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PERFORMANCE CHARACTERISTICS AND
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VS. NORMAL-WEIGHT CONCRETE MATERIALS

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PERFORMANCE CHARACTERISTICS AND FAILURE MECHANISM OF STRUCTURAL LIGHT-WEIGHT VS. NORMAL-WEIGHT CONCRETE MATERIALS

By

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ABSTRACT

PERFORMANCE CHARACTERISTICS AND FAILURE MECHANISM OF STRUCTURAL LIGHT-WEIGHT VS. NORMAL-WEIGHT CONCRETE MATERIALS

by

Mahboob Khan

Various aspects of the performance characteristics of light-weight concrete materials made with a ceramic-based coarse light-weight aggregate were investigated and compared with those of normal-weight concrete with similar mix proportion (by volume) and fresh mix properties.

Two synthetic fibers with different elastic moduli when used in light-weight and normal-weight concrete produced comparable effects on flexural strength and toughness, but the higher-modulus fiber gave higher impact strengths. Fibers were generally found to be more effective in light-weight concrete than in normal-weight concrete.

Light-weight concrete materials were, on the average, 40% more permeable than normal-weight concrete materials. Compressive loading up to 40% of the compressive strength increased the average permeability of normal-weight and light-weight concrete by 29% and 8%, respectively, indicating more severe damage in normal-weight concrete under compression.

The microcracking and failure mechanism of light-weight concrete under compression and impact loading is distinguished from that of normal-weight concrete by the lack of microcrack at the aggregate-paste interfaces and reduced intensity of microcracks in light-weight concrete.

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LIST OF ABBREVIATIONS

NWC	Normal Weight Concrete
LWC	Light-Weight Concrete
PPF	Polypropylene Fiber
PEF	Polyethylene Fiber
NWPPFRC	Normal-Weight Polypropylene Fiber Reinforced Concrete
LWPPFRC	Light-Weight Polypropylene Fiber Reinforced Concrete
LWPEFRC	Light-Weight Polyethylene Fiber Reinforced Concrete
Mod	Modulus
Elast	Elasticity
Flex	Flexure
FR	Fiber

CHAPTER 1

OBJECTIVES AND SCOPE

A comparative study was made on the following properties of light-weight vs. normal-weight concrete materials: (1) effectiveness of synthetic fibers in enhancing flexural strength and toughness; (2) permeability characteristics prior to and after loading; and (3) the nature of microcracking and failure mechanism under compression and impact.

In work on fiber reinforcement effects it was checked if reduced fiber-to-matrix modular ratio in light-weight concrete (noting that light-weight aggregate reduces the modulus of elasticity of concrete material) leads to increased effectiveness of fibers.

Light-weight aggregates are more porous than normal-weight aggregates; they are, however, more compatible with the cementitious paste (leading to reduced microcracking at the paste-aggregate interfaces). These two conditions have opposite effects on permeability. Increased loading also causes internal damage in light-weight and normal-weight concrete materials in distinctly different ways, producing different effects on permeability. These complex differences in the permeability characteristics of light-weight concrete (loaded and unloaded) prompted the work in this investigation on permeability.

The last part of this research dealt with the nature of microcrack propagation and failure in light-weight vs. normal-weight concrete materials subjected to compression and impact loading. Failure in normal-weight concrete emanates from defects such as microcracks existing at aggregate-paste interfaces. Under loading, these microcracks tend to propagate at interfaces and also through the paste. In light-weight aggregate concrete, the microcrack intensity at aggregate-paste interfaces is expected to be less severe than in normal-weight concrete, and the weakness of light-weight aggregates encourages the propagation of microcracks through aggregates. These differences were the subject of investigation in the last part of this research.

Light-weight concrete materials in this investigation were made with a ceramic based coarse light-weight aggregate (and normal-weight fine aggregate). All the normal-weight and light-weight concrete materials were designed to possess similar fresh mix proportions and comparable aggregate gradations; light-weight materials, however, had lower compressive strength when compared with normal-weight materials.

The conclusions derived in this investigation are mainly applicable to the ceramic-based light-weight aggregates used, and also to the specific ranges of compressive strength and impact resistance of light-weight and normal-weight concretes considered.

Chapter 2 of this thesis presents a comprehensive review on the literature of light-weight concrete; this literature review covers topics beyond the specific subject matters of this thesis. The work conducted in this research on fiber reinforcement, permeability characteristics, and microcracking are presented in Chapter 3, 4, and 5, respectively. A summary of the work and the resulting conclusions are presented in Chapter 6.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

The unit weight of normal-weight concrete varies from about 140 to 152 lb/cu.ft. (2258-2435 kg/cu.m.) and it is generally assumed to be 145 lb/cu.ft. (2324 kg/cu.m.). The unit weight of concrete can be reduced through the use of light-weight aggregates. Light-weight concrete may weigh from 20-115 lb/cu.ft. (320-1843 kg/cu.m.), depending on the type of light-weight aggregate used and the method of production. The strength of light-weight aggregate is roughly proportional to its density. The advantages of light-weight concrete over normal-weight concrete generally result from the decrease in foundation size because of reduced load, the increase in fire resistance, and the insulation against heat and sound when light-weight concrete is used. Light-weight aggregate concrete, however, is typically 30 to 50% more expensive than normal-weight concrete (1,6), and it has a greater porosity and more drying shrinkage than ordinary concrete.

Light-weight concrete can be classified in accordance to its density, or alternatively based on the purpose for which it is to be used. Distinctions can be made between structural and insulating light-weight concretes. Structural light-weight concrete has a unit weight between 90-115 lb/cu.ft. (1400-1840 kg/cu.m.), with a 28-day compressive strength not less than 2500 psi (17 MPa). Insulating light-weight concrete has a density generally lower than 50 lb/cu.ft. (800 kg/cu.m.) and a compressive strength between 100-1000 psi (0.7-7 MPa). Light-weight concretes with properties in between those of insulating and structural concretes can be classified as moderate strength light-weight concrete. (2,7,8)

A variety of light-weight aggregates (natural or man-made) have been used for the production of light-weight aggregate concrete. Such aggregates typically weigh less than 70 lb/cu.ft. (1120 kg/cu.m.). Their light weight results from the cellular or highly porous nature of their microstructure. The lightest type of aggregate possible is air which is used to reduce unit weight in aerated (cellular, foamed) concrete. Examples of the light-weight aggregate types commonly used for producing different classes of light-weight concrete are presented in Figure 2.1.

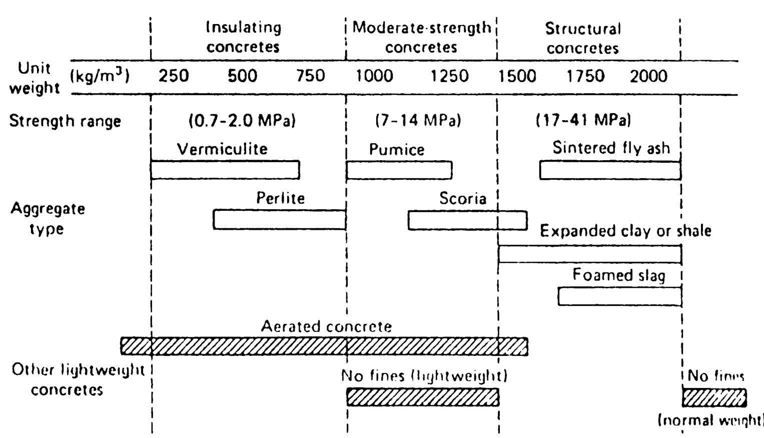


Figure 2.1 Classification of Light-Weight Concrete (4,7). (kg/cu.m. x 0.0624 = lb/cu.ft.; MPa x 145 = psi)

In Figure 2.1, depending on the unit weight and strength of concrete, distinctions are made between insulating and structural light-weight concretes.

While the use of light-weight aggregate in structural concrete elements has been increasing, (5,10) its primary use is still as an insulating material or in masonry blocks and secondary structural members (12). Like other materials, light-weight aggregate concrete also has certain limitations and it is only after evaluation of all the merits and demerits with respect to a particular project that final decision can be made regarding the suitability of its application (12).

Major technological advancements have been or are being made in the area of concrete materials. Examples include the use of short, randomly distributed fibers for improving the toughness characteristics, impact resistance and tensile strength of concrete, or the use of polymers in concrete for improving the impermeability and adhesiveness of the material. The field of light-weight concrete needs to take advantage of these technological developments in order to retain and increase its rapid growth rate in the years to come.

2.2 LIGHT-WEIGHT AGGREGATE

Light-weight concrete is a broad term covering concretes made with a wide variety of aggregates, natural or artificial, with or without treatment. The ranges of strength and density, and in fact all the characteristics of concrete, vary considerably with different aggregates.

Light-weight aggregates can be generally divided into natural (crushed rock or minerals) and manufactured, including industrial by-products and recycled waste products (2,7,14,49). Light-weight aggregates can also be classified (based on their density) as ultra light 4-35 lb/cu. ft. (64-561 kg/cu.m.) and light 35-70 lb/cu.ft. (561-1121 kg/cu.m.). There are also classifications of light-weight aggregates based on the potential strength, density or other characteristics of the resulting light-weight concrete. Light-weight aggregates having dry unit weights ranging from 4 to 35 lb/cu.ft. (64-561 kg/cu.m.) and thermal conductivities ranging from 0.45 to 1.5 Btu/ft^2.hr.^{o}F (0.65 to 0.22 W/mK) are generally classified as group I and are used for insulation purposes; whereas light-weight aggregates having dry unit weights from 35 to 65 lb/cu.ft. (561 to 1042 kb/cu.m.) are classified as group II and are used for structural purposes (2,11,38).

A summary of the properties and production techniques for some commonly used light-weight aggregates is presented in Appendix I.

2.3 MIX DESIGN AND MANUFACTURING

Mix proportioning of concrete consists of selecting suitable materials (cement, sand, water, etc.) and determining the quantities of these ingredients. The economy and performance characteristics of the concrete thus produced depends on the proportioning of these ingredients. The procedures adopted for mix proportioning are still empirical in spite of a considerable amount of work done on the theoretical aspects of mix proportioning.

2.3.1 Light-Weight Concrete Materials

Portland cement type I is normally used in light-weight aggregate concrete. Structural elements exposed to marine environments are made of cements having high tricalcium-aluminate contents (7%), an amount which can resist sulphate attack on the elements made with light-weight aggregate concrete in a similar fashion as in normal weight aggregate concrete.

Fly ash could be used to improve strength and sulphate resistance, and to reduce water absorption and improve curing properties. Light-weight aggregates should satisfy ASTM C-330 requirements (7). Typical gradation requirements are given in Table 2.1.

Table 2.1. Gradation requirements for light-weight aggregates (11).

Size	1in 25mm	3/4in 19mm	1/2in 12.5mm	3/8in 9.5mm	No.4 4.75mm	No.8 2.36mm	No.16 1.18mm	No.50 300@m	No.100 150@m
Designation									
Fine Aggregate									
No. 4 to 0	-	-	-						
Coarse Aggregate									
1in to No. 4	95-100	-	25-60	-	0-10	-	-	-	-
3/4in to No.4	100	90-100	-	10-50	0-15	-	-	-	-
3/8in to No.8	-	-	100	80-100	5-40	0-20	0-10	-	-
Combined Fine and Coarse Aggregate									
1/2in to 0	-								
3/8in to 0	-	-	100	90-100	65-90	35-65	-	10-25	5-15

Water free from salt and organic matters (fit for drinking) should be used in light-weight aggregate concrete mixtures. Air entraining admixtures should conform to ASTM C-26.

2.3.2 Peculiarities of Light-Weight Concrete Mix Proportioning

Light-weight aggregates tend to segregate and float on the surface of concrete in high-consistency mixtures. This problem can be controlled by limiting the maximum slump and by entraining air in fresh concrete mixtures made with light-weight aggregates (11).

A major factor necessitating adjustments in the proportioning and control procedures of normal-weight concrete when applied to light-weight aggregate concrete is the greater water absorption and higher absorption rate of light-weight aggregates (11).

Light-weight aggregate mixtures are usually proportioned by trial on a cement and air content basis at the required consistency, rather than on a water-to-cement ratio basis, because water-to-cement ratio cannot be established with accuracy due to absorption of water by light-weight aggregates.

Grading of fine and coarse aggregates and the proportions used have important effects on concrete properties. A well-graded aggregate will have a continuous distribution of particle size, producing a minimum void content and requiring a minimum amount of cement paste to fill the voids. This will result in economical use of cement and will provide maximum strength with minimum volume change due to shrinkage and temperature effects (11).

In light-weight aggregates, unlike normal-weight aggregates, the specific gravities of fractions retained on different sieves are not equal. Hence, it is the volume occupied by each size fraction, and not the weight of the materials retained on each sieve, that decides the void content and cement paste requirements in a mix.

For a typical light-weight aggregate, the percentage retained on each sieve by volume and weight are given in Table 2.2.

Table 2.2. Comparison of fineness moduli by weight and by volume for typical light-weight aggregates.(11)

Sieve Opening			Percent retained by		Specific	Cumulative percent retained by	
	In	Mm	Weight	Volume	Gravity	Weight	Volume
No. 4	.187	4.67	0	0	1.4	0	0
No. 8	.0937	2.36	22	26	1.55	22	26
No. 16	.0469	1.18	24	25	1.78	46	51
No. 30	.0234	.600	19	19	1.9	65	70
No. 50	.0117	.300	14	13	2.01	79	83
No.100	.0059	150μm	12	10	2.16	91	93
Passing No. 100			9	7	2.40	100	100

Fineness modulus by weight = 3.03 Fineness modulus by volume = 3.23

Fineness modulus by volume is greater than fineness modulus by weight which indicates that light-weight aggregates require a higher percentage of materials retained on fine sieves on a weight basis, than do normal-weight aggregates, to provide an equal size distribution (11).

The particular properties of light-weight aggregates pose special problems in calculating mix proportions for light-weight concrete. The absolute volume method, which is the basis of the ACI method for proportioning normal-weight concrete, can not be used with confidence for light-weight concrete. This is due to two major factors.

1. Variations in bulk specific gravity of light-weight aggregates.
2. Changes in the light-weight aggregate moisture content.

The bulk specific gravity of light-weight aggregates depends upon porosity which varies with particle size. Hence, grading curves determined on weight basis cannot be used for proportioning light-weight concrete because they cannot be converted directly to volumetric basis, as shown in Table 2.2.

The mix proportioning procedures commonly used for light-weight aggregate concrete are presented in Appendix II.

2.3.3. Peculiarities in Manufacturing Light-Weight Concrete

Production of uniform concretes with light-weight aggregate involves all the procedures and precautions that are necessary for ordinary concrete.(1) After mix design, the ingredients should be mixed according to ASTM C-94 as in the case of normal-weight concrete. The problem is, however, more difficult where light-weight aggregates are used because of greater variations in absorption, specific gravity, moisture content and gradation of aggregates. Uniform results can thus be obtained if the unit weight and slump tests are performed frequently, and the cement and water contents of the mix are adjusted as necessary to compensate for variations in properties (1,2,11,22,35).

Dry light-weight aggregates should not be used at the mixing stage although they will produce a concrete which can be placed right after being discharged. Continuous water absorption by dry light-weight aggregates will cause concrete to segregate and stiffen before placement is completed.

In order to insure uniformity, light-weight aggregates should be wetted 24 hours before use. This wetting will also reduce segregation during stock piling and transportation, (1). Presaturation of aggregates will help achieve uniformity but may reduce freeze-thaw durability (particularly if concrete is not allowed to dry before exposure to freezing temperature).

It is generally necessary to mix light-weight aggregates for longer periods than conventional concrete to assure proper mixing. Workability of light-weight concrete with the same slump as conventional concrete may vary more widely because of differences in such properties of light-weight aggregates as porosity and specific gravity. Workability of freshly made light-weight aggregate concrete requires special attention because, with high-consistency mixtures, the aggregate tends to segregate and float on the surface. To combat this tendency, it is often necessary to limit the maximum slump and entrain air. Approximately, 5 to 7 percent air entrainment is generally required to lower the mixing water requirement while maintaining the desired slump and reduce the tendency for segregation and bleeding.

Placing, compaction and finishing of light-weight aggregate concrete requires less effort than normal-weight concrete; therefore, 2 to 3 inches (50 to 75 mm) of slump may be sufficient to obtain workability levels that are usually shown by 4 to 5 inches (100 to 125 mm) of slump in normal-weight concretes. A slump of 2 to 3 inches (50-75 mm) represents a relatively high workability, and a compaction factor not less 0.8 or a Vebe time less than 12 sec correspond approximately to a medium workability. A slump in excess of 2-4 inches (50-100mm) may cause segregation with large light-weight aggregate particles floating to the top. The tendency towards floating of larger particles of light-weight aggregate may also be improved by adjusting the grading of aggregates. This can be done by crushing the larger particles, adding natural sand, or adding filler materials. In order to minimize segregation prior to discharge, the mix should be rotated at least ten revolutions at maximum speed (3). Concretes made with many light-weight aggregates may be difficult to place and finish because of porosity and angularity of the aggregates. The placability of concrete can be improved by adding air-entraining agents.

Quality control during manufacturing is achieved by keeping the cement content, slump and volume of dry aggregate constant per cubic yard of concrete regardless of variations in absorbed or surface water of aggregate. If the density of aggregate does not vary, constant volume can be maintained by keeping the dry weight of aggregate constant. Unit weight of fresh concrete should be determined at frequent intervals. A change in unit weight indicates a change in air content or change in weight of damp aggregate. An air content determination will establish whether or not the correct amount of air is entrained. If weight of aggregate is changed, it is due to a change in moisture content, gradation, and unit weight. The aggregate weight can be easily measured, and this will reveal the cause of the change.

Different types of light-weight concrete call for different aggregate gradings; a particular grading which is suitable for use with one type of light-weight aggregate may not be suitable with another type (2). Careful selection and handling of light-weight aggregates to prevent crushing and contamination, and to ensure uniform moisture content and uniform weight, are necessary for achieving quality light-weight concrete.

2.4 MECHANICAL PROPERTIES OF LIGHT-WEIGHT AGGREGATE CONCRETE

The following properties of light-weight aggregate concrete will be discussed in this section: Compressive and tensile strengths, modulus of elasticity and Poisson's ratio, impact resistance, ductility and creep characteristics.

2.4.1. Compressive Strength

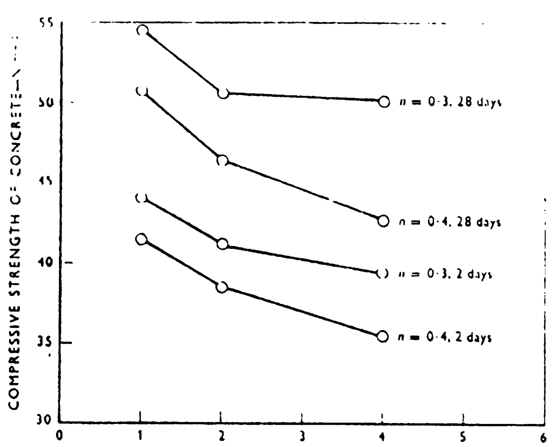
Design compressive strengths of 3000 to 4000 psi (26.7 - 27.5 MPa) at 28 days are common for structural light-weight concrete. By using high cement contents and good-quality light-weight aggregates of small size it has been possible in some precast and prestressed concrete plants to produce 6000-7000 psi (41.38 - 48.25 MPa) light-weight concretes (20). Light-weight aggregates with controlled microporosity have been developed to produce 10,000 to 11,000 psi (69-76 MPa) light-weight concretes which generally weigh 115 to 125 lb/cu.ft. (1843 to 2000 kg/cu.m.) (8,44,45).

With sintered fly ash and expanded clay or shale there is no difficulty in obtaining concrete strengths up to 6000 lb/in^2 (41 MPa) in spite of the high porosity and inherent weaknesses of aggregates. Pumice, scoria, and some expanded slags produce concretes of intermediate strengths near 2000 psi (14 MPa). Vermiculite and diatomite produce concretes of very low strength in range of 200-750 psi (1.4-5.2 MPa) (8).

