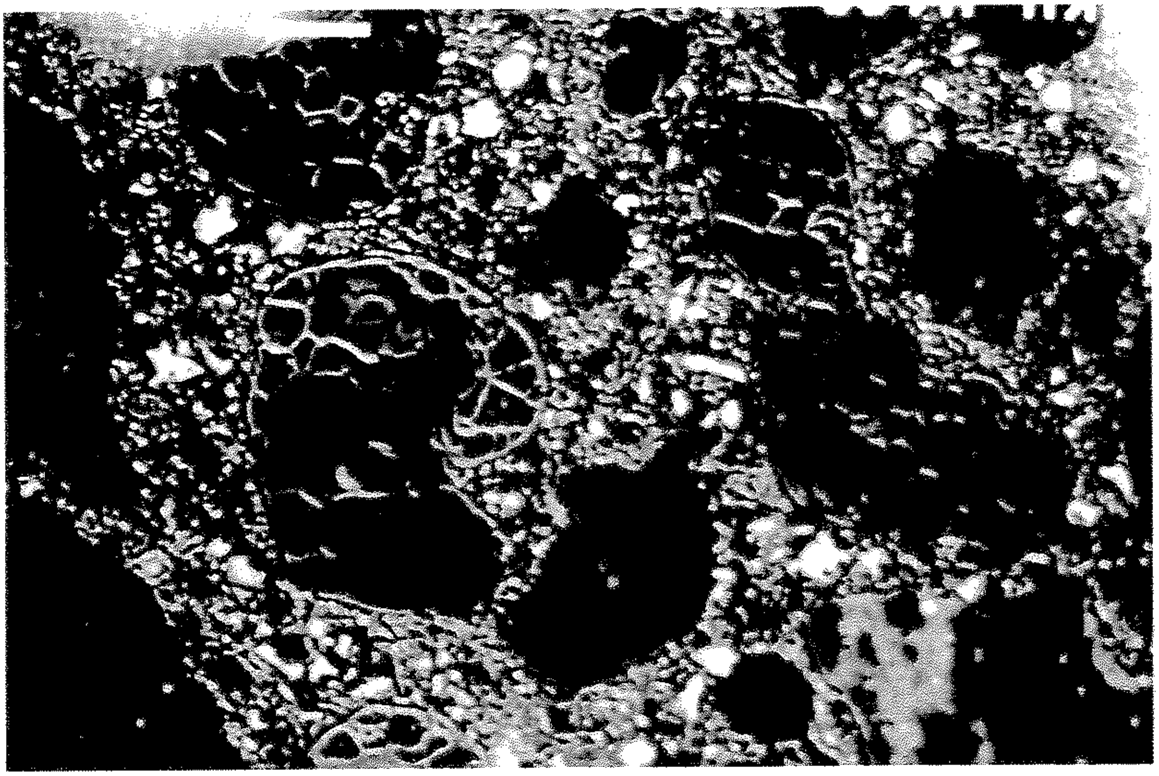
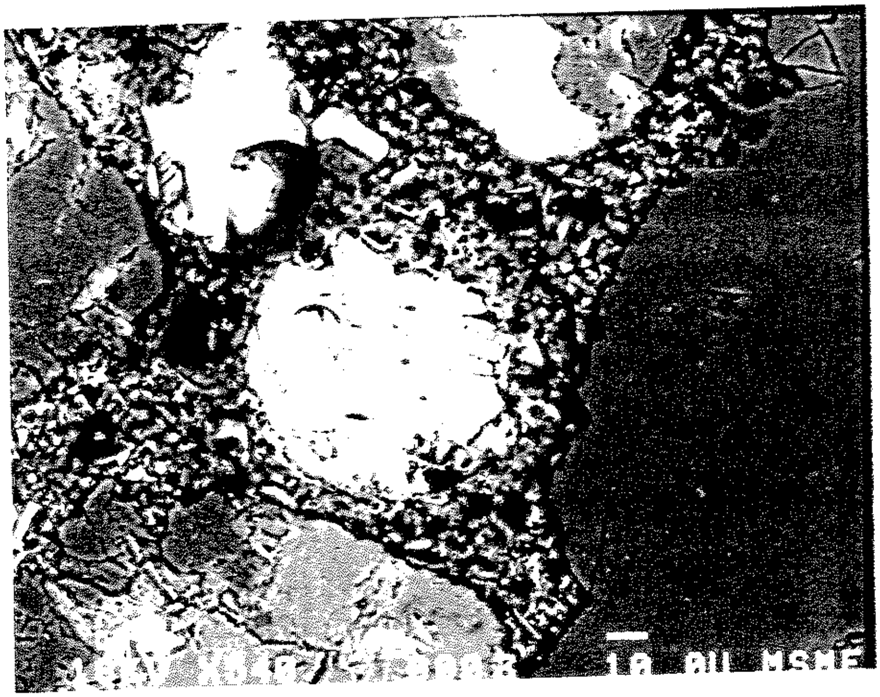


Figure 5.3.3c B.E.I. of Specimen from Mix Series 2B.