The following factors associated with light-weight aggregates may contribute towards the differences in compressive strength of light-weight and normal-weight concretes:

1. Aggregate strength.
2. Aggregate stiffness.
3. Aggregate surface texture.
4. Differences in surface area.
5. Aggregate shape.

The compressive strength of light-weight concrete depends partly upon the shape of light-weight aggregate particles (see Figure 2.2). Concretes made with round aggregates (volume concentration of sintered fly ash aggregates = 0.4) have 28-day compressive strengths about 870 to 1160 psi (6 to 8 MPa) higher than those obtained with elongated aggregates (length/thickness ratio = 4). The differences in specific surface area associated with the differences in shape contribute to strength variations.



n = Porosity of Aggregate

Figure 2.2 Effects of aggregate shape on the compressive strength of light-weight concrete.(29)

The shape of light-weight aggregates affects stress concentration in concrete under load, causing differences in the compressive strength of light-weight aggregate concretes made with different aggregate shapes.

2.4.2. Tensile Strength.

Direct tension test results show great scatter because of misalignment effects, stress concentration at the grips, and random effects associated with the location of aggregates. For this reason, direct tension tests are seldom conducted on concrete materials. The splitting tensile strength of concrete cylinders (ASTM C-496) is a convenient relative measure of tensile strength. The data in Table 2.3 shows that, like normal-weight concrete, the ratio between the splitting tensile and compressive strengths decreases significantly with increasing strength of light-weight concrete. The modulus of rupture of continuously moist-cured light-weight concrete also behaves in the same manner; tests on dried specimens show that the results are extremely sensitive to the moisture state. For normal-weight concrete the modulus of rupture is usually between $8\sqrt{f'c}$ and $12\sqrt{f'c}$, whereas for light-weight aggregate it may range from $6\sqrt{fc}$- and $8\sqrt{fc}$- (44).

Examination of fractured specimens of light-weight concrete after splitting tension test clearly reveals that, unlike normal-weight concrete, the aggregate, and not the transition zone, is generally the weakest component in the system. Holmi, et.al.(4) have presented scanning electron micrographic evidence of this phenomenon.

Table 2.3. Requirements for Structural Light-Weight Concrete (4).

Air-dried 28-day unit weight, Max.[lb/ft^3(kg/m^3)]	28-day splitting tensile strength, Min. [psi (MPa)]	28-day compressive strength, Min. [psi (MPa)]
All light-weight aggregates		
110 (1760)	320 (2.2)	4000 (28)
105 (1680)	300 (2.1)	3000 (21)
100 (1600)	290 (2.0)	2500 (17)
Combination of normal sand and light-weight aggregate		
115 (1840)	330 (2.3)	4000 (28)
110 (1760)	310 (2.1)	3000 (21)
105 (1680)	300 (2.1)	2500 (17)

The compressive strength and unit weight shall be obtained based on the average measurements made on three specimens, and the splitting tensile strength shall be the average obtained using eight specimens.

2.4.3. Modulus of Elasticity and Poisson's Ratio

The modulus of elasticity of light-weight concrete Ec, that is the slope of the initial straight part of the compressive stress-strain curve, tends to increase with increasing strength of concrete. Typical compressive stress-strain curves for light-weight concrete are shown in Figure 2.3.

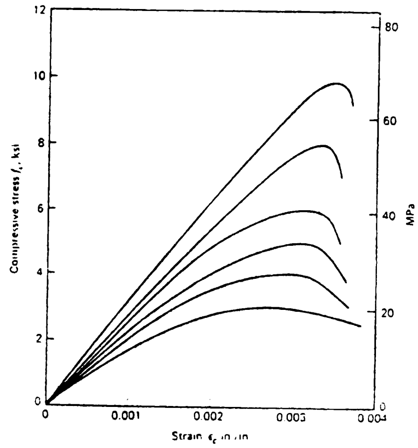


Figure 2.3. Typical Compressive Stress-Strain Curves for Light-Weight Concrete (44).

Modulus of elasticity of light-weight concrete is typically lower than that of normal-weight concrete. The following equation is recommended for calculating the modulus of elasticity of light-weight concrete with compressive strengths ranging from 3,000 to 7,000 psi (21 to 48 MPa) (44).

$$Ec = 40,000\ (fc- + 1,000,000)(Wc/145)^{1.5}$$

The poisson's ratio for light-weight concrete ranges from 0.17 to 0.21, with an average value of 0.20.

2.4.4. Dynamic Behavior Under Impact Loads

Stress wave velocity is about 20% less in light-weight concrete than in normal-weight concrete, with the length of stress wave being about the same. Period of vibration is longer in normal-weight concrete when compared with light-weight concrete, and vibration damping is greater, probably due to the interface condition between paste and coarse aggregates.

Shock and energy absorption of light-weight aggregate concrete is believed to be substantially greater than those for normal-weight concrete.

2.4.5. Ductility

Ductility supplies the ability to sustain inelastic deformations after peak load without a significant drop in load- resisting capacity prior to collapse. The ductility of reinforced concrete members depends, among other factors, on the stress-strain behavior and ductility of concrete materials.

Light-weight aggregate concrete is increasingly being used as a structural material in reinforced and prestressed concrete structures. The strength properties of light-weight aggregate concretes have been studied extensively, but the ductility of the material, especially at higher strengths and for members confined with lateral reinforcement, has not been understood (17,34).

Very little information is available on complete compressive stress-strain behavior of light-weight concrete. Typical comparisons between the ductility of light-weight and normal-weight concretes (confined and unconfined) are shown in Figure 2.4.

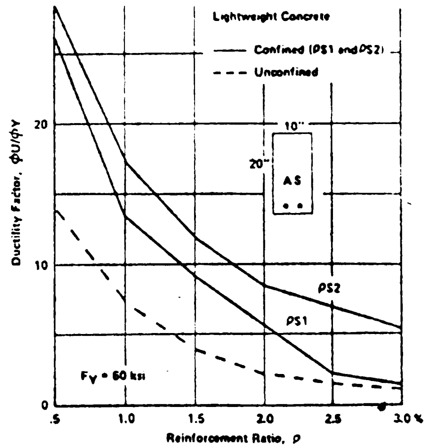


Figure 2.4. Typical effects of confinement on the stress-strain behavior of light-weight and normal-weight concretes (23,34).

2.4.6 Creep

There are considerable variations in the creep characteristics of concretes with comparable densities, and the magnitude of creep depends on the cement content, water-cement ratio of the paste, modulus of elasticity of aggregates, and the rate of moisture loss. Creep is usually greater in light-weight concrete than in normal-weight concrete at the same strength (see Figure 2.5).

Light-weight aggregates have relatively low moduli of elasticity because of their high porosity. The lower elastic moduli of light-weight aggregates would offer less restraint to time-dependent deformations such as creep (7).

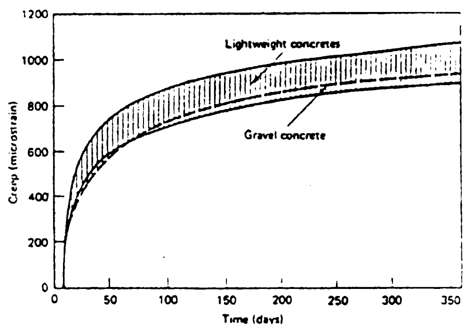


Figure 2.5. Comparison of the Creep of Light-Weight and Normal-Weight Concretes.(7)

Present-day research has proved that the effect of cement paste content on creep in light-weight concrete is the same as in normal-weight concrete; however, the modulus of elasticity of the aggregate affects the magnitude of creep through the medium of exponent *a* in the expression (30):

$$C = C_p(1-g- \quad)^a$$

Creep of concrete (made with either light-weight aggregate or normal-weight aggregate) can be predicted by this equation for periods up to 7 months under load.

$$a = \frac{3(1 - \mu)}{1 + \quad + 2(1 - 2 \quad_{a})\, E/E_a}$$

where,

μ = Poisson's ratio of surrounding materials.

a = Poisson's ratio of aggregate

E = Modulus of Elasticity of Surrounding Materials (Elasticity)

E_a = Modulus of Elasticity of Aggregate

g = Volume of Aggregate

C = Creep of Concrete

C_p = Creep of Cement Paste

2.5 PHYSICAL PROPERTIES

This section presents discussions on the shrinkage, specific gravity and thermal properties of light-weight concrete materials.

2.5.1 Shrinkage:

The shrinkage of light-weight concrete is generally greater than that for normal-weight concrete with similar mix proportions and consistency, but some impervious light-weight aggregates produce concretes having relatively low shrinkage (36). Light-weight aggregates usually give higher shrinkage because they have lower moduli of elasticity and thus produce smaller restraint against the shrinkage movements of cement paste. Aggregates with a larger fraction of fine materials smaller than 75 microns (No 200 sieve) show higher shrinkage movements, as fines lead to larger void contents.

The fact that the elastic properties of aggregates determine the degree of restraint against shrinkage movements is demonstrated in the observation that steel aggregates lead to shrinkage strains that are one-third less, and expanded shale light-weight aggregates give one-third more shrinkage strains, when compared with ordinary aggregates (46). A typical correlation between shrinkage and modulus of elasticity of concrete, which depends on the compressibility of aggregates, is shown in Figure 2.6.

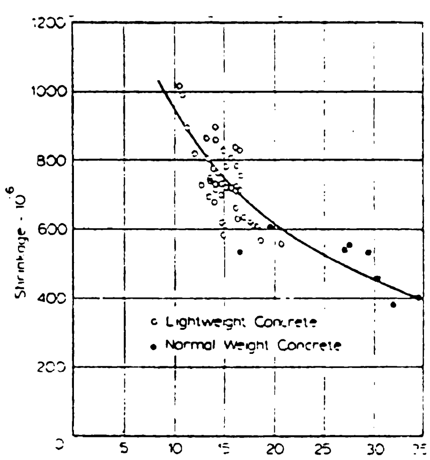


Figure 2.6. Relation Between Drying Shrinkage after 2 years and Secant Modulus (2).

Ref. 4 suggests that light-weight aggregate concrete exhibits higher moisture movements (i.e. higher rates of drying shrinkage) and a somewhat higher ultimate shrinkage (typically 1600 x 10^{-6}) when compared with normal-weight aggregate concrete. It seems that the low strength and low modulus of elasticity of light-weight aggregates have more pronounced effects on creep than on shrinkage.

As mentioned above, the results of many tests (2,48) show that the shrinkage of light-weight concrete might be 6 to 38% higher than that of normal-weight concrete. Other test results (47), however, indicate that shrinkage movements are comparable in light-weight and normal-weight concrete. It may thus be concluded that shrinkage strains in light-weight aggregate concrete depend on its specific types of light-weight aggregate used.

Figure 2.7 shows the drying shrinkage movements of plain light-weight aggregate (lytag & sand) concrete for three different sizes of prismatic specimens tested under constant conditions of 68°F (20°C) and 50% relative humidity. It can be observed that at the first two days, unlike normal-weight concrete, there is some expansion in light-weight concrete and the smallest specimen shows the largest expansion. This behavior possibly is due to the water absorption of relatively high amounts of water by light-weight aggregates (46). The absorbed water in the aggregate tends to move to the surface, a phenomenon which causes the expansion of concrete. The movements of water depend on the rate of evaporation at the surface and, as the smallest specimen has the highest surface area-to-volume ratio, the highest expansion tendencies at early drying periods are observed with the smallest specimen. As expected, the smaller specimens also show higher rates of shrinkage development which again can be attributed to their higher rate of moisture loss.

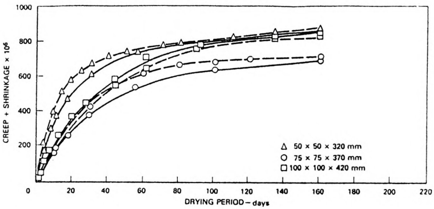


Figure 2.7. Drying shrinkage of prismatic light-weight concrete specimens with different dimensions (49).

In work with shrinkage-compensating expansive cements water curing is required; otherwise, expansion potential may be reduced significantly (10). With light-weight aggregates, the large quantity of water contained within the porous aggregate particles produces a much better curing environment for expansive cement, and the expansion can be as much as 50% greater than that obtained with comparable normal-weight aggregate concretes.

2.5.2 Specific Gravity

Since light-weight aggregates generally contain pores, both permeable and impermeable, the term specific gravity has to be defined carefully, and there are indeed several types of specific gravity.

The absolute specific gravity is based on the volume of solid material excluding all pores, and can therefore be defined as the ratio of the weight of solid material excluding the pores (7).

If the volume of the solid includes the impermeable pores but not the capillary ones, the resulting specific gravity is called the apparent one. The apparent specific gravity is then the ratio of the weight of the aggregate after drying in oven at 212 to 230^{o}F (100 to 110^{o}C) for 24 hours, to the weight of water occupying a volume equal to that of the solid including impermeable pores.

The specific gravity of natural aggregates varies from 2.6 to 2.7. The values for artificial aggregates extend from considerably below to very much above this range (7). The specific gravity is difficult to calculate for light-weight aggregates because of the water absorption characteristics of the aggregate.

The specific gravity of light-weight aggregates varies with their size; the finer particles tend to be heavier than the larger ones. Hence, on a weight basis, the percentage of finer materials in light-weight aggregates has to be more than that in ordinary solid aggregate concrete in order to achieve comparable gradations on a volume basis. As far as the proportioning of mix is concerned, it is the volume occupied by each size fraction (and not the weight) that determines the final cement paste content and workability of the light-weight concrete mix.

The higher-strength materials typically have lower void contents. Foamed concretes, with air acting as light-weight aggregate, have higher void contents than ordinary concrete. As observed in Figure 2.8, the strength of light-weight concrete depends on the density of the material. The density of concrete is itself a function of specific gravity of aggregates.

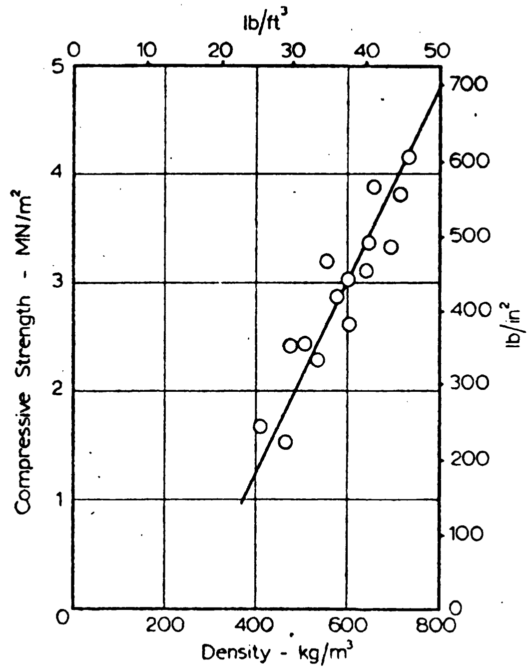


Figure 2.8. Strength vs. Density of Light-Weight Concretes (2).

Another term, specific gravity factor, refers to the ratio of the weight of the aggregate, as introduced to the mixer, to the effective volume displaced by aggregate. The weight of aggregate includes any moisture content, absorbed or free, at the time of placing the aggregate in mixer. Specific gravity factor is recommended for calculating adjustments in mix proportions if any variations in the properties of fresh light-weight aggregate concrete are observed. The specific gravity factor is not a true specific gravity; its value incorporates compensation for the free water of aggregate, but it is used in exactly the same way as conventional specific gravity to calculate the volume relationships. Specific gravity factor depends on initial moisture content of the aggregate as shown in Figure 2.9.

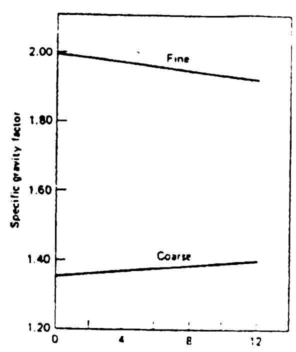


Figure 2.9. Specific Gravity Factor vs. Moisture Content of Light-Weight Aggregates (7).

2.5.3 Thermal Properties

The coefficient of thermal expansion of light-weight concrete is the same as that of normal-weight concrete, but its thermal conductivity is considerably lower because of the large amount of void space present in light-weight aggregates. Thermal conductivity depends upon unit weight as shown in Figure 2.10. The lower thermal conductivity makes light-weight concrete more fire-resistant than normal-weight concrete; light weight concrete also provides a better protection against fire for the reinforcement.

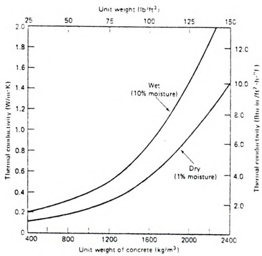


Figure 2.10. Thermal Conductivity vs. Unit Weight of Concrete (7).

The thermal transmittance of light-weight concrete is about 50% that of normal-weight concrete. This greater thermal insulation is a key factor in many insulating

applications of light-weight concrete. It also has important effects on prestressing applications because with light-eight aggregates one gets: (a) greater camber when one side is exposed to sun; (b) better response to steam curing; and (c) better fire resistance.

2.6 DURABILITY AND PERMEABILITY

Durability is the ability of concrete to withstand the exposure conditions for which it is designed over the period of its life time.

An important factor deciding the durability of concrete is permeability; water permeation into concrete is a necessary condition for the initiation of many forms of concrete deterioration.

2.6.1 Permeability

The permeability of light-weight aggregate concrete is reported to be generally lower than that of the normal-weight concrete (4). The principal reason for low permeability of light-weight aggregate concrete is the general absence of microcracks in the aggregate-cement paste transition zone. According to Holmet (4), the reduced intensity of interface microcracks in light-weight concrete is due to the similarity of elastic moduli between light-weight aggregates and cement mortar.

Some concretes made with light-weight aggregate may exhibit higher moisture movements than normal-weight concrete (2,4). In order to prevent early corrosion of reinforcement due to moisture movements in such light-weight aggregate concretes, the depth of cover should be increased, generally up to twice that of normal-weight concrete. In exposed situations the British Code CP 110 requires 0.4" (10 mm) additional cover for light-weight concrete when compared to dense concretes. Alternatively, the use of a rendered finish or coating of the reinforcement with rich mortar has been found useful. In the case of concretes made with clinker aggregate, there is the additional danger of corrosion due to the presence of sulfur in the clinker and coating of steel is necessary (2,4).

2.6.2 Freeze-Thaw Durability

The freeze-thaw resistance of light-weight concrete is reported to be similar to that of ordinary concrete. Air entrainment should be used when the concrete will be exposed to repeated freezing and thawing. The moisture content of aggregates can be critical because when aggregates are close to saturation, the freezing water in aggregate pores will force water out of aggregate particles into the surrounding paste. The resulting hydraulic pressure may cause tensile failure if sufficient entrained air is not present to accommodate the excess water. In order to avoid this situation the aggregates should have as low a moisture content as practical during mixing, or the concrete should have ample time to dry out before being exposed to freezing temperatures.

Laboratory freezing and thawing test performed on non-air-entrained and air-entrained concretes made with light-weight aggregate and normal-weight natural aggregate concretes. Each aggregate was used in air-dried and soaked conditions. The concrete were made at two different strength levels. On the basis of these tests, the following observation were made:

(a) The amount of intentionally entrained air required for adequate durability of concretes made with light-weight aggregate is similar to that for normal-weight concrete;

(b) Concretes incorporating light-weight aggregate can be made, through air entrainment, as resistant to the effect of deicer salts as concretes made with normal-weight aggregate; and

(c) The spread in durability test results among concretes made with different light-weight aggregates appears to be greater than might be encountered with normal-weight aggregate.

The resistance of light-weight concrete to deicer salt scaling is reported to be similar to normal-weight aggregate concrete. Salt sealing resistance is improved by air entrainment, low water-cement ratio, adequate curing, and a period of drying before service.

2.6.3 Abrasion Resistance

Light-weight aggregates are porous and therefore more friable than normal-weight rock and minerals. Consequently, concretes containing light-weight aggregates generally show

poor resistance to heavy abrasion. Replacement of light-weight fine aggregates with natural sand improves the abrasion resistance.

2.6.4 Marine Durability & Sulfate Resistance

Marine durability of light-weight aggregate is generally believed to be comparable to that of normal-weight aggregate concrete.

Prestressed light-weight concrete piles have been in service in sea water since 1955 (4). Inspection in 1968 showed no deterioration problems. Volume change problems have occurred in some other applications, principally with prestressed light-weight concrete floor and roof slabs. These problems are similar to those occurring with prestressed normal-weight concrete, but are aggravated because of the low modulus of elasticity of light-weight concrete and its lower dead load-to-live load ratio, greater shrinkage, and increased thermal insulation.

The presence of excessive iron sulfide in slag may cause discoloring and durability problems in concrete products incorporating slag light-weight aggregates. Under certain conditions sulfide can be converted to sulfate, which is undesirable from the stand point of sulfate attack on concrete. British specification limits the contents of soluble acid SO_3 and total sulfide sulfur in slag to 0.7 to 2 percent (4).

2.6.5 Fire Resistance

Thermal conductivity of light-weight concrete is about half as much as that of normal-weight concrete and therefore the fire endurance is considerably better. The fire resistance of light-weight aggregate concrete is better by 20 to 50% than normal-weight aggregate concrete.

The type of aggregate affects the strength reduction under fire, as shown in the Figure 2.11. Light-weight aggregates gradually lose their strength at temperatures above 1200°F (684°C). Concretes made with carbonate normal-weight aggregates (e.g. limestone and dolomite) are also relatively unaffected by temperature rise up to 1200 to 1300°F (684 to 740°C) at which time they undergo chemical change and rapidly loose strength. The quartz in silicon aggregates, such as quartzite, granite, sandstone and schists, undergoes a phase change at about 800 to 1000°F (475 to 590°C), which causes an abrupt change in volume and spalling of the surface.

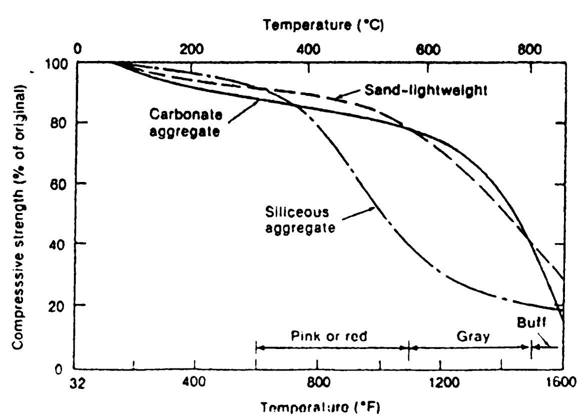


Figure 2.11 Temperature Effects on Compressive Strength (40).

2.7 APPLICATIONS

The use of light-weight concrete leads to reductions in the overall weight of structures, thereby lowering the concrete and steel requirements for load-carrying purposes. This is especially important when dead load is the major portion of total loads applied on the structure, or when the weight of the member is a factor to be considered for transportation and erection purposes.

The development of light-weight pumice concrete with a 28-day compressive strength greater than 3500 psi (24 MPa)(25), has considerably increased the use of light-weight aggregate concrete in residential construction (31). Pumice light-weight concrete is strong enough for load-bearing walls, and it weighs only 80 to 90 lb/ft^3 (1280-1440 kg/m^3). Reduced weight has also been the determining factor in the selection of light-weight concrete for prestressed bridge girders, particularly the suspended span in cantilever-suspended span bridges (27,33).

Another property of light-weight concrete which is of great potential use is its low submerged weight. This is directly attributable to low unit weight (9,10). Prestressed light-weight concrete weighs 75 to 80% of prestressed normal-weight concrete in air; when submerged in water, the ratio is only 50%. This makes prestressed light-weight aggregate concrete an ideal material for barrages, ships, and dry docks (39,47).

Light-weight aggregate concretes incorporating plastic aggregates are strong and fire-resistant, and combine good thermal insulating properties with a high strength-to-weight ratio. The density of plastic light-weight concrete is in the low range of 20 to 50 lb/cu.ft. (320 to 800 Kg/m^3). Typical applications are precast roof and wall panels, floor and roof fills, core material for sandwich panels, and light-weight blocks (1).

Some of the most common uses of light-weight concrete are in composites with normal-weight concrete. Different combinations have been employed successfully. These combinations are the following: (a) Prestressed light-weight concrete joist or girders with a cast-in-place normal-weight composite slab; (b) Prestressed light-weight concrete joists or girders with a cast-in-place light-weight concrete slab; and (c) Prestressed normal-weight concrete joists or girders with a cast-in-place light-weight concrete slab. All of these combinations, especially combination (c), require careful consideration for the differential moduli of elasticity and shrinkage. Composite construction has been employed in USSR where cellular (aerated) concrete is joined with ribs or slabs.

Lower elastic modulus of light-weight concrete permits better energy absorption and impact resistance, leading to applications such as in fender pile and navigation light stands where the lower elastic modulus permits deflections under impact loading which delay cracking. Prestressed concrete piles as long as 132 ft (40 m) have been manufactured and installed with light-weight aggregates.

Vermiculite and perlite present two recent developments in light-weight concrete. Vermiculite is made from a lamellar micaceous material, and perlite from silica lava. Both raw materials contain combined water, so that, upon a quick heating to the softening temperature, the material puffs. For both of these aggregates the fine size is produced more readily than coarse. Neither of them is suitable for high-strength structural concrete, but they have found many other uses, as for concrete partitions and roofs, insulating walls, and plaster applications (36).

Concrete masonry represents an important application field for light-weight aggregates. Concrete blocks are made in a variety of machines that consolidate a relatively dry concrete mix into the desired size and shape. The blocks might be hollow or solid, and load-bearing or non-load-bearing. Examples of light-weight aggregates typically used for the production of blocks include: cinder, expanded slag, granulated slag, expanded shales and clays, pumice, scoria, and vermiculite.

Examples of important buildings made of light-weight aggregate concrete include (10):

1 - Hilton Hotel at San Antonio, Texas.

2 - Nation Airline hanger in Miami which is a 111 ft (34 m) cantilever.

3 - A Hyperbolic roof 186 ft (56.7 m) x 192 ft (58.5 m) x 3 in (7.5 mm) thick at Colorado.

4 - John Hancock building 100 stories high, with 5 in (125 mm) thick light-weight aggregate concrete floor slabs acting compositely with steel beams.

5 - Shell plaza which is 714 ft (217.6 m) tall.

2.7.1 Economic Aspects of Using Light-Weight Concrete

According to ACI 213R-79, the use of light-weight aggregate concrete in a structure usually leads to lower overall cost of the structure. This is in spite of the fact that light-weight concrete will cost more than normal-weight concrete per cubic yard, partly because cement contents are usually higher than for normal-weight concrete for a given strength. The price of light-weight concrete per unit volume is typically 30% to 40% higher than that of normal-weight concrete (10).

The reduced weight associated with the use of light-weight concrete leads to savings in the structural frame itself, and particularly to savings in foundation. In good soils, settlements can be reduced, or alternatively the size of footing can be reduced. In poor soils, the number of piles may be reduced. In the case of in-between soils it may be possible to use spread footing or a mat in lie of piles. Savings in foundation costs have been cited as a major economic advantage associated with the use of light-weight concrete.

Wilson cites several examples, including the following, to demonstrate that use of light-weight concrete can result in lower costs of foundations, reinforcing steel and construction.

The construction of the light-weight concrete bridge deck for the San Francisco - Oakland Bay bridge in 1936 resulted in a $3 million saving in steel (4,23). Since then numerous light-weight concrete decks have been built throughout the world.

Strength is not a major consideration in floor slabs; therefore, a large amount of light-weight aggregate is used to reduce concrete dead weight in floors of high-rise buildings. An example of this application is the Lake Point Tower in Chicago, Illinois, which was built in 1968 and is 71 stories high.(4) The Australian Square in Australia, completed in 1967, is a circular tower with 50 stories 603.7 ft (184m) high and 1394.5 ft (425m) in diameter (4). A 13 percent saving in construction cost was achieved through the use of 333,560 ft^3 (31,000 m^3) of light-weight concrete in beams, columns and floors above the seventh-floor level. Shell plaza, Houston, Texas is an all light-weight concrete structure of 52 stories containing a 229.6 x 170.6 by 8.2 ft (70 by 52 by 2.5 m) light-weight concrete pad 59.1 ft (18 m) below grade. If normal-weight concrete had been used, only a 35-story structure could have been safely designed due to limited soil bearing capacity.

Light-weight aggregate concrete continues to be used worldwide in the production of precast concrete elements and prefabricated panels due to the lower handling, transportation and construction costs (1,4,15).

It has been suggested (48) that with the rise in labor costs compared to material costs in the construction industry, the cost of the light-weight aggregate concrete slabs in building structures tends to be further reduced below that of normal-weight concrete for large-volume productions (48). The savings in reinforcement area is also of significance where live loads are small in comparison with dead loads.

CHAPTER 3

EFFECTIVENESS OF DIFFERENT SYNTHETIC FIBERS IN NORMAL- AND LIGHT-WEIGHT AGGREGATE CONCRETE

3.1 INTRODUCTION

Concrete is weak in tension and fails in a brittle manner under different stress systems. Any technique that can help increase the tensile strength and ductility of concrete would be very valuable. Fiber reinforcement is an effective technique for this purpose. Steel fiber reinforced concrete has been investigated since 1910, when Porter (17) attempted to increase the tensile strength of concrete. During the past decade there has been a growing interest in the use of different fiber types in cement paste, mortar and normal-weight concrete, but the field of light-weight fiber reinforced concrete has been largely neglected.

In this study synthetic fibers (polypropylene and polyethylene) were used in normal-weight and light-weight aggregate concrete materials. The main thrust in this part of the research was to verify if the increase in fiber-to-matrix modular ratio in light-weight concrete, which has a lower elastic modulus when compared with normal-weight concrete, leads to increased effectiveness of synthetic fibers in light-weight concrete. The effectiveness of fibers in different concrete matrices was assessed through flexure and impact tests.

3.2 BACKGROUND

Different fiber types have been found suitable for use in normal-weight and light-weight concrete. These fibers include steel, glass, polymeric, carbon and cellulose; they vary considerably in both cost and effectiveness as cement and concrete reinforcement. Steel and glass fibers are generally used in cement-based materials to improve the flexural strength, ductility, and impact resistance of the material. Synthetic fibers generally have lower elastic moduli than concrete, and can not significantly increase the flexural strength of concrete; they are, however, effective in increasing the impact resistance and reducing the intensity of plastic shrinkage cracking.

Attempts to develop light-weight fiber reinforced concrete with different types of light-weight aggregate have been reported in the literature. Successful results have been obtained through the use of foamed slag with steel fibers (32).

Like normal-weight concrete, the properties of fresh light-weight aggregate concrete depends on the size and shape of fibers (7, 28). Since fibers have relatively large surface areas, they tend to increase water requirements in concrete; they also exhibit a tendency to interlock or ball. As a general rule, concrete workability decreases in the presence of fibers, and it is difficult to measure the workability of fiber reinforced concrete; however, the Vebe test provides a rough measure of workability. The results of compaction, Vebe, and slump tests of steel fiber reinforced light-weight aggregate concrete are shown in Figure 3.1 (32), which indicates the damage to workability of light-weight fiber reinforced concrete with increasing volume fraction of fibers.

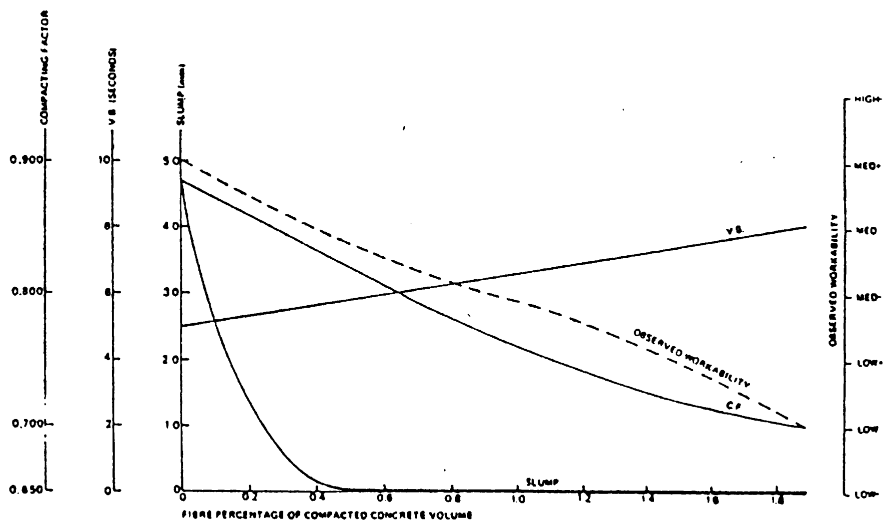
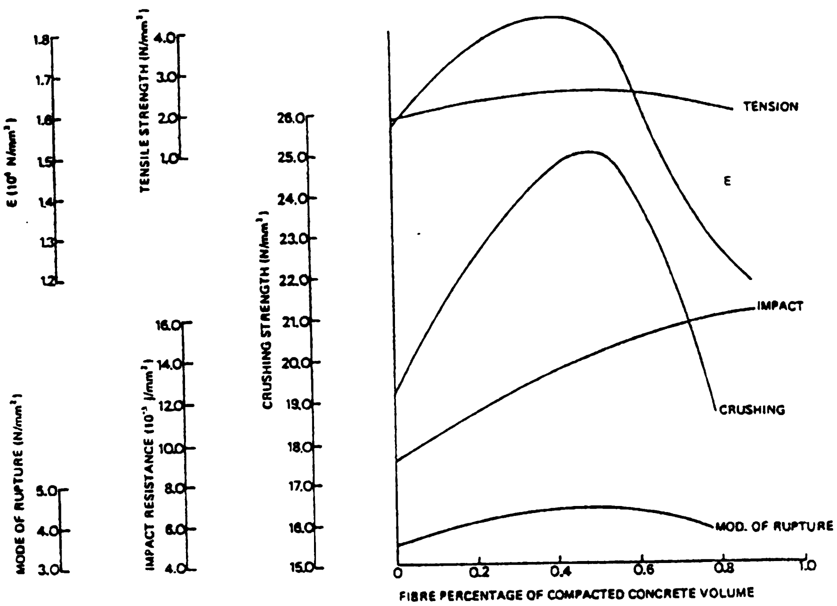


Figure 3.1. Effect of Polymer Fiber Reinforcement on the Workibility of Fresh Light-Weight Concrete (1 mm = 0.04 in.)

The mechanical properties of light-weight aggregate concrete generally improved with the addition of fibers up to a limit. These effects would be different for different types of light-weight aggregate.



(a) Polypropylene Fibers

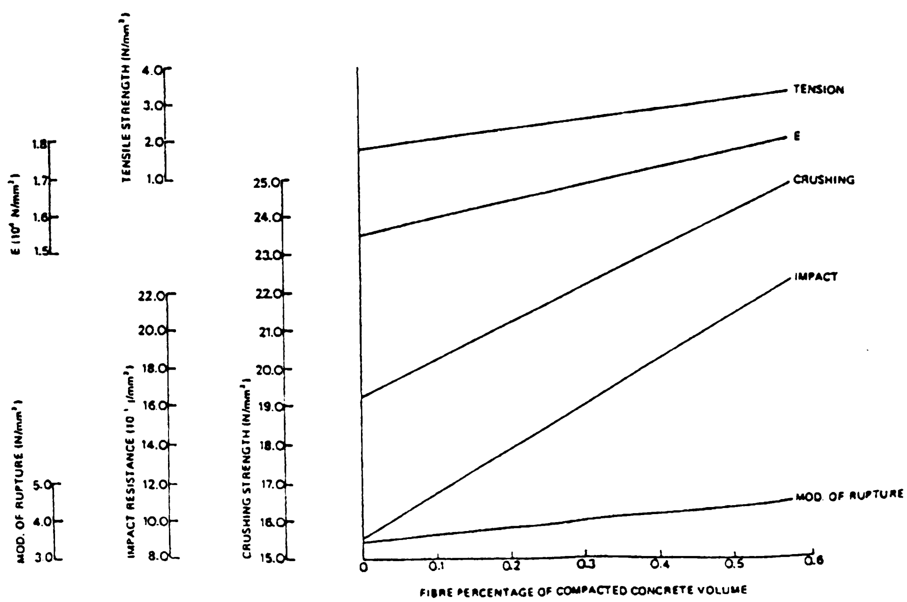


Figure 3.2. Effects of Fiber Reinforcement on the Mechanical Properties of Light-Weight Aggregate Concrete (in/mm^2 = 144 psi) (32).

The trends observed in Figure 3.2 regarding the effects of fiber reinforcement on the flexural and tensile strengths of light-weight aggregate concrete are basically similar to those observed for normal-weight concrete. The flexural strength of light-weight aggregate concrete is shown in Figure 3.2(b) to increase by about 100 percent with the addition of steel fibers (18, 32). The increase in flexural strength with fiber reinforcement is more-pronounced than the corresponding increase in tensile strength. Both polypropylene and steel fibers are observed in Figure 3.2 to be highly effective in improving the impact resistance of light-weight concrete. Similar trends were observed for the effects of fiber reinforcement on the compressive (crushing) strength and modulus of elasticity (E) of light-weight concrete.

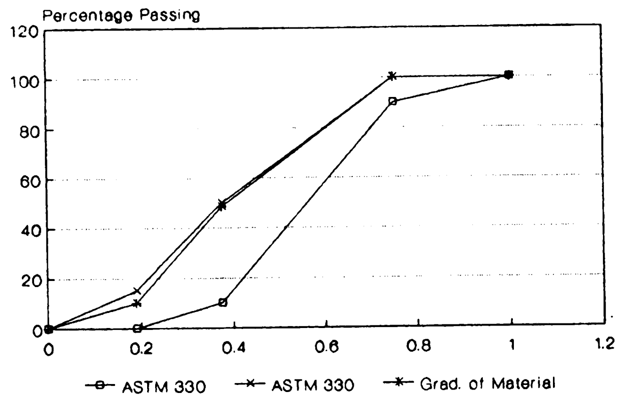
3.3 EXPERIMENTAL PROGRAM

The effectiveness of different synthetic fibers in normal-weight and light-weight concrete materials were investigated experimentally. Six concrete mixes of normal-weight and light-weight concrete were studied (see Table 3.1); in four mixes synthetic fibers (polypropylene and high-modulus polyethylene) were used at a 0.25% volume fraction, and the remaining two mixes were without fibers (plain).

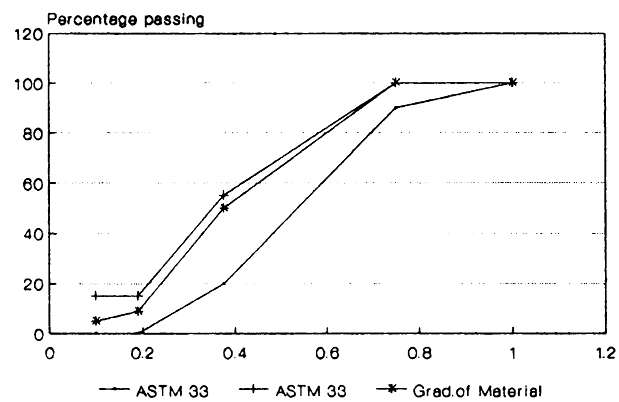
Table 3.1. The Experimental Program of Light-Weight and Normal-Weight Fiber Reinforced Concrete.