Figure 5.3.3d S.E.I. of Specimen from Mix Series 1B Showing a Large Concentration of Calcium Hydroxide.



Concentration of Calcium Hydroxide.

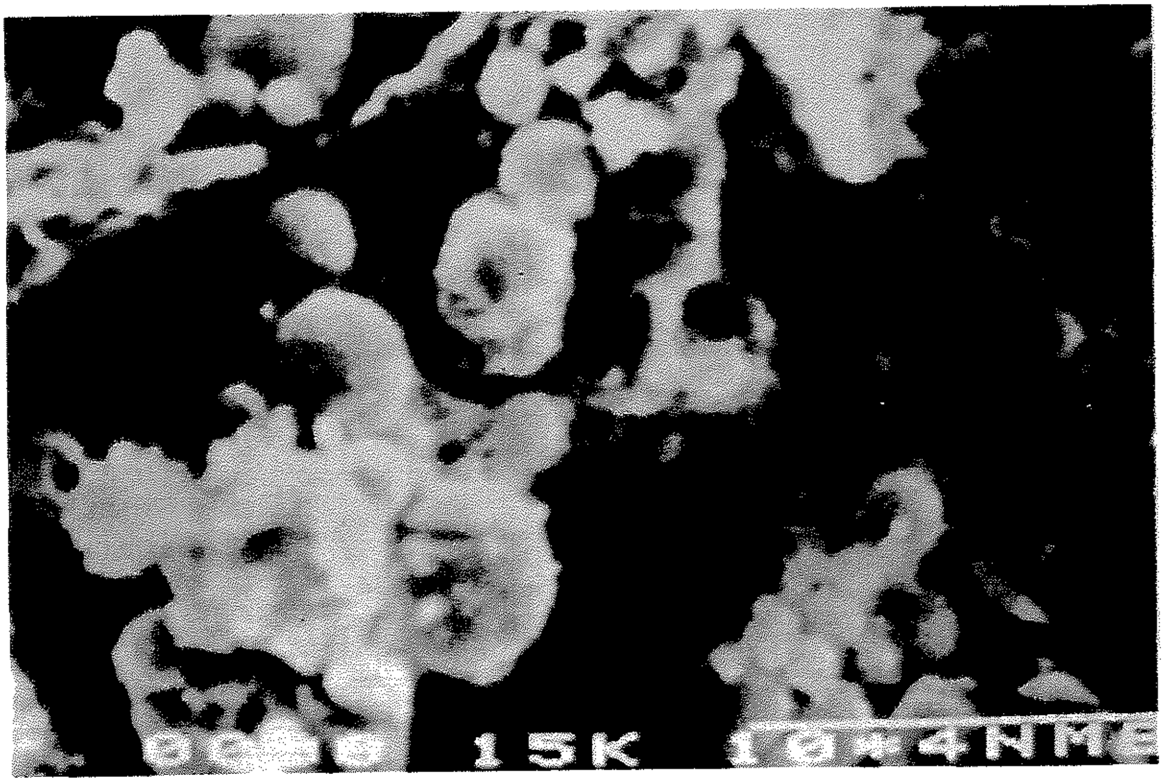


Figure 5.3.3f S.E.I. of Specimen from Mix Series 4B.