Concrete	Fiber Reinf. Condition		
	Plain	0.25% Poly.	0.25% Polyeth
Light-Weight			
Normal-Weight			

The basic mix ingredients were Type I Portland cement, light-weight coarse aggregate, normal-weight aggregate (coarse and fine), water, superplasticizer (naphtalene formaldehyde sulfonate-based) only in fibrous mixtures, and an air-entraining agent. Gradations of the normal-weight coarse and fine aggregates are shown in Tables 3.2 and 3.3 respectively. The gradation of the light-weight coarse aggregate is shown in Table 3.4. The light-weight aggregate used in this investigation (43) was ceramic-based with specific gravity of about 0.6 (ranging from 0.58 to 0.62). Macrolite ceramic spheres are low-density spheres (36 lb/cu. ft.) consisting of multiple minute independent air cell encircled by an out shell which is very tough. The sphere has less absorption capacity as compared to other light-weight aggregate (less than 0.5% by weight) and can function at a higher temperature. The properties of synthetic fibers are shown in Table 3.5. The higher modulus polyethylene fiber used in this study is observed to possess higher tensile strength and subtantially higher elastic modulus when compared with polypropylene fibers.



(a) Light-Weight Aggregate



(b) Normal-Weight Aggregate

Figure 3.3.--Gradation of Coarse Light-Weight and Normal-Weight Aggregate ASTM C-330 and C-33.

The fine normal-weight aggregates satisfy gradation requirements of ASTM C-33; the normal- and light-weight coarse aggregate gradations both satisfy the ASTM C-33 and C-330 requirements (maximum aggregate size was 3/4" (19 mm) both in light-weight and normal-weight coarse aggregate. Figure 3.3 compares the gradations of the two coarse aggregates with the ASTM C-33 requirements.

Table 3.2.--Gradation of Normal-Weight Coarse Aggregate (Specific Gravity = 2.52)

Sieve No.	% Passing
3/4" (19 mm)	100
5/8" (15.5 mm)	99
1/2" (12.5 mm)	94
3/8" (9.5 mm)	50
0.265" (6.625 mm)	30
#4 (4.75 μm)	9
#8 (2.36 μm)	5

Table 3.3.--Gradation of Normal-Weight Fine Aggregate (Specific Gravity 2.54)

Sieve No.	% Passing
3/8" (9.5 mm)	100
#4 (4.75 mm)	99
#8 (2.36 mm)	88
#16 (148 μm)	74
#30 (450 μm)	48
#50 (300 μm)	22
#100 (150μm)	9

Table 3.4.--Gradation of Light-Weight Aggregate

U.S. SIEVE	3/4" (19 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	#4 (4.75 mm)	#8 (2.36 mm)
PASSING	100	98.5	48.5	12.12	2

Table 3.5.--Properties of Synthetic Fibers (145 Psi = 1 Mpa)

NAME OF FIBER	LENGTH (IN)	SPECIFIC GRAVITY	MODULES OF ELASTICITY KSI	TENSILE STRENGTH KSI
POLYPROPYLENE	0.75	0.91	1.2	100
POLYETHYLENE	0.75	0.96	17	375

The variables in the experimental design were matrix type (normal- and light-weight) fiber type (polypropylene or polyethylene) and fiber volume fraction (0% and 0.25%). The coarse aggregate/cement and fine aggregate/coarse aggregate ratios were kept constant at 2.0 and 1.0 by volume, respectively, in all mixes. A slump of 3" ± .5" (75 mm ± 12.5 mm) was maintained in plain and fiber reinforced concrete mixtures. The superplasticizer dosage was adjusted for achieving the required slump. Fibers tend to damage the fresh mix workability and increase the required dosage of superplasticizer. An air entraining agent was used to maintain the air content of all fresh mixtures in the range from 7% to 9% in order to ensure the frost resistance of the resulting concretes. For this purpose the dosage rate of the air entraining agent was adjusted in different mixes.

Table 3.6 represents mix proportions for normal-weight plain and fibrous concretes.

Table 3.6.--Mix Proportion of Normal Weight Concrete

Mix	Cement*	Water*	Aggregate Coarse*	Aggregate Fine*	Air Entraining Agent % of cement by weight	Super Plasti-Cizer (Solid)*
Plain Concrete	704(418)	311(185.4)	1454(866)	1469(871)	0.1	---
Polypropylene Fiber Reinforced Concrete	738(438)	315(187)	1440(869)	1460(855)	0.05	4.38(2.6)
Polyethylene Fiber Reinforced Concrete	728(432)	323(192)	1466(870)	1478(877)	0.05	3.89(2.3)

* $lb/yd^3 (kg/m^3)$

Mix proportions of the light-weight plain and fibrous concrete mixtures are shown in Table 3.7. Normal-weight fine aggregate (sand) was used with light-weight coarse aggregates in the light-weight concretes considered in this investigation.

Table 3.7.--Mix Proportion of Light-Weight Aggregate Concrete

Mix	Cement*	Water*	Aggregate Coarse*	Aggregate Fine*	Air Entraining Agent % of cement by weight	Super Plasti-Cizer (Solid)*
Plain Concrete	800(475)	315(187)	404(240)	1617(960)	0.07	----
Poly-propylene Fiber Rein-forced Concrete	800(475)	320(190)	404(240)	1621(962)	0.045	6.08(4.0)
Polye-thylene Fiber Rein-forced Concrete	800(475)	326(191)	404(240)	1626(965)	0.049	6.4(4.95)

* $lb/yd^3 (kg/m^3)$

A conventional concrete mixer was used for manufacturing all the plain and fibrous concrete mixtures. The following mixing procedure was adopted:

1. Add the coarse and fine aggregates with half the water into the mixer.
2. Start the mixer and add cement into it while the mixer is running.
3. Add the remainder of water with air entraining agent.
4. Add superplasticizer.
5. Add fibers gradually in order to avoid balling.
6. Continue mixing for three minutes.

7. Stop the mixer for two minutes.

8. Start the mixer and run for two minutes.

In the case of plain concrete all the above steps were taken except that the addition of fibers and superplasticizer was eliminated from the process.

The fresh mix was tested for slump (ASTMC 143), Vebe Time British Standard (BS 1881), air content (ASTMC 231), and unit weight (ASTMC 138). Samples were made for the hardened material flexure and impact tests. The hardened specimens were cast in molds and compacted through external vibrator. The specimens were demolded after 24 hours, during which they were covered under wet burlap and plastic sheet and stored at 74°F (22°C). Thereafter the specimens were moist-cured at 74°F (22°C) and 100% relative humidity for five days, and then air dried for 22 days. The size and number of samples are shown in Table 3.8. Each hardened material test was replicated ten times (on ten different specimens) in order to provide data for statistical analysis.

Table 3.8. Size and Number of Hardened Material Test Specimens.

	FLEXURE	IMPACT
SIZE	4" X 4" X 14" (100 mm x 100 mm x 350 mm)	6" did 2.5" LONG (150 x 52mm)
NUMBER PER MIX	10	12

The flexure tests on hardened material were conducted by four point loading on the 4" x 4" x 14" (100 x 100 x 350 mm) specimens. Deflections were measured at the center of the specimen with respect to the loading point (Figure 3.4). This method of displacement measurement eliminated any error associated with the rigid body movements of the specimen or penetration at support or load points into the specimen.

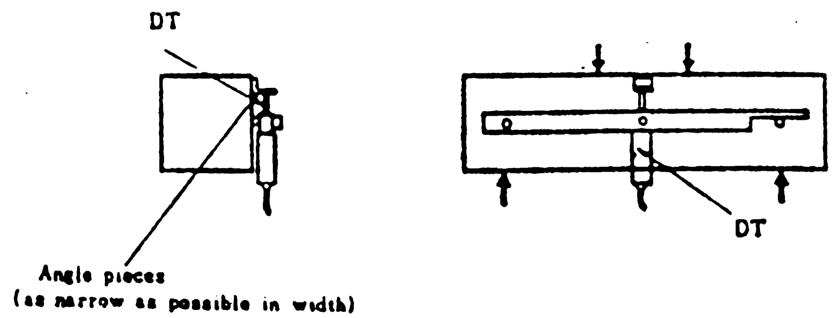


Figure 3.4. Flexure Test Set-Up

The flexural loading was displacement-controlled with a quasi-static deflection rate of about 1/1000 times the span length per minute. These flexure tests will produce a flexure load deflection curve which can be characterized through strength (modulus of rupture) and toughness. The Japanese Concrete Institute specifications (51) were followed for calculating flexural toughness. Toughness was defined as the area underneath flexural load-deflection curve up to a deflection equal to the span length divided by 150.

The impact tests were carried out following the procedure recommended by ACI committee 544 (54). This test measures the amount of impact energy necessary to start a visible crack in concrete and then to continue to open that crack with failure.

The equipment for the impact test (Fig. 3.5) consists of a standard 10-pound (448N) compaction hammer with 18 in. (457 mm) drop, a 2.5 in. (635 mm) diameter steel ball, and positioning fixtures. The impact test is performed by dropping the hammer repeatedly and recording the number of blows required to cause the first visible crack at top and then ultimate failure.

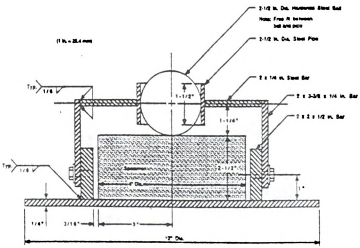


Figure 3.5. Impact Test Set-Up

3.4 EXPERIMENTAL RESULTS AND DISCUSSIONS

The fresh mix test results are presented in Table 3.9. The slump and vebe time test results are indicative of a reasonable success in this study in achieving comparable fresh mix workability conditions in all the mixtures. The air content test results also indicate that all the fresh mixtures had similar air contents. Fiber reinforcement is observed in Table 3.9 to have negligible effects on unit weight. On the average the light-weight concrete mixtures (with and without fibers) had a unit weight of 66% that of normal-weight concrete materials.

Table 3.9. Test Results of Fresh Concrete

	UNIT WEIGHT lb(kg)	SLUMP in (mm)	VEBE TIME (sec.)	AIR CONTENT (%)
Normal Weight Polyethylene Fiber Reinforced Concrete	146(2296)	3.25"	5-6 sec.	7.5
Light Weight Polyethylene Fiber Reinforced Concrete	95.96(1537)	3.5"	5 sec.	8.25
Light-Weight Polypropylene Fiber Reinforced Concrete	95(2331)	2.75"	4 sec.	7.75
Light Weight Plain Concrete	96(1546)	2.5"	6.5 sec.	8.00
Normal Weight Polypropylene Fiber Reinforced Concrete	145(2295)	2.75"	4.5 sec.	7.25

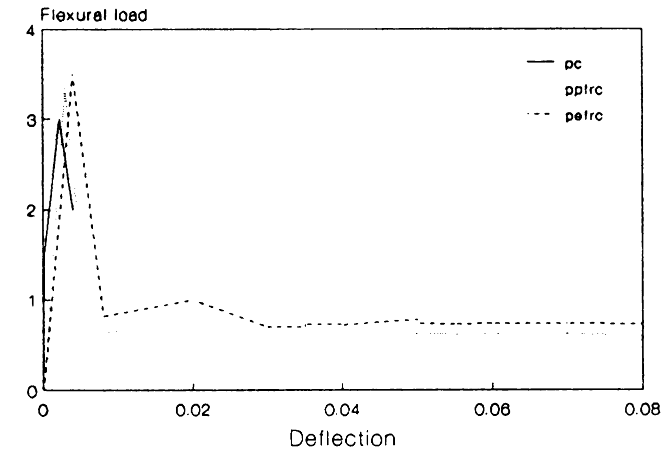
Table 3.9.--Continued

	UNIT WEIGHT lb(kg)	SLUMP in (mm)	VEBE TIME (sec.)	AIR CONTENT (%)
Normal Weight Polypropylene Fiber Reinforced Concrete	143(1517)	2.75"	5.5 sec.	7.1

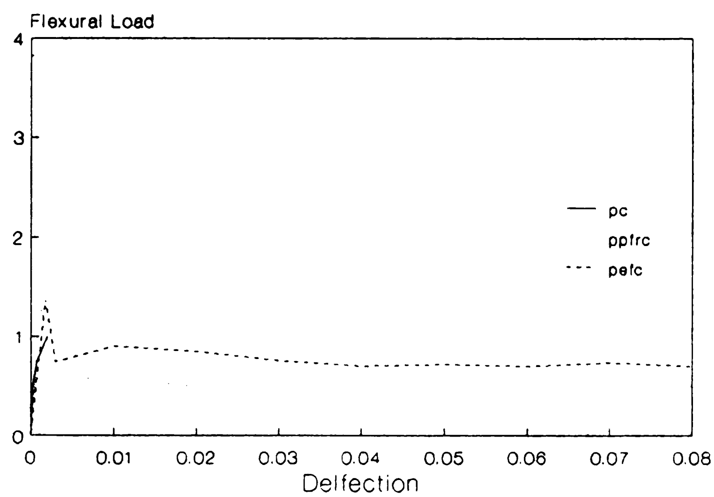
3.4.1 FLEXURAL BEHAVIOR

Typical load deflection curve for normal-weight and light-weight concretes incorporating no fibers and 0.25 percent polypropylene or polyethylene fibers are shown in Figures 3.6a and 3.6b. The flexural strength test results are given in Tables 3.10 and 3.11 for normal-weight and light-weight concrete materials, respectively. Tables 3.12 and 3.13 present the flexural toughness for normal-weight and light-weight cements, respectively.

Figures 3.6a and 3.6b are indicative of the positive effects of fibers on the post-peak ductility and toughness of concrete materials in flexure. The initial stiffness does not seem to be influenced significantly by the fiber reinforcement, but flexural strength tends to increase in the presence of synthetic fibers. Polyethylene fibers seem to be more effective than polypropylene fibers in enhancing the flexural behavior of normal-weight and light-weight concrete.



(a) Normal-Weight Concrete



(b) Light-Weight Concrete

Figure 3.6.--Flexural Load Deflection Curve

Table 3.10 Flexural Strength Test Result for Normal-Weight Aggregate Concrete in Psi (145 Psi = 1 Mpa).

Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
606.7	688	768
571	771	593
532.4	660	693
444.4	646	661
454	688	782
481	660	675
544.2	644	676
604.9	748	700
666.8	732	782
545.8		
Sample Mean - 545 Psi	695 Psi	696 Psi
Standard Deviation - 95 Psi	44 Psi	56 Psi
Co-efficient of Variation - 17.16%	6.95%	8.18%
95% Confidence Interval		
Lower Limit 456	662	652
Upper Limit 622	727	739

Table 3.11.--Flexural Strength Test Results for Light-Weight Aggregate Concrete in Psi (145 Psi = 1 Mpa)

Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
142.00	303.00	248.00
169.00	194.00	332.00
130.00	170.00	278.00
278.00	204.00	442.00
280.00	330.00	447.00
305.60	351.80	262.60
254.40	303.80	317.00
254.60	207.50	261.90
172.10	380.50	417.10
215.70	318.80	419.20
Sample Mean - 227 Psi	282 Psi	342 Psi
Standard Deviation - 62 Psi	71.24 Psi	84 Psi
Co-efficient of Variation - 27.6%	25%	24.37%
95% Confidence Interval		
Lower Limit 175	231	284
Upper Limit 285	333	400

Table 3.12.--Flexural Toughness Test Results for Normal-Weight Aggregate Concrete in K-in. (1 K-in - 113 N.M.)

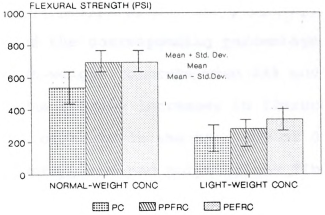
Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
0.0047	0.024	0.100
0.0040	0.021	0.059
0.0039	0.041	0.047
0.0051	0.067	0.056
0.0071	0.065	0.071
0.0076	0.051	0.073
0.0049	0.076	0.095
0.0035	0.067	0.076
0.0048	0.053	0.067
Mean - 0.005	0.051	0.071
Standard Deviation - 0.0014	0.019	0.017
95% Confidence Interval		
Lower Limit 0.004	0.038	0.059
Upper Limit 0.006	0.636	0.083

Table 3.13.--Flexural Toughness Test of Light-Weight Concrete in K-in (1 K-in = 113 N.M.).

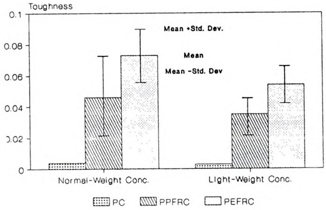
Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
0.0026	0.029	0.041
0.0014	0.033	0.063
0.0051	0.07	0.050
0.0040	0.06	0.049
0.003	0.03	0.045
0.0035	0.02	0.055
0.004	0.039	0.051
0.001	0.034	0.048
0.0033	0.031	0.062
Mean - 0.0031	0.038	0.051
Standard Deviation - 0.0019	0.018	0.0189
95% Confidence Interval		
Lower Limit 0.0019	0.036	0.038
Upper Limit 0.0043	0.06	0.063

Chi-Square goodness-of-fit test confirmed the normality of sample distributions for flexural strength test results at 5% level of significance, but showed poor fit of the flexural toughness test data to normal distribution. The relatively small sample size and the relatively large variations in toughness test data might be responsible for the deviation of replicated toughness test results from normal distribution.

The flexural strength and toughness test results are shown in Figures 3.7a and 3.7b, respectively.



(a) Flexural Strength



(b) Toughness

Figure 3.7 Effect of Synthetic Fiber Reinforcement at 0.25% Volume Fraction on the Flexural Strength and Toughness of Normal-Weight and Light-Weight Concrete Materials (PC = Plain Concrete; PPFRC = Polypropylene Fiber Reinforced Concrete; and PEFRC = Polyethylene Fiber Reinforced Concrete).

On the average, the flexural strength of normal-weight concrete increased by 26% and 27% in the presence of 0.25% volume fraction of polypropylene and polyethylene fibers, respectively, and the corresponding percentage increases in the case of light-weight concrete were 24% and 52%, respectively. The average increases in flexural toughness of normal-weight concrete in the presence of 0.25% volume fraction of polypropylene and polyethylene fibers were 1,000% and 1,300%, respectively, and the corresponding increases in the case of light-weight concrete were 1,300% and 1,500%, respectively.

Simple observation of the flexure test data together with analyses of variance of the results at 5% level significance led to the following conclusion regarding the effectiveness of polypropylene and polyethylene fibers in enhancing the flexural properties of normal-weight and light-weight concrete materials:

1. Both the synthetic fibers increase the flexural strength and toughness of normal-weight and light-weight concrete materials;

2. Polyethylene fibers are more effective than polypropylene fibers in enhancing the flexural strength and toughness of light-weight concrete; and

3. Considering the variations in flexural strength and toughness test results, in the flexural behavior of normal-weight concrete with polyethylene fiber reinforcement are not significantly superior to those obtained through polypropylene fiber reinforcement; this is in spite of the fact that polyethylene fibers produce higher average values of flexural toughness than polypropylene fibers;

4. There is a tendency in the variations in fluxural strength test results to be reduced with fiber reinforcement; and

5. The percentage increase in flexural strength with polypropylene fiber reinforcement is comparable in light-weight and normal-weight concrete. Polyethylene fibers, however, tend to be more effective in light-weight concrete than in normal-weight concrete (as far as the percentage increase in flexural strength is concerned). Both these conclusions are valid from the generated test data, at 5% level of significance.

The ratio of fiber modulus of elasticity to that of matrix is suggested to be one of the factors deciding the effectiveness of fibers in concrete materials. The higher this modular ratio the more effective it would be. With this hypothesis one may conclude that the same fibers can be more effective in light-weight concrete than in normal-weight concrete because of the lower modulus of elasticity of light-weight concrete. In order to verify the validity of this hypothesis the relationship between the flexural strength ratio (of fibrous to plain concrete materials) were investigated (see Figure 3.8) for the four fiber reinforced concrete materials considered in this project (polypropylene and polyethylene fiber reinforced concrete, with normal-weight and light-weight aggregates). The relationship between flexural strength ratio and modular ratio in Figure 3.8 is not consistent; this figure does not provide evidence of the dependence of flexural strength ratio on modular ratio, suggesting that the effectiveness of fibers in increasing flexural strength is not dependent on modular ratio for the specific conditions of this investigation. The correlation coefficient of flexural strength ratio versus modular ratio is 0.334, confirming the weak dependency of flexural strength ratio on modular ratio.

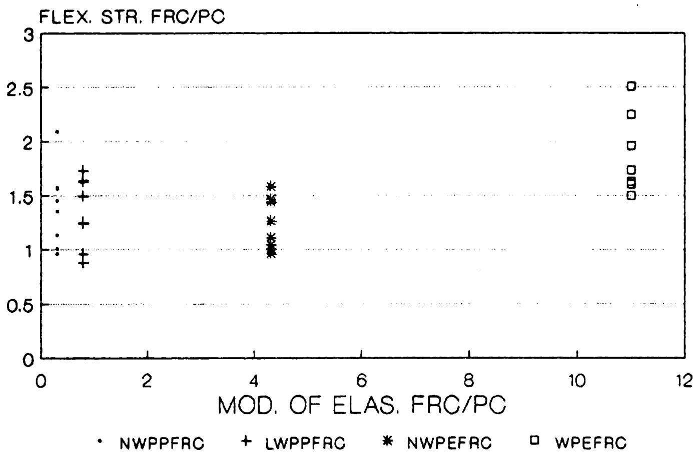


Figure 3.8 Relationship Between Flexural Strength Ratio and Modular Ratio.

The relationship between toughness ratio (of fibrous to plain concrete) and modular ratio in Figure 3.9 also does not provide evidence for the dependence of flexural toughness ratio on modular ratio, but the effectiveness of fibers in increasing flexural toughness is not dependent on modular ratio for the specific condition of this investigation. The correlation coefficient of flexural toughness ratio versus modular ratio is 0.358, conforming the weak dependency of flexural toughness ratio on modular ratio.

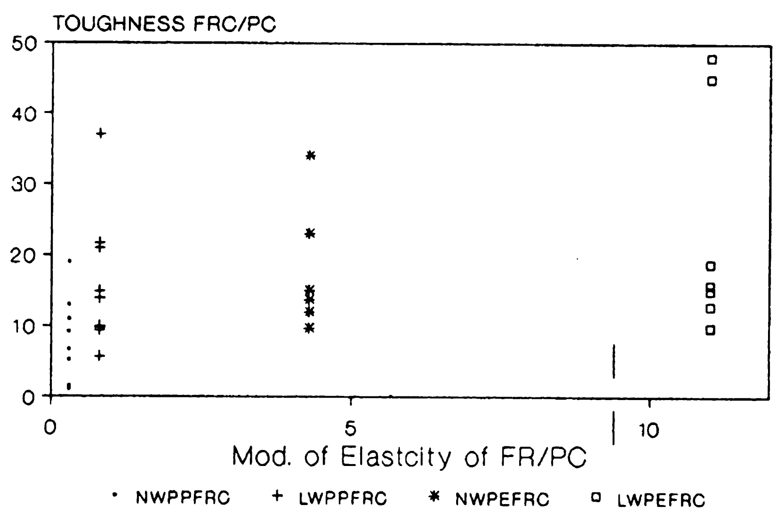


Figure 3.9.--Relationship Between Flexural Toughness Ratio and Modular Ratio

3.4.2 Impact Strength

Tables 3.14 and 3.15 present the impact strength test results at first crack and failure, respectively, for normal-weight concrete, and Tables 3.16 and 3.17 present the impact test results at first crack and failure, respectively, for light-weight concrete.

Table 3.14 Impact Test Results (No. of Blows to First Crack) for Normal-Weight Concrete.

Plain Concrete		Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
	11	23	42
	9	26	21
	7	11	24
	13	14	42
	24	20	20
	10	13	24
	20	11	50
	33	32	18
	17	12	135
	23	22	25
Mean	16	18	40
Std Dev	8	8.5	33
Coefficient of Variation	50%	46%	46%
95% Confidence Interval			
Lower Limit -	11	7	20
Upper Limit -	20	29	60

Table 3.15.--Impact Test Results (No. of Blows to Failure) for Normal-Weight Concrete.

	Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
	13	58	81
	11	51	51
	8	30	74
	14	38	81
	25	46	64
	12	40	50
	23	45	38
	35	47	155
	18	55	45
	24	38	75
Mean	17	46	71
Standard Deviation	8	9	33
Coeff-icient of Variation	45%	20%	46%
95% Confidence Interval			
Lower Limit -	12	39	51
Upper Limit -	21	46	91

Table 3.16.--Impact Test Results (No. of Blows to First Crack) for Light-Weight Concrete.

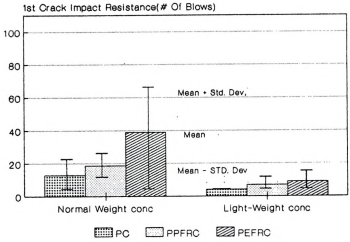
Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
1	6	8
2	6	13
3	10	10
2	6	12
7	7	6
7	6	12
5	5	9
4	9	11
2	4	6
4	4	14
Mean 4	6	10
Standard Deviation 2	2.1	2.8
Coeff-icient of Variation 57%	34%	29%
95% Confidence Interval		
Lower Limit 2.2	4.6	7.7
Upper Limit 5.2	7.6	11.7

Table 3.17 Impact Test Results (No. of Blows to Failure) of Light-Weight Concrete.

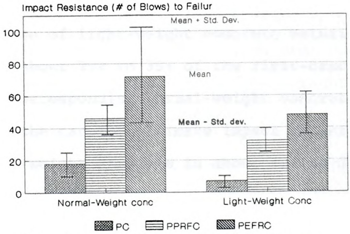
	Plain Concrete	Polypropylene Fiber Reinforced Concrete	Polyethylene Fiber Reinforced Concrete
	3	25	43
	5	20	64
	6	31	45
	6	34	61
	9	25	43
	10	31	27
	9	46	31
	6	38	42
	6	40	44
	5	35	64
Mean	7	32	47
Standard Deviation	2.2	7.7	13
Coeff-icient of Variation	33%	24%	28%
95% Confidence Interval			
Lower Limit -	4	27	37
Upper Limit -	8	38	55

Chi-square goodness-of-fit tests at 5% level of significance showed poor fit of the impact strength test data to normal distribution. The relatively small sample size and the relatively large variations in impact strength test results might be responsible for the deviation of replicated impact test data from normal distribution.

The first crack and ultimate impact strength test results for normal-weight and light-weight concrete materials are shown in Figures 3.10a and 3.10b, respectively.



(a) Impact Strength at First Crack



(b) Impact Strength at Failure

Figure 3.10.--Effect of Synthetic Fiber Reinforcement at 0.25% Volume Fraction on the Impact Strength at First Crack and Failure of Normal-Weight and Light-Weight Concrete Materials.

The average first-crack impact resistance of normal-weight concrete is improved by 12% and 150% through polypropylene and polyethylene fiber reinforcement, respectively. The corresponding improvements in the case of light-weight concrete are 50% and 180%, respectively, noting that plain light-weight concrete has a relatively low impact resistance. The ultimate impact strength of normal-weight concrete is improved by 170% and 310% through polypropylene and polyethylene fiber reinforcement, respectively. The corresponding improvements in ultimate strength of light-weight concrete are 357% and 570%, respectively. Reinforcement with synthetic fibers leads to more significant improvements in the ultimate impact resistance of concrete materials than in the first crack impact resistance.

It should be noted that on the average, the first-crack impact resistance of light-weight concrete materials (plain or fibrous) is about 25% to 35% of the first-crack impact resistance of corresponding normal-weight concrete materials. In the case of ultimate impact resistance, the value for light-weight concrete is about 40% to 70% that of normal-weight concrete.

Simple observations of impact test results together with factorial analyses of variance of the data at 5% level of significance led to the following conclusions regarding the effectiveness of polypropylene and polyethylene fibers in enhancing the impact properties of normal-weight and light-weight concrete materials.

1. Both synthetic fibers increases the first-crack and ultimate impact strength of normal-weight and light-weight concrete materials.
2. Polyethylene fibers are more effective than polypropylene fibers in enhancing the impact strength (1st crack and ultimate) of light-weight concrete and normal-weight concrete.
3. Both polypropylene and polyethylene fibers are more effective, at 5% level of significance, in increasing the ultimate impact assistance of light-weight concrete when compared with normal-weight concrete.
4. The light-weight concrete materials considered in this investigation (plain or fiber reinforced) possess lower impact resistance when compared with the corresponding normal-weight concrete materials (at 5% significance level).

The relationship between the ratios of fibrous concrete to plain concrete ultimate impact strengths and the modular ratio (of fibers to matrix) is presented in Figure 3.11. The modular ratio by itself does not seem in this figure to truly represent the degree of effectiveness of specific fiber types in a concrete matrix for the conditions of this investigation. The correlation coefficient for impact strength ratio versus modular ratio was 0.475, the weak dependence of impact strength ratio o ratio.

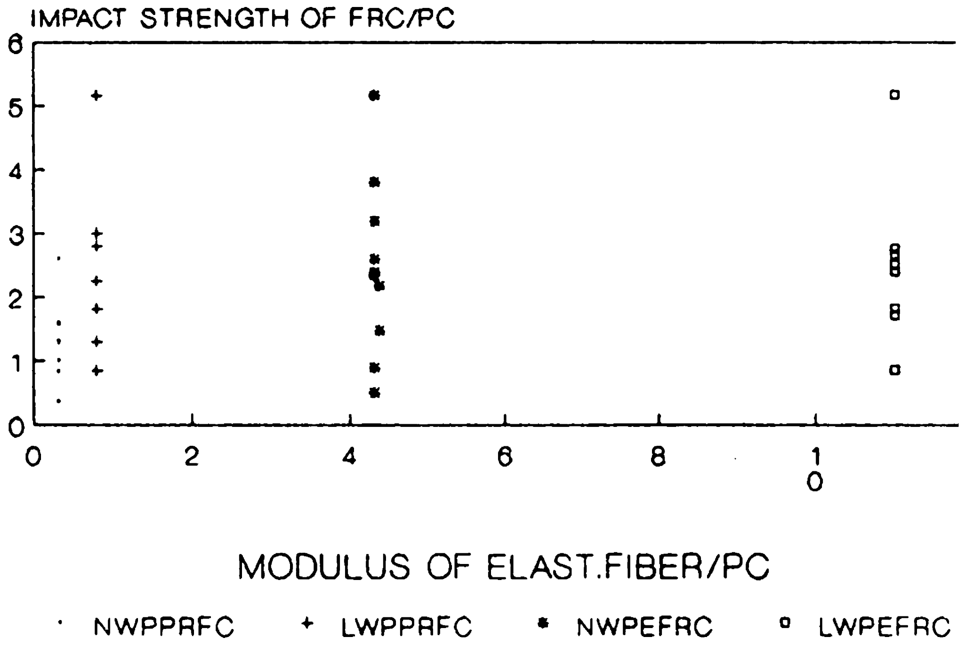


Figure 3.11.--Relationship Between Impact Stre Modular Ratio.

3.5 SUMMARY AND CONCLUSIONS

The effectiveness of different synthetic normal-weight and light-weight concrete materi investigated experimentally. Six concrete mix weight and light-weight concrete were studied; synthetic fibers (polypropylene and polyethyle at 0.25% volume fraction, and the remaining tw without fibers (plain). The light-weight conc incorporated a ceramic-based light-weight coar with normal-weight fine aggregate. The normal light-weight coarse aggregates had similar gra satisfying the ASTM C-33 and C-330 requirement proportions of coarse aggregate, fine aggregat

were kept constant in all mixtures. The dosage of superplasticizer was adjusted to give a constant slump in different mixes. The air content of different mixtures was maintained at a desirable level for frost resistance through the use of an air entraining agent at required dosages. The high-modulus polyethylene fiber used in this investigation had a higher tensile strength and a substantially higher modulus of elasticity when compared with the polypropylene fiber.

The fresh concrete mixtures were tested for slump, Vebe time, air content, and unit weight. The hardened concrete materials were tested for flexural behavior and impact resistance. The hardened material test data were replicated in order to allow for powerful analyses of variance of the test data. The following conclusions, derived based on the generated test data, are valid at 5% level of significance:

1. Fiber reinforcement has negligible effects on the unit weight of light-weight and normal-weight concrete materials. In the specific mixtures of this study, the light-weight concrete materials had unit weight of about 66% those of normal weight concrete (with and without fibers).
2. Both synthetic fibers increased the flexural strength and toughness of normal-weight and light-weight concrete materials.

3. Considering the variations in flexural strength and toughness test results, the improvement in flexural behavior of normal-weight concrete with polyethylene fiber reinforcement were not significantly superior to those obtained through polypropylene fiber reinforcement; this is in spite of the fact that polyethylene fibers produced higher average values of flexural toughness than polypropylene fibers.
4. There is a tendency in variations in the flexural strength test results to be reduced with fiber reinforcement.
5. As far as the percentage increase in flexural strength is concerned, polypropylene fibers produced comparable results in light-weight and normal-weight concretes at 5% level of significance. Polyethylene fibers are more effective in light-weight concrete than in normal-weight concrete.
6. No consistent relationship was observed in this study between the improvements in flexural properties with fiber reinforcement and the ratio of fiber-to-matrix modular elasticity.
7. Both synthetic fibers increased the first crack and ultimate impact strength of normal-weight and light-weight concrete materials.

8. Polyethylene fibers were more effective than polypropylene fibers in enhancing the impact resistance of light-weight and normal-weight concrete materials.

9. Both polypropylene and polyethylene fibers were more effective at 5% level of significance in increasing the impact resistance of light-weight concrete when compared with normal-weight concrete.

10. No consistent relationship was observed between the ultimate impact strength ratio (of fibrous to plain concrete) and the modular ratio of fibers to matrix.

11. The light-weight concrete materials considered in this investigation (plain or fibrous) possessed lower flexural strength, toughness, and impact resistance when compared with the corresponding normal-weight concrete materials (at 5% level of significance); an exception to this rule was observed for the flexural toughness of light-weight polypropylene fiber reinforced concrete which, at 5% level of significance, was comparable to that of normal-weight polypropylene fiber reinforced concrete.

CHAPTER 4

PERMEABILITY OF NORMAL- AND LIGHT-WEIGHT CONCRETE: EFFECT OF PRELOADING

4.1 INTRODUCTION

Permeability is one of the important factors effecting the durability of concrete. It controls the rate of entry of moisture that may contain aggressive chemicals responsible for the disintegration of concrete. Permeability of concrete depends on the volume and size of the interconnected capillary pores in cement paste, the microcracks that are present at the aggregate paste interfaces, and possibly the pore system characteristics of aggregate.

The interface microcracks seem to play an important role in establishing the interconnection between capillary cavities and increasing the permeability of concrete. They appear due to the differential shrinkage and thermal strains between the cement paste and aggregates, and can grow under externally applied loads. The interface microcracks are larger in width than most capillary pores present in cement paste.

Light-weight aggregates are typically more porous than normal-weight aggregates; they, however, may produce more desirable interface conditions with reduced microcracking. These two effects of light-weight aggregates tend to influence permeability in opposite directions.

4.2. OBJECTIVE AND SCOPE

The nature of the interface microcrack system is expected to be different in normal-weight and light-weight concrete materials. Light-weight aggregates with lower elastic modulus are expected to be more compatible with cement paste than normal-weight aggregates. Less interface cracks are expected to occur in light-weight concrete (4,9). Light-weight aggregates are, on the other hand, generally more porous and thus more susceptible to cracking under stress when compared with normal-weight aggregates. These differences are expected to lead to different permeability characteristics in light-weight concrete when compared with normal-weight concrete. One objective of this investigation is to compare the permeability of light-weight and normal-weight concrete materials.

Considering the significance of interface microcracks in deciding the permeability of concrete materials, the increase in microcrack intensity under increasing load is expected to influence the permeability of concrete materials. The nature of microcrack propagation is different in light-weight concrete when compared with normal-weight concrete. Another objective of this investigation is to assess and compare the effects of loading on the permeability of normal-weight and light-weight concrete materials.

This study has been conducted with specific types of light-weight and normal-weight aggregates, and with certain concrete mix proportions. The results are strictly applicable to these conditions.

The results are strictly applicable to these conditions. Within these conditions, however, replicated tests were conducted and the results were analyzed statistically in order to produce reliable conclusions with specified levels of confidence.

4.3 MEASUREMENT OF PERMEABILITY

Concrete permeability can be measured by different methods, including hydraulic head and rapid chloride permeability test techniques. In the hydraulic head method the concrete specimen is placed between two chambers having different pressure of fluid flow from the high-pressure chamber through the specimen to the lower chamber. Permeability in this method is usually expressed in ft/sec (m/sec) of fluid moving through the specimen (60). In the rapid chloride permeability test method a positive correlation has been shown between chloride ion penetration into concrete after 90 days of ponding and the electrical charge passed through the sample of concrete. An example of this correlation is shown in Figure 4.1.(58,59,60)

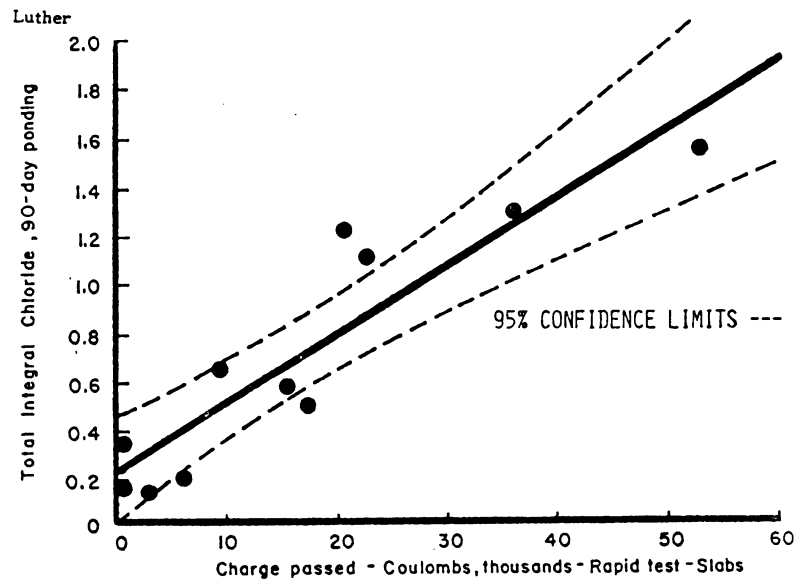


Figure 4.1.--Relationship Between Charges Passed During Rapid Chloride Test and Total Chloride Values in 90-Day Ponding Test.(59)

Basically, lower passed charge measurements were associated with lower permeability. Ultimately, a version of this passed electrical charge method was standardized as AASHTO T277-83 (Rapid Chloride Permeability Test). Although the AASHTO T277-83 method measures a specific passed charge number, the result is reported as lying within one of the following ranges or "classes": High, Moderate, Low, Very Low and Negligible. Table 4.1 represents the rapid chloride permeability passed charge levels (60).

Figure 4.1.--AASHTO T277 Test Classes of Chloride Permeability from Reference 60.

CHARGE PASSED COULOMBS	CHLORIDE PERMEABILITY	TYPICAL OF
>4000	HIGH	High Water Cement Ratio (^0.6) Portland Cement Concrete
2000 - 4000	MODERATE	Moderate Water Cement Ratio (0.4-0.5) Portland Cement Concrete.
1000 - 2000	LOW	Low Water Cement Ratio (0.4) Portland Cement Concrete
100 - 1000	VERY LOW	Latex Modified Concrete
<100	NEGLIGIBLE	Polymer Impregnated Concrete; Polymer Cement

4.4 EXPERIMENTAL PROGRAM

The effects of two variables on the permeability of concrete were studied experimentally. The variables were aggregate type (normal-weight versus light-weight), and the level of preloading (unloaded verses loaded in compression to 40% of compressive strength).

The basic concrete mix ingredients were Type I Portland Cement, light-weight and normal-weight fine sand, water, and an air entraining agent.

Gradation of light-weight and normal-weight aggregates are shown in Tables 3.2 and 3.4. The normal-weight and light-weight coarse aggregates both had a maximum particle size 1-3/4" (19 mm) and satisfied the ASTM C-330 and ASTM C-33 requirements. The normal-weight fine aggregates also satisfied ASTM C-33 gradation requirement. It is worth emphasizing that the aggregate gradations (by volume) in normal-weight and light-weight concrete materials were comparable.