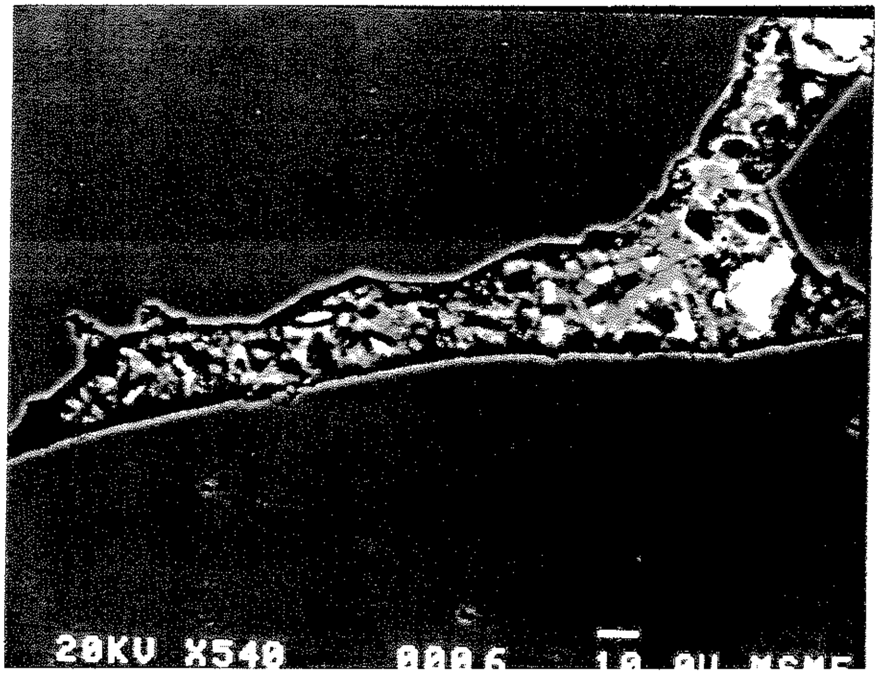


Figure 5.3.3g *B.E.I. of Specimen from Mix Series 2B Showing the Transition Zone between a Sand Particle and the Cement Paste.*

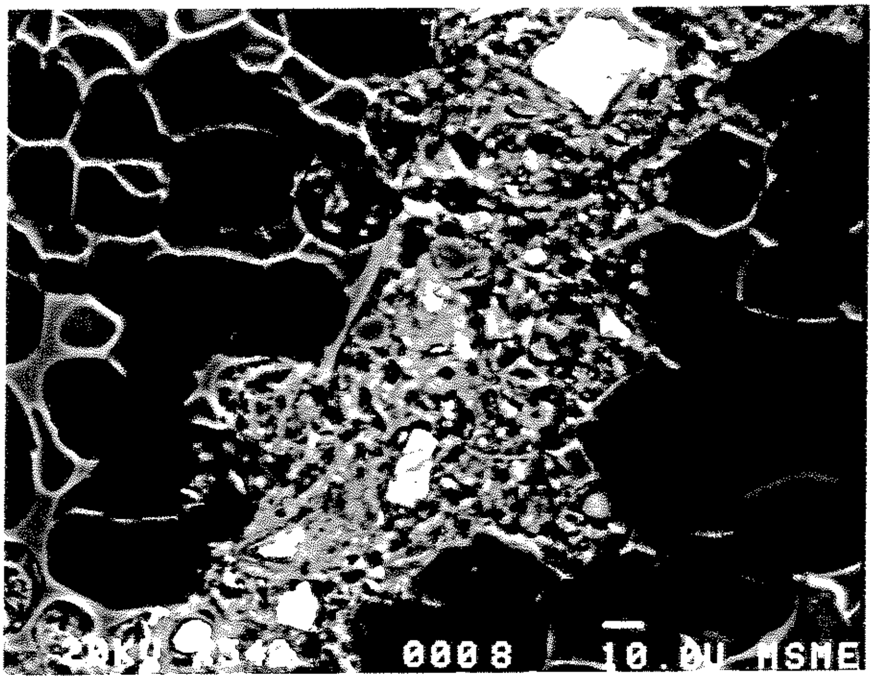


Figure 5.3.3h *B.E.I. of Specimen from Mix Series 2B Showing the Transition Zone between a Light Weight Aggregate Particle and the Cement Paste.*