A slump of 3" ± .5" (75 mm ± 12.5mm) was maintained in both light-weight and normal-weight concrete materials, through adjustment of water content. An air entraining agent was used to maintain the air content of fresh mixture in the range of 7 to 9% in order to ensure the frost resistance of concrete materials.

The mix proportions and fresh mix properties for normal-weight aggregate concrete is shown below:

		lb/yd^3 (kg/m^3)
Cement	=	704 (433.75)
Normal Weight Coarse Aggregate	=	1461 (867.5)
Normal Weight Fine Aggregate	=	1469 (871.5)
Water	=	(314) (185)
Air Entraining Agent	=	1% by weight of cement.
Slump	=	3 inches
Air Content	=	8%
Unit Weight		146 (2340)

The Mix Proportion for Light-Weight Concrete was as follows:

	lb/yd^3 (kg/m^3)
Cement	= 808 (475)
Light Weight Coarse Aggregate	= 404 (240)
Normal-Weight Fine Aggregate	= 1600 (950)
Water	= 318 (187)
Air Entraining Agent	= 1% by weight of cement.
Slump	= 2.75 inch
Air Content	= 8.9%
Unit Weight	= 95 (1522)

A conventional rotary drum concrete mixer was used for the production of normal-weight and light-weight concrete materials. The procedure adapted for producing the materials is described below:

1. Add the coarse and the fine aggregate with half the water into the mixer;
2. Start the mixer and add cement as the mixer is running.
3. Add remaining water with air entraining agent.
4. Continue mixing of concrete for three minutes.
5. Stop the mixer for two minutes
6. Start the mixer and run for two minutes.

From each mix (normal-weight and light-weight) twenty specimens (10 for unloaded and 10 for loaded permeability tests) were made. The specimens were prepared by placing concrete inside molds and compacting it through external

vibration. The sizes of cylindrical samples for loaded and unloaded permeability tests were 4 in. (100 mm) diameter by 8 in. (200 mm) long. The specimens were moist-cured for five days (one day inside the moulds, and four days after demoulding), and were then air-dried until the test usage of 28 days.

4.5 TEST PROCEDURES

The fresh mix workability was assessed by the slump test (ASTM C-143). The unit weight and air content tests on fresh mix were conducted according to ASTM C-138. The specimens used for the preloaded permeability tests were subjected to a compressive stress equal to 40% of the compressive strength of concrete. The compressive strength of normal-weight concrete materials, obtained through the performance of 10 replicated compression tests on 4 in. (100 mm) diameter by 8 in. (200 mm) high cylindrical specimens were 4850 psi (33 Mpa) and 2280 psi (15.5 Mpa) for normal-weight and light-weight concrete materials respectively. The corresponding co-efficient of variations were 7% and 18% respectively.

The test procedures outlined in AASHTO 277-83(59) were used to conduct chloride permeability tests on normal-weight and light-weight concrete materials. The cylindrical specimens to be used for this standard test are 4 in. (100 mm) in diameter and 2 in. (50 mm) high; they were cut from the mid-height of the cylindrical samples (unloaded or loaded) prepared from the mixtures considered in this investigation.

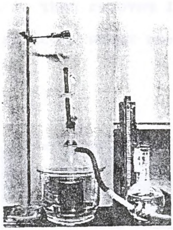


Figure 4.2.--Vacuum Saturation Apparatus

The equipment for the chloride permeability test consists of a vacuum saturation apparatus (Fig. 4.2), separatory funnel (500 ml capacity), beaker, vacuum desiccator, vacuum pump, voltage application apparatus and cell. Test procedure is as follows: (1) Brush the side of the specimen (4 in. diameter, 2 in. long) with rapid setting epoxy; (2) Place specimen in a beaker (1000 ml), and transfer the beaker to the vacuum desiccator; (3) Seal desiccator and attach it to a vacuum pump; (4) Start vacuum pump and maintain vacuum in the desiccator for three hours; (5) Drain water from the separatory funnel (500 ml) through the stopcock into the beaker after three hours of running the pump, submerge the specimen inside the beaker in water;

(6) Allow the pump to run one hour after submerging the specimen in water; (7) Stop the pump and soak specimen under water for (18±1) hours.

The specimen is then removed from water and sealed temporarily with silicon rubber sealant to the cell (Figure 4.3).

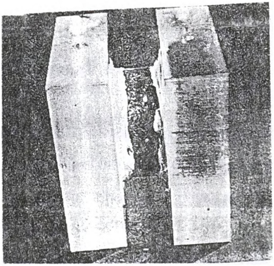


Figure 4.3.--Specimen for Testing.

The left side of the cell containing the top surface of the specimen is filled with a 3% solution (by weight) of NaCl, and the right side of the cell is filled with a 0.3N NaCl solution. The cell is then attached to post as shown in Figure 4.4.

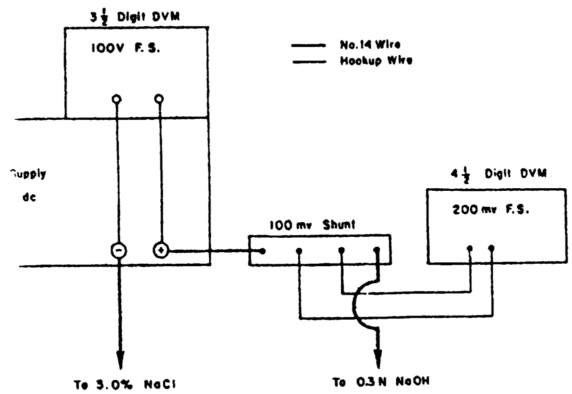


Figure 4.4. Electrical Block Diagram

A 60 DC voltage is applied across the specimen for 6 hours. The total cumulative charge passed through the specimen during this 6 hours is noted.

4.6 EXPERIMENTAL RESULTS AND DISCUSSIONS

The raw test data for the chloride permeability tests performed on normal-weight and light-weight aggregate concrete materials are shown in Table 4.2.

Chi-Square goodness-of-fit tests showed poor fit of the test data to normal distribution. This deviation may be due to the relatively small sample size and relatively large variations in test results. The permeability test results for light-weight and normal-weight concretes are shown in Figure 4.5. Simple observations together with one-way and two-way analyses of variance of test results (at 5% level of significance) indicate that:

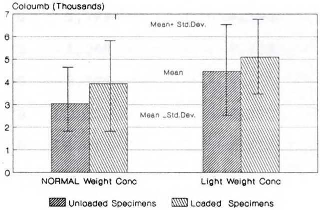


Figure 4.5. Permeability Test Results for Light-Weight and Normal-Weight Concrete.

Table 4.2.--Permeability Test Results

	Normal Weight Concrete		Light-Weight Concrete	
	Unloaded Coulomb	Loaded Coulomb	Unloaded Coulomb	Loaded Coulomb
1	4,600	4,977	6,442	6,378
2	4,600	5,799	6,595	6,615
3	1,203	2,349	4,135	5,380
4	2,080	2,349	1,625	2,122
5	2,840	2,173	2,778	3,335
6	3,450	7,195	5,798	6,627
7	1,880	2,780	4,136	4,326
8	1,767	2,211	3,388	3,510
9	4,193	4,649	6,442	6,328
10	3,880	4,856	3,380	3,910
Mean	3,040	3,933	4,471	4,853
Std Dev.	1,251	1,794	1,751	1,624
Co-Efficient of Variance	41%	45%	39%	31%
95% Confidence level				
Lower Limit	2,144	2,549	3,218	3,690
Upper Limit	3,935	5,217	5,724	5,015

1. The average chloride permeability of the unload light-weight concrete is 47% more than that of the corresponding normal-weight concrete; the variations in chloride permeability test results are, however, so

large (about 40% Co-efficient of variation) that a one way analysis of variance of test results, given the small sample size (10 specimens for each condition), can hardly confirm the difference in permeability of light-weight and normal-weight concrete materials at 5% level of significance.

2. Loading up to 40% of compressive strength increases the average permeability of normal-weight and light-weight concrete by 29% and 8%, respectively. Pre-loading seems to increase the permeability of normal-weight concrete more than light-weight concrete, possibly because the aggregate-paste interfaces in normal-weight concrete, when compared with light-weight concrete, are more susceptible to microcracking. Considering the large variations in test results, one way analysis of variance showed no major difference in the permeability of loaded and unloaded concrete materials for the relatively small sample size of 10 for each condition at 10% level of significance.

   Two-way analysis of variance also showed no effects (at 10% level of significance) of preloading on the chloride permeability of normal-weight and light-weight concrete materials.

3. While one-way analysis of variance at 10% level of significance showed higher permeability in unloaded light-weight concrete when compared with unloaded normal-weight concrete, since loading increased the average permeability of normal-weight concrete more than that of light-weight concrete, no difference could be detected between the permeability of preloaded normal-weight and light-weight concrete materials through one-way analysis of variance at 10% level of significance. This observation was made (considering the relatively large variation in test results) in spite of the fact that average permeability of preloaded light-weight concrete was 23% higher than that of preloaded normal-weight concrete.

4. Considering the relatively large variations in permeability test results (when compared with the effects of preloading in light-weight versus normal-weight concrete), the sample size chosen in this investigation (ten permeability test specimens for each condition) did not seem to be sufficient for powerful analyses of variance of test results. The power of one-way analysis of variance conducted in this investigation typically was less than 0.5, indicating that there is about a 50% chance of accepting a false hypothesis for the sample sizes used in this investigation.

4.7 SUMMARY AND CONCLUSION

The differences between permeability characteristics of normal-weight and light-weight concrete materials were investigated and the effects of compressive loading (up to 40% of compressive strength) on the permeability of normal-weight and light-weight concrete materials were studied. The light-weight and normal-weight concrete had comparable mix proportions (by volume) and performed similarly in the fresh state as far as slump and air content were concerned (the dosage of air entraining agent was adjusted for achieving comparable air contents). The light-weight coarse aggregate used in this investigation was ceramic-based, with specific gravity 0.58 and relatively low water absorption. The normal-weight coarse aggregates (crushed limestone) had a gradation similar to that of light-weight coarse aggregate, both satisfying ASTM requirements. The fine aggregate in both normal-weight and light-weight concrete was natural sand satisfying the ASTM gradation requirements.

The normal-weight concrete considered in this investigation had a specific gravity of 2.32 and a compressive strength 4880 psi (33 Mpa). The light-weight concrete had a specific gravity of 1.52 and a compressive strength 2280 psi (15.5 Mpa). The permeability test was conducted following the AASHTO T227-83 rapid chloride permeability test procedure which measures permeability based on the rate of diffusion of chloride ion into concrete.

Ten replicated permeability tests were conducted for each condition (unloaded and preloaded concrete materials of normal and light weight) and the results were analyzed statistically in order to compare the permeability in different conditions in light of the variations in test results. The following conclusions were derived based on the test data generated in this investigation.

1. Light-weight concrete materials were on the average 47% more permeable than normal-weight concrete materials. The variation in test results were, however, high (40% coefficient of variation), and a one-way analysis of variance at 5% level significance could hardly confirm the difference between the permeability of light-weight and normal-weight concrete. This difference was more easily distinguishable at 10% level of significance.

2. Compressive loading up to 40% of compressive strength increased the average permeability of normal-weight and light-weight concrete by 29% and 8%, respectively, indicating that interface microcracks under compression are more severe in normal-weight concrete than in light-weight concrete. The variation in test results were so high that one-way and two-way analyses of variance at 10% level of significance could not confirm the effect of loading on the permeability of normal-weight and light-weight concrete.

3. While unloaded light-weight concrete was more permeable than unloaded normal-weight concrete (as confirmed by one-way analysis of variance at 10% level of significance), smaller effect of loading on the permeability of light-weight concrete led to a condition where preloaded light-weight and normal-weight concretes showed comparable permeability characteristics as indicated by the results of one-way analysis of variance of the test data. This was partly a result of large variations in test results, noting that preloaded light-weight concrete was still 23% more permeable than preloaded normal-weight concrete.

4. Large variations in permeability test data require larger sample sizes to be used for more powerful statistical analyses of the permeability test data.

CHAPTER 5

MICROCRACKING AND FAILURE MECHANISM IN LIGHT-WEIGHT VERSUS NORMAL-WEIGHT CONCRETE

5.1 INTRODUCTION

Failure in concrete materials results from the propagation and interconnection of microcracks in the material under different load and environmental effects. Microcracks exist in concrete materials, particularly at aggregate-cement paste interfaces, prior to any loading due to differential movements between aggregate and cement paste caused by shrinkage and thermal movements or settlement of aggregates in the paste.

Past investigations on the microcracking and failure mechanism of concrete materials have mainly dealt with the effect of quasi-static loading on normal-weight concrete. This investigation is concerned with the effects of impact as well as quasi-static loads on microcracking and failure in normal-weight and light-weight concrete materials.

5.2 BACKGROUND

When concrete is subjected to increasing compression, at a certain critical stress the volume of concrete begins to increase rather than to decrease; the significance of this phenomenon was first recognized by Brandtzaseg (57), who suspected that the beginning of volume dilation indicates the beginning of internal disruption. Since then,

many investigators have realized the importance of critical stress. HSU, et al. (57), observed that in the vicinity of critical stress (70 to 90 percent of ultimate stress), internal microcracking through mortar starts to increase significantly (57).

Research in the last 20 years has proved that failure of concrete is subject to the process of microcracking, particularly at the interfacial region between cement paste and aggregate particles (7,2), which is the weakest link in concrete composites. These cracks were attributed to bleeding, segregation and volume change of cement paste during hydration of cement.

Like in other brittle materials, the failure process in concrete consists of three stages: crack initiation; slow crack growth; and rapid crack growth (4). The three stages determine the stress-strain behavior and failure of concrete, as shown in Figure 5.1 for normal-weight concrete (4). (56,57)

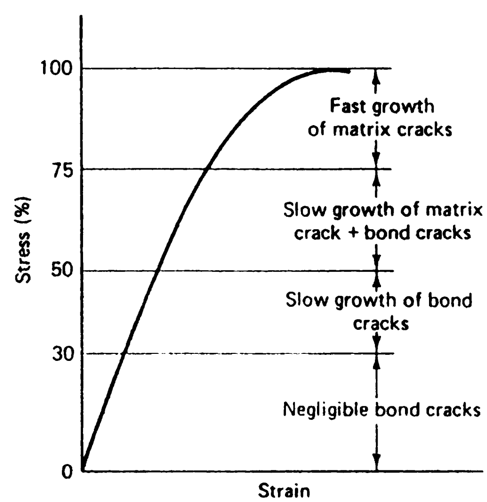
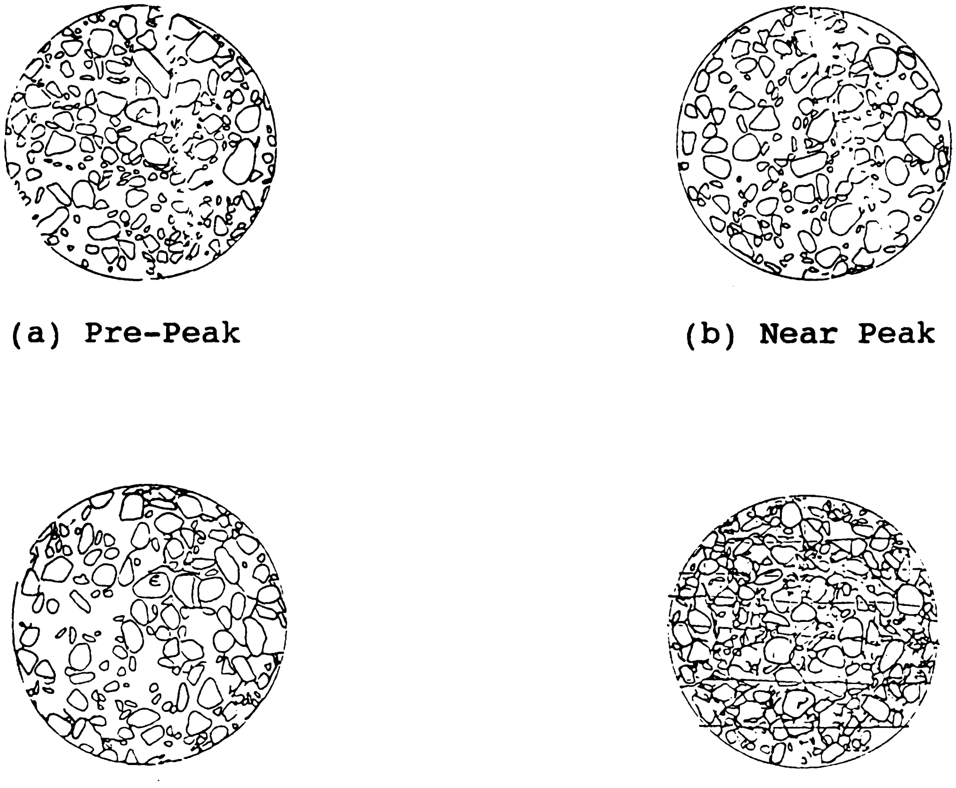


Figure 5.1.--Stress strain curve of concrete in Compression (7).

Below about 30 percent of the ultimate compression load, the stress-strain curve is almost linear (4) and at this stage, for normal-weight concrete, bond cracks exist in the material (Figure 5.2a); but these are quite stable and have little tendency to propagate. At 75-80% level of the ultimate compression load, propagation of cracks start in normal-weight concrete, as typically shown in Figures 5.2b and 5.2c for the pre-peak and post-peak conditions respectively. Severe growth and interconnection of microcracks in the post-peak region cause the fracture of concrete (See Figure 5.2d.



(a) Pre-Peak

(b) Near Peak

(c) Post-Peak

(d) Failure

Figure 5.2.--Microcrack Growth in Normal-Weight Concrete Under Compression (56).

5.3 EXPERIMENTAL PROGRAM

Microcracking and failure mechanism of light-weight versus normal-weight concrete under quasi-static and impact loads were investigated experimentally.

The basic mix ingredients were Type I Portland cement, light-weight coarse aggregate (for the light-weight mixtures), normal-weight coarse aggregate (for the normal-weight mixtures, normal-weight fine aggregate (for all mixtures), water, and an air entraining agent.

Gradation of normal-weight coarse and fine aggregates, and properties of the light-weight coarse aggregate, were presented in Chapter 3. The normal-weight and light-weight concrete materials had comparable gradations. A slump of 3" ± 0.5" (75 ± 12.5 mm) was maintained in normal-weight and light-weight concretes through adjustments in water content. An air entraining agent was used to maintain the air content of fresh mixtures in the range from 7% to 9% in order to ensure the frost resistance of the resulting concrete. For this purpose, the dosage rate of the air entraining agent was adjusted in the normal-weight and light-weight mixtures. The mix proportion for normal-weight and light-weight concrete are shown in Table 5.1. Both normal-weight and light-weight concrete materials have comparable proportions by volume of aggregates and cement.

Table 5.1 Mix Proportion

NAME	Cement lb/yd^3 (kg/m^3)	Water lb/yd^3 (kg/m^3)	Coarse Aggregate lb/yd^3 (kg/m^3)	Fine Aggregate lb/yd^3 (kg/m^3)
Normal-Weight Concrete	708(431)	311(185)	1452(862)	1458(865)
Light-Weight Concrete	800(476)	328(192)	404(240)	1592(949)

A conventional concrete mixer was used for the production of normal-weight and light-weight concrete. The procedure adapted for producing concrete is as follows:

1. Add the coarse and the fine aggregate with half of the water into the mixer;
2. Start the mixer and add all the cement while the mixer is running.
3. Add the remainder of water with air entraining agent.
4. Continue mixing of concrete for three minutes.
5. Stop the mixer for two minutes
6. Start the mixer and continue mixing for two minutes.

The specimens for microcracking studies through image analysis were cylinders 3 in. (75 mm) in diameter and 6 in. (150 mm) in length for quasi-static compression tests and 6 in. (150 mm) in diameter and 2.5 in. (62.5 mm) in length for impact tests. They were cast in molds and externally vibrated for compaction. The specimens were kept under a wet burlap with plastic sheet for 24 hours and then demolded and further moist-cured for another 4 days before being air-dried until the test age of 28 days. A total of thirty six compression and sixteen impact specimens were manufactured and tested for each of the normal-weight and light-weight concrete mixtures.

The workability of fresh mixtures was assessed by slump tests (ASTM C-143); the unit weight and air content tests on fresh mix were conducted according to ASTM C-138.

The compression tests were displacement-controlled with a quasi-static strain rate of 10^{-5}/sec. The compressive strength values were measured for ten specimens of each mix and are shown in Table 5.2.

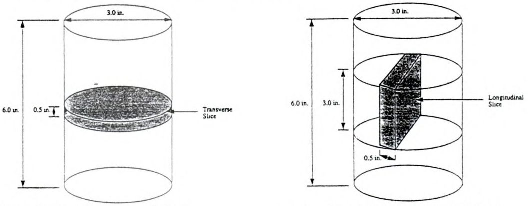
Table 5.2. Compressive Strength Test Results of Normal-Weight and Light-Weight Concrete.

	Normal-Weight Concrete, psi (Mpa)	Light-Weight Concrete, psi (Pma)
	4542 (31)	2075 (14)
	4712 (32.5)	2381 (16)
	5185 (35)	2648 (18)
	4934 (34)	2867 (19)
	4735 (32)	2507 (17)
	5610 (38)	2262 (15)
	4682 (32)	1485 (10)
	4592 (31)	2110 (14)
	4721 (32.5)	1870 (15)
	4312 (30)	1970 (13.5)
Mean	4733 (32)	2215 (15)
Standard Deviation	345 (2.37)	400 (2.75)
Co-efficient of Variation	7.2%	18%
95% Confidence Interval		
Lower Limit	4496 (31)	1928 (13)
Upper Limit	4990 (34)	2502 (15)

Based on the average compressive strength (f'c) obtained from ten tests for each mix eight stress levels were selected and two specimens of the same mix were loaded to eight stress levels. The following stress levels were considered in this study:

0.00 fc
0.30 fc Pre-Peak
0.83 fc Pre-Peak
1.00 fc Peak
0.93 fc Post-Peak
0.89 fc Post-Peak
0.81 fc Post-Peak
0.71 fc Post-Peak

Each specimen was then encased in a polyethylene fiber reinforced mortar in order to maintain the integrity of specimens during loading and preparation for image analysis (especially those loaded to large strains in the post-peak region). The specimens were then cut transversely and longitudinally; 1/2" (12 mm) slices were cut from the center of specimens as shown in Figure 5.3.



(a) Transverse Slice (b) Longitudinal Slice

Figure 5.3.--Location of Transverse and Longitudinal Slices

Impact tests were performed following the procedure recommended by ACI committee 544 (54). This test measures the amount of impact energy necessary to start a visible crack in concrete and then continue the opening of cracks until failure. The impact test is performed by dropping a standard 18 lb. (8.2 kg) hammer repeatedly and recording the number of blows required to cause the first crack on the top of the specimens.

The first-crack impact strength test results for 10 specimens of normal-weight and light-weight concrete are shown in Table 5.3.

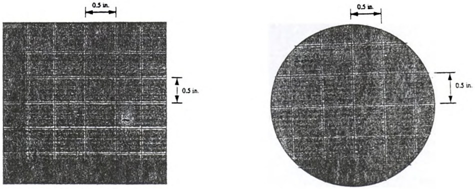
Table 5.3. First Crack Impact Test Results

	Normal-Weight Concrete	Light-Weight Concrete
	11	1
	9	2
	23	7
	7	4
	13	3
	24	5
	10	7
	10	4
	20	2
	33	2
	17	
Mean	16	4
Standard Deviation	8.26	2
Co-efficient of Variance	54%	50.0%
95% Confidence Interval		
Upper Limit	20	7
Lower Limit	11	4

Microcracking studies were conducted on impact specimens subjected to 0%, 35%, and 70% of the average first-crack impact loads. Image analyses were conducted only on transverse slices (Figure 5.3a) of impact test specimens.

5.4 IMAGE ANALYSIS PROCEDURE

Concrete slices were washed in a jet of water and allowed to dry in the lab environment for 24 hours. They were then stained with black indian ink, ground with silicon carbide on rotating laps over a sequence of 5 grit sizes: #180, 240, 320, 400, and 600. These specimen preparation steps help distinguish the microcracks under microscope. Figure 5.4 shows a view of longitudinal and transverse slices after being prepared for microstructural studies.



(a) Longitudinal Slice (b) Transverse Slice

Figure 5.4. Longitudinal and Transverse Slices Ready to be Viewed.

The slices were then examined for microcracking characteristics using an image analysis system (typical magnification 25 x). The cracks at the prepared faces of the slices were visible as black lines.

Image analyses were conducted after dividing the surface area of the slice into about thirty 13 by 13 mm (0.5 by 0.5 in.) squares, each to be viewed as a separate field of measurement (see Figure 5.5).

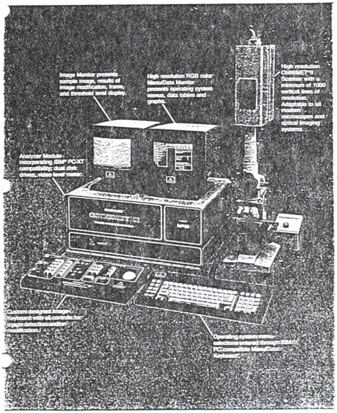


Figure 5.5. Image Analysis System.

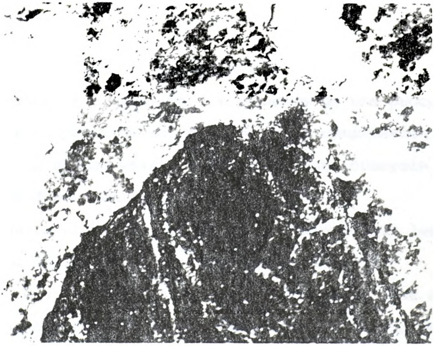
Once subdivided, the slices were looked at through a microscope connected to the image analysis system. For each field of view of microscope (which covers a 4 mm by 3 mm area within each 13 mm by 13 mm square of the mesh), the following three measurements were taken:

1. The intensity of bond microcracks at aggregate-cement interfaces shown in Figure 5.6 (with intensity defined as the total microcrack length per unit area);

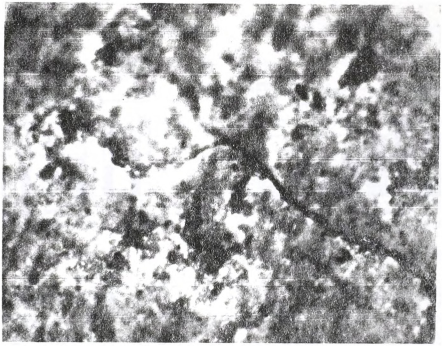
2. The intensity of matrix microcracks (Figure 5.6b); and

3. Microcrack orientations defined as the average inclination of microcracks with respect to the direction of loading (performed on the longitudinal slices only).

The measurements on microcrack intensity will reveal information on the process of failure in concrete materials under increasing stress levels and impact loads. The inclination of microcracks will also provide indications of the nature of failure mechanism under compression.



(a) Aggregate-Cement Interface Microcrack



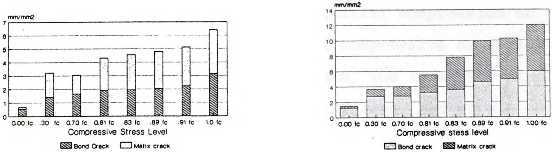
(b) Matrix Microcrack

Figure 5.6. Microcracks in Concrete Materials.

5.5 EXPERIMENTAL RESULTS AND DISCUSSIONS

The results of microstructural studies on the process of microcrack propagation and failure under compression and impact loads in normal-weight and light-weight concrete materials are discussed in this section.

The results of microcrack intensity (microcrack length per unit area of the cross section) measurements at different levels of compressive stress and impact load on normal-weight concrete materials are presented in Figures 5.7 and 5.8.



(a) Transverse Slice (b) Longitudinal Slice

Figure 5.7.--Microcrack Intensity at Different Compressive Stress Levels in Normal-Weight Concrete.

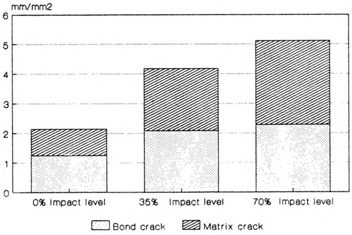
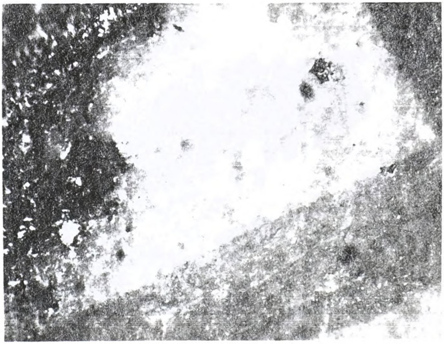
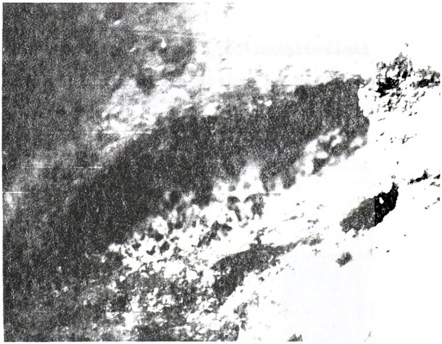


Figure 5.8. Microcrack Intensity at Different Impact Loading Levels in Normal-Weight Concrete (Transverse Slices).

Figures 5.7 and 5.8 indicate that normal-weight concrete incorporates microcracks (mainly at aggregate-paste interfaces) before any loading. These microcracks result from differential shrinkage and thermal movements between the paste and aggregates. Under initial compression or impact loading (up to about 30% of compressive or impact strengths) in normal-weight concrete, the intensity of microcracks at aggregate-paste interfaces, and within the paste increase rather rapidly. Thereafter, the increase in microcrack intensity with increasing compression or impact loading takes place mainly in the cement paste phase of normal-weight concrete materials. Typical micrographs of normal-weight concrete materials subjected to compression loading up to 70% of compressive strength, and impact loading up to 70% of impact resistance, are presented in Figures 5.9a and 5.9b, respectively. The aggregate-paste interface and paste microcracks can be observed in these micrographs.



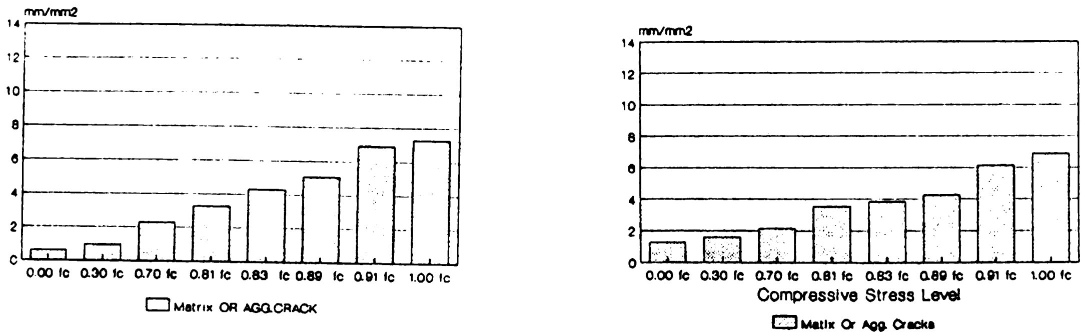
(a) Under Compression Loading (70% Compressive Strength)



(b) Under Impact Loading (70% of Impact Loading)

Figure 5.9. Microcrack of Normal-Weight Concrete Material (Magnification 5x).

The microcrack intensities in light-weight concrete under increasing levels of compressive stress are shown in Figures 5.10 and 5.11.



(a) Transverse Slice (b) Longitudinal Slice

Figure 5.10.--Microcrack Intensity at Different Compressive Stress Levels in Light-Weight Concrete.

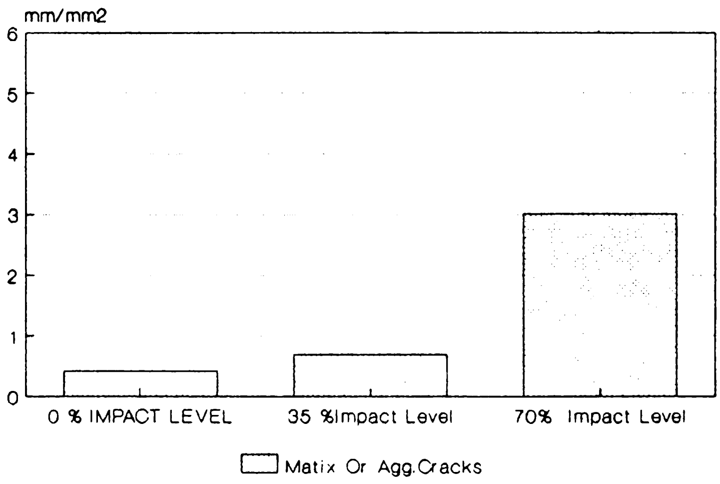
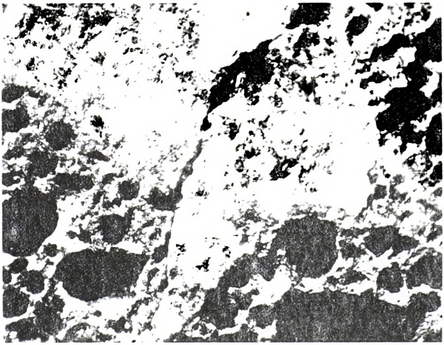


Figure 5.11. Microcracking Intensity at Different Impact Loading Levels in Light-Weight Concrete (Transverse Section).

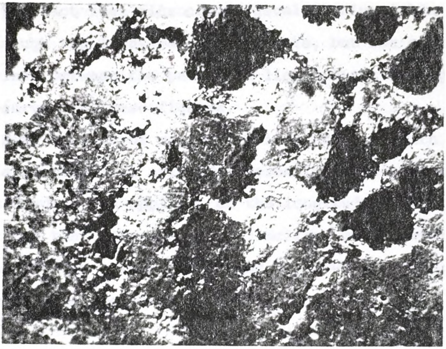
The process of microcracking and failure in light-weight concrete is distinguished from that in normal-weight concrete by the lack of interface cracks between cement paste and light-weight aggregates. Before any loading as shown in Figures 5.10 and 5.11, light-weight concrete incorporates only matrix cracks. This could be illustrated by the lower stiffness of light-weight aggregates which provide less restraint against shrinkage and thermal movements in paste, preventing the development of major interfacial stresses. Reduced settlement of light-weight aggregates inside the paste and thus reduced bleeding in light-weight concrete also leads to improved interface zone characteristics, further reducing the chance of microcrack development at aggregate-paste interfaces in light-weight concrete.

Comparison of Figures 5.7 and 5.10 and Figures 5.8 with 5.11 indicate that the microcrack system is more stable in light-weight concrete. Microcrack propagation in light-weight concrete takes place at a relatively slow rate initially (prior to about 50% of compressive or impact strength), and it does not reach the relatively high microcrack intensities observed in normal-weight concrete near ultimate compressive strength or impact resistance. The propagation of microcracks in light-weight concrete takes place either within the paste or through the aggregates. This could result from the relative weakness of light-weight aggregates when compared with the interface zone, and also from the fact that light-weight aggregates, due to their reduced stiffness, are more compatible with paste, causing a reduction in the level of interface cracks under load.

Typical micrographs of light-weight concrete materials subjected to compressive loading up to 70% of compressive strength, and impact loading of up to 70% impact strength, are presented in Figures 5.12(a) and 5.12(b), respectively.



(a) Under Compressive Loading (70% of Compressive Load)



(b) Under Impact Loading (70% Impact of Impact Strength).

Figure 5.12. Microcracking of Light-Weight Concrete Materials (Magnification 5x).

The fact that microcracks develop only within the paste or through the light-weight aggregate, but not at the interface between the paste and light-weight aggregates, can be observed in these figures.

Measurements of microcrack inclinations (with respect to the longitudinal axis of compressive specimens along which loading was applied) on the longitudinal slice indicated that microcracks are inclined on the average by 20° and 30° in normal-weight and light-weight concrete materials, respectively.

5.6 SUMMARY AND CONCLUSION

The process of microcrack propagation and failure in normal-weight and light-weight concrete materials under compression and impact loads were investigated experimentally using image analysis techniques. The results indicated that:

(1) Microcracks exist in concrete prior to any loading. In the case of normal-weight concrete, these microcracks appear both at the aggregate paste interfaces and also within the paste; for light-weight concrete, however, microcracks appear initially only within the paste.

(2) Microcrack intensities tend to increase under increasing compression and impact loads. This increase takes place in normal-weight concrete first mainly at the interfaces and then, at higher load levels, dominantly within the paste. In the case of light-weight concrete,

microcrack propagation takes place within the paste and through the aggregates, but not at the interfaces. The rate of microcrack propagation in light-weight concrete under compression and impact loads is lower than normal-weight concretes, and the microcrack intensity does not reach the relatively high levels observed in normal-weight concrete under ultimate compression and impact loadings.

(3) Matrix microcracks tend to be more inclined (with respect to the compressive stress direction) in light-weight concrete than in normal-weight concrete.

The lack of interface microcracks and the relatively stable nature of the microcrack system in light-weight concrete, when compared with normal-weight concrete, may be attributed to a number of factors including: (a) better compatibility of light-weight aggregates with cement paste (as far as the similarity of their elastic moduli are concerned) which reduce the interfacial stresses caused by differential shrinkage and thermal movements between the paste and aggregates; (b) reduced settlement of light-weight aggregates within the paste which leads to reduced bleeding and improved interface zone characteristics; (c) relative weakness of light-weight aggregates when compared with the interface zone; and (d) capability of flexible light-weight aggregates to absorb the energy transferred to the material by impact loading without damage to the interface zone.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 INTRODUCTION

Structural light-weight concrete materials possess higher strength-to-unit weight rations when compared with normal-weight concrete. This provides opportunities for reduction of dead load in concrete-based high rise buildings and long-span bridges. Production of now lower-cost light-weight aggregates using industrial by-products and recycled waste presents a recent development which can lead to major increases in the use of light-weight concrete. Various aspects of the performance characteristics of light-weight concrete materials made with a ceramic-based coarse light-weight aggregate were investigated and compared with those of normal-weight concretes with similar mix proportions (by volume) and fresh mix properties. The research was performed in three phases: (1) Assessment of the effectiveness of synthetic fibers with different elastic moduli; (2) measurement of permeability characteristics as influenced by loading; and (3) investigation of the microcracking process and failure mechanism under static and dynamic loads. A summary of the work conducted under each of these categories and the relevant conclusions are presented below.

6.2 EFFECTIVENESS OF DIFFERENT SYNTHETIC FIBERS IN NORMAL-WEIGHT AND LIGHT-WEIGHT AGGREGATE CONCRETE

The effectiveness of different synthetic fibers in normal-weight and light-weight concrete materials was investigated experimentally. Six concrete mixes of normal-weight and light-weight concrete were studied; in four mixes synthetic fibers (polypropylene and polyethylene) were used at 0.25% volume fraction, and the remaining two mixes were without fibers (plain). The light-weight concrete mixtures incorporated a ceramic-based light-weight coarse aggregate with normal-weight fine aggregate. The normal-weight and light-weight coarse aggregates had similar gradations satisfying the ASTM C-33 and C-330 requirements. The volume proportions of coarse aggregate, fine aggregate and cement were kept constant in all mixtures. The dosage of superplasticizer was adjusted to give a constant slump in different mixes. The air content of different mixtures was maintained at a desirable level for frost resistance through the use of an air entraining agent at required dosages. The high-modulus polyethylene fiber used in this investigation had a higher tensile strength and a substantially higher modulus of elasticity when compared with the polypropylene fiber.