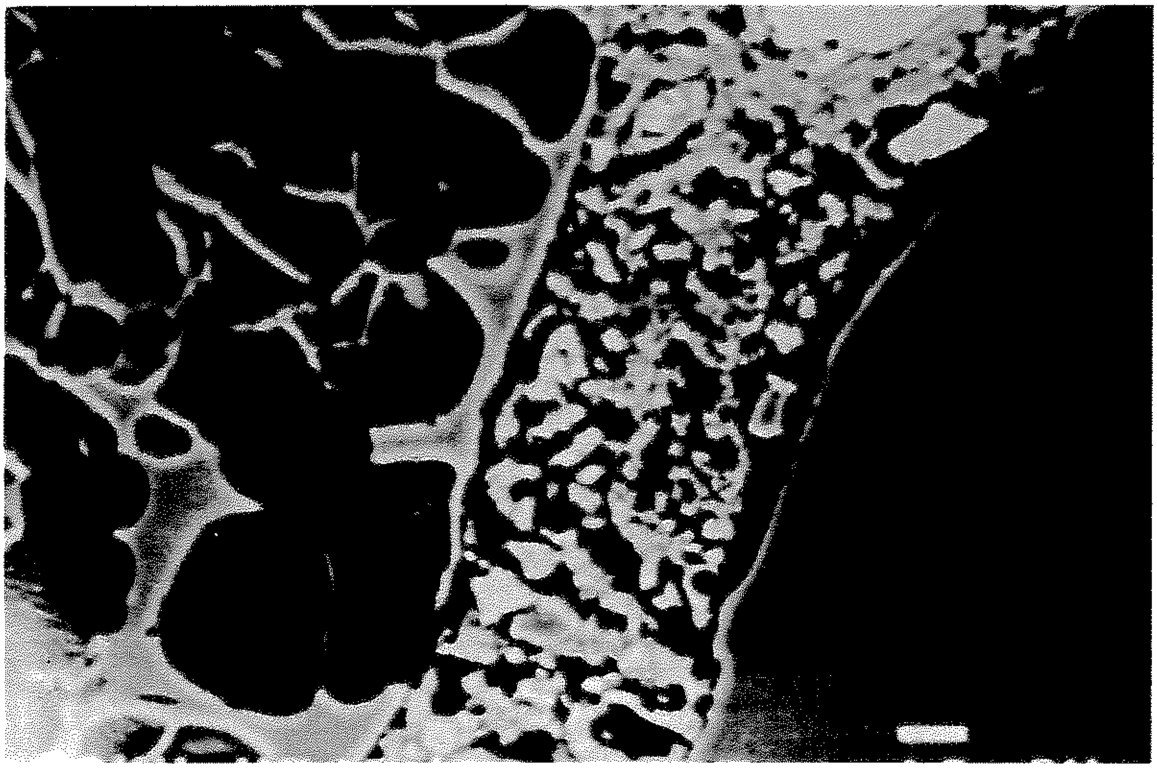


Figure 5.3.3i *B.E.I. of Specimen from Mix Series 4B Showing the Transition Zone between a Light Weight Aggregate Particle and the Cement Paste.*

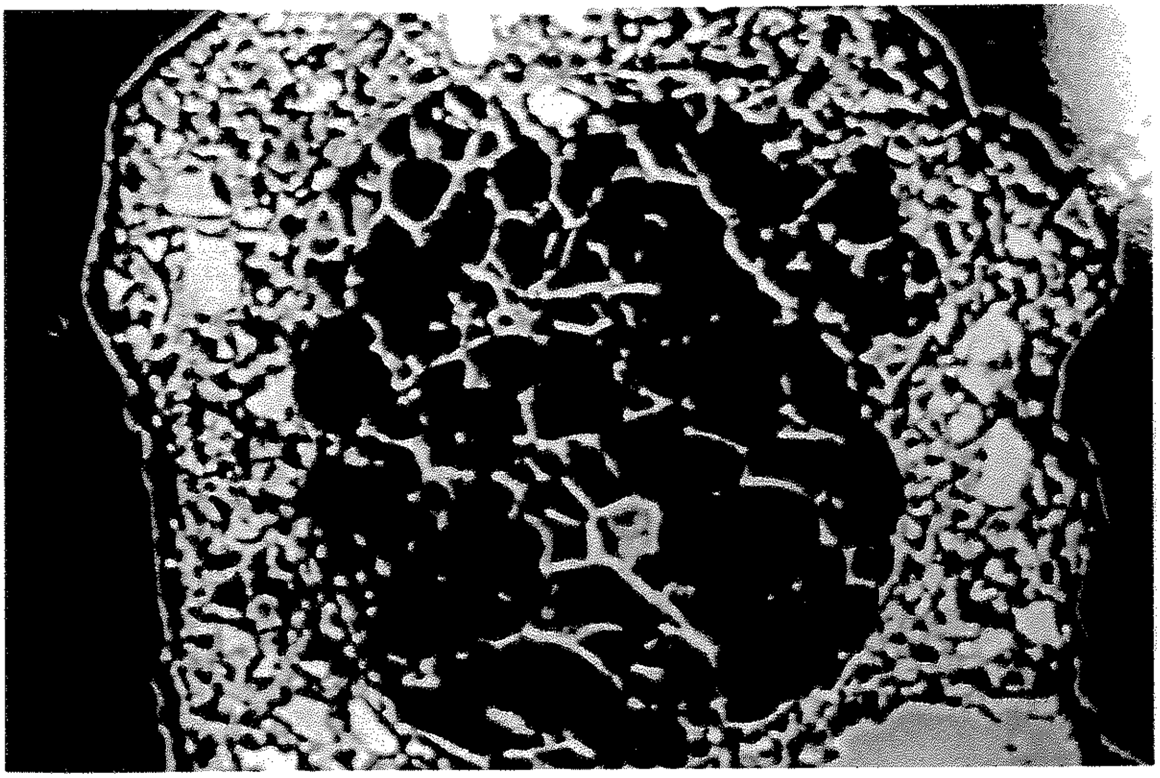


Figure 5.3.3j *B.E.I. of Specimen from Mix Series 4B Showing the Transition Zone between a Light Weight Aggregate Particle and the Cement Paste.*

6.0 Conclusions and Recommendations

6.1 Research Overview

The main objectives of this research were to establish a rational mix design procedure for mortars containing fine LWA using a scientific approach and to determine the effect of LWA on the properties of mortars. The design of a mortar or concrete mixture containing a new admixture can only be adequately accomplished by conducting a mechanical and structural characterization of the material. Thus, the first phase of this research defined a the mix design methodology for mortar mixtures.

The second phase described the research program to characterize the mechanical properties, and the microstructure of the different mortars. Mix design diagrams were constructed for each mortar series; these diagrams allow the user to proportion a mortar mixture for given performance criteria. The diagrams also allow precise comparisons between two or more mix series; hence, the effect of LWA on the mechanical properties of the mortar can be assessed. Finally, by combining the mechanical properties and the microstructural characterization, the overall effect of LWA on the mortar behavior can be estimated.

6.2- Conclusions

1. LWA exhibits a very small transition zone with cement paste, when compared to natural sand.
2. LWA by itself does not improve the compressive strength, splitting tensile strength, and flexural strength of the mortar. However, the addition of LWA composite to a mortar mixture improves the quality of the cement paste. Hence, the compressive strength, splitting tensile strength, and flexural strength characteristics of the mortar mix are greatly improved. Therefore, if the strength requirements are used as performance criteria, it is

possible to design mortar mixtures with less cement content than the control mix.

3. LWA lowers the chloride permeability of the mortar. Due to the pozzolanic admixtures in LWA composite, mortars containing LWA composite have lower chloride permeability than when only LWA is used. Moreover, LWA composite mortars with water-to-cement ratio below 0.46 had such low chloride permeability at 91 days, that they may be considered as almost impermeable.
4. LWA reduces the elastic modulus of the mortar. However, when using LWA composite the reduction in elastic modulus due to the LWA is compensated by the lower cement requirements. Thus, for mortar mixtures with w/c ratios higher than 0.53 (about 6000-6500 psi at 28 days) the mortar with LWA composite will provide a higher elastic modulus (and higher compressive strength) than the control mix for the same w/c ratio. If the w/c ratio is lower than 0.53, the mortar mix with LWA composite will have a lower elastic modulus than the control mix for the same w/c ratio. It was observed that the maximum LWA content to avoid a reduction in the elastic modulus is about 17-19% by volume.
5. The energy absorption characteristics of mortars containing LWA are very similar to the one observed for the control mix.

6.3- Recommendations for Future Research

The analysis and conclusions presented above give some recommendations for future research. These following recommendations are suggested considering the potential construction applications which could benefit from the use of fine LWA:

1. The excellent behavior of mix series #4 for chloride permeability suggests the possibility of obtaining highly durable mortar mixtures. Therefore, to fully characterize the durability of the mortar it is advisable to perform the following durability studies:

- Drying Shrinkage. This study can determine the effect of LWA on the drying shrinkage of mortar and concrete. This is particularly important for the precast industry.
- Freeze and Thaw. This study can establish if the cellular structure of LWA can improve the freeze and thaw resistance of mortar.
- Creep. The study can determine the long-term deformation of the material under sustained loading for LWA mortar.
- Resistance to Chemical Attack. The study to find out the behavior of LWA mortar subjected to aggressive environment.

2. Due to the large water absorption of LWA, it is possible that the curing of mortars containing LWA can be greatly simplified. Therefore, a comparison between the mechanical properties for different curing conditions is recommended.

3. Since the results of this research can not be directly extrapolated to predict the effect of fine LWA on the mechanical properties of concrete, a similar study with the one presented in this paper should be carried out for concrete.

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