The fresh concrete mixtures were tested for slump, Vebe time, air content, and unit weight. The hardened concrete materials were tested for flexural behavior and impact resistance. The hardened material test data were replicated in order to allow for powerful analyses of variance of the

test data. The following conclusions, derived based on the generated test data, are valid at 5% level of significance:

1. Fiber reinforcement has negligible effects on the unit weight of light-weight and normal-weight concrete materials. In the specific mixtures of this study, the light-weight concrete materials had unit weight of about 52% those of normal weight concrete (with and without fibers).
2. Both synthetic fibers increase the flexural strength and toughness of normal-weight and light-weight concrete materials.
3. Considering the variations in flexural strength and toughness test results, the improvement in flexural behavior of normal-weight concrete with polyethylene fiber reinforcement are not significantly superior to those obtained through polypropylene fiber reinforcement; this is in spite of the fact that polyethylene fibers produce higher average values of flexural toughness than polypropylene fibers.
4. There is a tendency in variations in flexural strength test results to be reduced with fiber reinforcement.
5. As far as the percentage increase in flexural strength is concerned, polypropylene fibers produce comparable results in light-weight and normal-weight concretes at 5% level of

significance. Polyethylene fibers are more effective in light-weight concrete than in normal-weight concrete.

6. No consistent relationship was observed in this study in the improvements in flexural properties with fiber reinforcement and the ratio of fiber-to-matrix modular ratio of elasticity.
7. Both synthetic fibers increased the first crack and ultimate impact strengths of normal-weight and light-weight concrete materials.
8. Polyethylene fibers were more effective than polypropylene fibers in enhancing the impact resistance of light-weight and normal-weight concrete materials.
9. Both polypropylene and polyethylene fibers were more effective at 5% level of significance, in increasing the impact resistance of light-weight concrete when compared with normal-weight concrete.
10. No consistent relationship was observed between the ultimate impact strength ratio (of fibrous to plain concrete) and the modular ratio of fibers to matrix.
11. The light-weight concrete materials considered in this investigation (plain or fibrous) possessed lower flexural strength, toughness, and impact resistance when compared with the corresponding

normal-weight concrete materials (at 5% level of significance); an exception to this rule was observed for the flexural toughness of light-weight polypropylene fiber reinforced concrete which, at 5% level of significance, was comparable to that of normal-weight polypropylene fiber reinforced concrete.

6.3 PERMEABILITY CHARACTERISTICS OF LIGHT-WEIGHT AND NORMAL-WEIGHT CONCRETE

The differences between permeability characteristics of normal-weight and light-weight concrete materials were investigated and the effects of compressive loading (up to 40% of compressive strength) on the permeability of normal-weight and light-weight concrete materials were studied. The light-weight and normal-weight concretes had comparable mix proportions (by volume) and performed similarly in the fresh state as far as slump and air content were concerned (the dosage of air entraining agent was adjusted for achieving comparable air contents). The light-weight coarse aggregate used in this investigation was ceramic-based, with specific gravity 0.58 and relatively low water absorption. The normal-weight coarse aggregates (crushed limestone) had a gradation similar to that of light-weight coarse aggregate, both satisfying ASTM requirements. The fine aggregate in both normal-weight and light-weight concrete was natural sand satisfying the ASTM gradation requirements.

The normal-weight concrete considered in this investigation had a specific gravity of 2.32 and a compressive strength 4880 psi (33 Mpa). The light-weight concrete had a specific gravity of 1.52 and a compressive strength 2280 psi (15.5 Mpa). The permeability test was conducted following the AASHTO T227-83 rapid chloride permeability test procedure which measures permeability based on the rate of diffusion of chloride ion into concrete.

Ten replicated permeability tests were conducted for each condition (unloaded and preloaded concrete materials of normal and light weight) and the results were analyzed statistically in order to compare the permeability in different conditions in light of the variations in test results. The following conclusions were derived based on the test data generated in this investigation.

1. Light-weight concrete materials were on the average 47% more permeable than normal-weight concrete materials. The variation in test results were, however, high (40% coefficient of variation), and a one-way analysis of variance at 5% level significance could hardly confirm the difference between the permeability of light-weight and normal-weight concrete. This difference was more easily distinguishable at 10% level of significance.

2. Compressive loading up to 40% of compressive strength increased the average permeability of normal-weight and light-weight concretes by 29% and 8%, respectively, indicating that interface microcracks under compression are more severe in normal-weight concrete than in light-weight concrete. The variations in test results were so high that one-way and two-way analyses of variance at 10% level of significance could not confirm the effect of loading on the permeability of normal-weight and light-weight concrete.
3. While unloaded light-weight concrete was more permeable than unloaded normal-weight concrete (as confirmed by one-way analysis of variance at 10% level of significance), smaller effects of loading on the permeability of light-weight concrete led to a condition where preloaded light-weight and normal-weight concretes showed comparable permeability characteristics as indicated by the results of one-way analysis of variance of the test data. This was partly a result of large variations in test results, noting that preloaded light-weight concrete was still 23% more permeable than preloaded normal-weight concrete.

4. Large variations in permeability test data require larger sample sizes to be used for more powerful statistical analyses of the permeability test data.

6.4 MICROCRACKING AND FAILURE MECHANISM IN LIGHT-WEIGHT VERSUS NORMAL-WEIGHT CONCRETE

The process of microcrack propagation and failure in normal-weight and light-weight concrete materials under compression and impact loads were investigated experimentally using image analysis techniques. The results indicated that:

(1) Microcracks exist in concrete prior to any loading. In the case of normal-weight concrete, these microcracks appear both at the aggregate paste interfaces and also within the paste; for light-weight concrete, however, microcracks appear initially only within the paste.

(2) Microcrack intensities tend to increase under increasing compression and impact loads. This increase takes place in normal-weight concrete first mainly at the interfaces and then, at higher load levels, dominantly within the paste. In the case of light-weight concrete, microcrack propagation takes place within the paste and through the aggregates, but not at the interfaces. The rate of microcrack propagation in light-weight concrete under

compression and impact loads is lower than normal-weight concretes, and the microcrack intensity does not reach the relatively high levels observed in normal-weight concrete under ultimate compression and impact loads.

(3) Matrix microcracks tend to be more inclined (with respect to the compressive stress direction) in light-weight concrete than in normal-weight concrete.

The lack of interface microcracks and the relatively stable nature of the microcrack system in light-weight concrete, when compared with normal-weight concrete, may be attributed to a number of factors including: (a) better compatibility of light-weight aggregates with cement paste (as far as the similarity of their elastic moduli are concerned) which reduces the interfacial stresses caused by differential shrinkage and thermal movements between the paste and aggregates; (b) reduced settlement of light-weight aggregates within the paste which leads to reduced bleeding and improved interface zone characteristics; (c) relative weakness of light-weight aggregates when compared with the interface zone; and (d) capability of flexible light-weight aggregates to absorb the energy transferred to the material by impact loading without damage to the interface zone.

APPENDIX I

DESCRIPTION OF LIGHT-WEIGHT AGGREGATES

APPENDIX I

DESCRIPTION OF LIGHT-WEIGHT AGGREGATES

This appendix presents the properties and production techniques of some commonly used light-weight aggregates.

Aggregate: Leca (Expanded Clay) (12,14,42):

Dry unit weight: 35-65 lb/cu.ft. (561-1041 kg/cu.m.)

Particle shape: Spherical

Concrete unit weight: 80-100 lb/cu.ft. (1282-1602.5 kg/cu.m.)

Concrete 28-day compressive strength: 2400-2500 psi (16.5-17.25 MPa)

Typical concrete applications: structural elements and insulating components.

Aggregate: Foamed Slag (Expanded Slag) (2,12,14,42):

Dry unit weight: 43.4 .b/cu.ft. (694 kg/cu.m.)

Water absorption (% by weight): 5-25

Production technique: This is an artificial light-weight aggregate manufactured from molten blast furnace slag which is heated up to 2192^{o}F (1200^{o}C); water and air are used for bloating the slag.

Typical practice size: 0.2-0.48 in. (5-12 mm)

Particle shape: Irregular.

Concrete unit weight: 86.8-117.8 lb/cu.ft. (1400-1900 kg/cu.m.)

Concrete 28-day compressive strength: 1015-4060 psi (7-28 MPa)

Typical concrete applications: structural reinforced concrete, and roof insulation.

Aggregate: Aglite (Sintered Shale)

Dry unit weight: 44 lb/cu.ft. (700 kg/cu.m.)

Production technique: Raw materials are diffused in a rotary kiln at temperature of 1832 to 2732^{o}F (1000 to 1500^{o}C); expansion occurs due to generation of gases. The fused materials are cooled and reduced to the required particle size.

Typical particle size: 0.4-0.6 in (10-15mm)

Particle shape: Irregular

Concrete unit weight: 100-115 lb/cu.ft. (1613-1855 kg/cu.m.)

Concrete 28-day compressive strength: 6000 psi (41.4 MPa)

Typical concrete applications: Structural light-weight concrete, roof insulation, and non-load-bearing walls.

Aggregate: Lytag (2,12,41,42):

Dry unit weight: 37-63 lb/cu.ft. (597-1016 kg/cu.m.)

Production technique: The raw material for the production of this aggregate is fly ash and coal dust. the fly ash and coal slurry are mixed together in a mixer. Mixing should be done carefully in order to keep the water and carbon contents controlled to produce strong pellets; these pellets are then heated up to a temperature of 2192 to 2372^{o}F (1200 to 1300^{o}C). This sintered fly ash aggregate is then crushed and graded.

Typical particle size: 0.2-0.5 in (5-12 mm)

Particle shape: Irregular

Concrete unit weight: 85-120 lb/cu.ft. (1371-1935 kg/cu.m.)

Concrete 28-day compressive strength: 2000-6000 psi (13.8-41.38 MPa)

Typical concrete applications: Structural reinforced and prestressed concrete.

Aggregate: Solite (expanded solite) (2,12,42):

Dry unit weight: 40-55 lb/cu.ft. (640-880 kg/cu.m.)

Production technique: Expanded solite is manufactured by heating solite in a rotary kiln at 1832 to 2192^{o}F (1000 to 1200^{o}C). The expanded mass thus produced due to the generation of gases in the kiln is cooled gradually to reduce the specific gravity of the expanded structure.

Typical particle size: 0.2-0.4 in (5-10 mm)

Particle shape: Irregular

Concrete unit weight: 50-118 lb/cu.ft. (806-1903 kg/cu.m.)

Typical concrete applications: Structural reinforced and prestressed concrete elements in high-rise buildings (to reduce load on foundations).

<u>Aggregate: Cinder (2,4)</u>:

Dry unit weight: 45-65 lb/cu.ft. (720-1040 kb.cu.m.)

Production techniques: Cinders are residues from combustion of coal or coke in industrial furnaces.

Concrete unit weight: 45-95 lb/cu.ft. (720-1000 kg/cu.m.)

Concrete 28-day compressive strength: 305-1000 psi (2.1-6.9 MPa).

Typical concrete applications: Concrete block, and plain concrete.

Comments: Use of cinders in reinforced concrete is not recommended because of sulphate contents which affect durability of concrete.

<u>Aggregate: Expanded slag (2,4,14,42)</u>:

Unit weight: 20-70 lb/cu.ft. (320-1121.8 kg/cu.m.)

Water absorption (% by weight): 5-25

Production techniques: There are two methods of producing expanded slag:

i) When molten slag is coming out of the furnace, water in the form of spray comes in contact with it. The steam thus generated makes the slag surface porous, leading to weight reductions. This process is called water jet process.

ii) A controlled amount of water is agitated with molten slag. Steam is entrapped in molten slag and, together with gas, reduces the slag weight. This process is called machine process.

Typical particle size: 0.2-0.4 in (5-10 mm)

Particle shape: Irregular

Concrete unit weight: 70-115 lb/cu.ft. (1121.8-1843 kg/cu.m.)

Compressive strength: 2000-6000 psi (13.8-42.4 MPa)

Concrete thermal conductivity: 0.98-1.9 Btu/ft^2.hr.^{o}F (1.7-3.3 W/mK)

Cost (\$/yd^3): 5-12 in 1972

Typical concrete applications: Insulating and structural concrete components.

Expanded shale and clay (2,4,14):

Unit weight: 35-65 lb/cu.ft. (561-1042 kg/cu.m.)

Water absorption (% by weight): 5-15

Production technique: The aggregates are produced by heating raw materials (clay, shale); at 1832 - 2192^{o}F (1000-1200^{o}C) expansion of these materials occurs due to generation of gases. These gases are entrapped within the diffused mass which is cooled to produce light-weight materials. Raw materials are processed to the desired size before heating.

Concrete unit weight: 70-115 lb/cu.ft. (1122-1829.5 kg/cu.m.)

Concrete 28-day compressive strength: 2000-6000 psi (13.8-41.4 MPa)

Concrete thermal conductivity: 1.1-2.6 Btu/ft^2.hr.^{o}F (1.9-4.5W/mK)

Particle shape: Spherical

Cost ($\$/yd^3$): 5-12 in 1972

Typical concrete applications: Prestressed and reinforced concrete elements.

Comments: If pelletized materials are used for the manufacture of aggregates, the particles will be nearly spherical in shape and they will have less water absorption rate.

Pumice and scoria, lava, tuft, volcanic cinder (2,14):

Dry unit weight: 33-55 lb/cu.ft. (529-881 kg/cu.m.)

Production technique: Natural light-weight aggregates.

Concrete unit weight: 50-80 lb/cu.ft. (801-1282 kg/cu.m.)

Concrete 28-day compressive strength: 580-725 psi (4-5 MPa)

Concrete thermal conductivity: 0.087-0.17 $Btu/ft^2.hr.^oF$ (0.15-0.30 W/mK)

Typical applications: Roof insulation

Comments: Pumice causes high shrinkage.

Ceramic spheres (43)

Dry unit weight: 35-65 lb/cu.ft. (560-1041 kg/cu.m.)

water absorption (% by weight): less than 0.5

Typical particle size: 0.12 - 0.40 in. (0.3 - 10 mm)

Particle shape: Spherical

Concrete thermal conductivity: 0.67-0.86 $Btu/ft^2.hr.^oF$ (1.08-1.48 W/mK)

Typical concrete applications: Insulation, light-weight structural concrete, and light-weight precast concrete units.

Comments: Macrolite ceramic spheres, typical ceramic spheres, are low-density spheres consisting of multiple minute independent air cells encircled by an outer shell which is very tough. The sphere has less absorption capacity as compared to other light-weight aggregates and can function at high temperatures.

Lycrete (42,CP110):

Aggregate unit weight: 87 lb/cu.ft. (1394 kg/cu.m.)

Production technique: The raw material is remnant of steel production; these remnants are heated up to 1832-2732^{O}F (1000-1500^{O}C) in kiln. Expansion occurs due to generation of gases during calcination.

Typical particle size: 0.2-0.56 in (5-14 mm)

Particle shape: Spherical

Unit weight of concrete: 45-125 lb/cu.ft. (1400-2000 kg/cu.m.)

Concrete 28-day compressive strength: 980-7000 psi

Typical concrete applications: Structural reinforced concrete.

Expanded polystyrene (14):

Unit weight: 2-10 lb/cu.ft. (32-192 kg/cu.m.)

Water absorption (% by weight): 5-10

Production technique: Produced by heating and treatment of polystyrene. Raw material is saturated hydrocarbon (low molecular weight).

Unit weight of concrete: 20-55 lb/cu.ft. (322-877 kg/cu.m.)

Concrete 28-day compressive strength: 100-1800 psi (0.69-12.4 MPa)

Typical concrete applications: Insulation concrete

Comments: More research is needed to make plastic-originated aggregates suitable for structural use.

Carbonized cereal (14):

Unit weight: 4-12 lb/cu.ft. (64-192 kg/cu.m.)

Production technique: Raw materials are wheat, corn and rice. By the process of puffing and distilling, the raw materials are converted into aggregates.

Unit weight of concrete: 40 lb/cu.ft. (641 kg/cu.m.)

Concrete 28-day compressive strength: 800 psi (5.5 MPa)

Concrete thermal conductivity: <0.58 Btu/ft^2.hr.^{o}F (<1.0 W/mK)

Cost (\$/yd^3): 2.7 in 1972

Typical concrete application: roof decking

Comments: The aggregates have large pores and are highly porous. If the large pores are either reduced or eliminated, the strength of aggregate could be improved.

Exfoliated vermiculite (2,7,14):

Unit weight: 4-12 lb/cu.ft. (64.5-192 kg/cu.m.)

Water absorption (% by weight): 20-35

Production technique: Vermiculite is magnesium-aluminum-iron hydrous silicate. Expanded vermiculite is manufactured by heating vermiculite to 1202-1832^{o}F (650-1000^{o}C). Due to high temperature, vermiculite expands and becomes light as compared to its original weight.

Unit weight of concrete: 25-60 lb/cu.ft. (403-968 kg/cu.m.)

28-day compressive strength: 95-420 psi (0.65-3.9 MPa)

Concrete thermal conductivity: 0.29-0.64 Btu/ft^2.hr.^{o}F (0.5-1.1 W/mK)

Cost (\$/yd^3): 4.3-13 in 1972

Typical concrete applications: Roof insulation

Comments: More expensive than regular light-weight aggregates; highly porous; greater water absorption capacity.

Expanded glass (7,12,14:

Unit weight: 15-30 lb/cu.ft. (250-500 kg/cu.m.)

Water absorption (% by weight): 5-10

Production technique: Origin is glass. Production of expanded glass is possible by heating pelletized mixtures of glass and expanding the material in rotary kiln at 1292-1472^{o}F (700-800^{o}C).

Concrete unit weight: 17 lb/cu.ft. (1209 kg/cu.m.)

7-day compressive strength: 1300 psi (8.9 MPa)

Concrete thermal conductivity: 0.162 Btu/ft^2.hr.^{o}F (0.28W/mK)

Typical applications: roof insulation, blocks, and panels.

Comments: New material, yet to be improved.

Expanded perlite (2,14):

Unit weight: 29-113 lb/cu.ft. (465-1810 kg/cu.m.)

Water absorption (% by weight): 10-50

Production technique: It has a volcanic origin. The raw material is heated up rapidly to 1832^{o}F (1000^{o}C) for the production of expanded perlite aggregate. During the heating process the moisture which is present in the raw material converts into steam and causes expansion of the original material and reduction of weight.

Concrete unit weight: 35-60 lb/cu.ft. (564-960 kg/cu.m.)

28-day compressive strength: 80-500 psi (.55-3.4 MPa)

Concrete thermal conductivity (k factor): 0.29-0.58 Btu/ft^2.hr.^{o}F (0.5-1.0 W/mK)

Typical applications: Roof insulation

Comments: This aggregate has a relatively high water absorption capacity; concrete made with expanded perlite is fast-drying and can be finished rapidly.

Brick rubble (14):

Unit weight: 47 lb/cu.ft. (758 kg/cu.m.)

Water absorption (% by weight): 19-36

Production technique: Origin is clay. Sand and clay are

blended in water; bricks are made from this mixture and dried in the sun. The dried bricks are heated in kiln and, after cooling, cut to size.

Particle shape: Irregular

Unit weight of concrete: 110-120 lb/cu.ft. (1779-1935 kg/cu.m.)

Concrete 28-day compressive strength: 3000 psi 20.7 MPa).

Concrete thermal conductivity (k factor): 2.2-2.9 $Btu/ft^2.hr.^oF$ (3.8-5.0 W/mK)

Typical applications: Concrete blocks; Floors.

<u>Fused clinker (4)</u>:

Unit weight: 65-100 lb/cu.ft. (1048-1613 kb/cu.m.)

Concrete thermal conductivity (k factor): 1.8-3.8 $Btu/ft^2.hr.^oF$

Typical concrete applications: Interior concrete; precast clinker blocks.

Comments: Highly expansive, could not be used in reinforced concrete.

<u>Air cooled slag (14)</u>:

Unit weight: 70-90 lb/cu.ft. (1129-1451 kg/cu.m.)

Water absorption (% by weight): 1-5

Production technique: Raw material is iron ore. Molten slag is let to cool under atmospheric pressure.

Concrete thermal conductivity (k factor): 3.48-4.64

Btu/ft^2.hr.^{o}F (6-8 W/mK)

Unit weight of concrete: 115-130 lb/cu.ft. (1885-2096 kg/cu.m.)

Concrete 28-day compressive strength: 3000-6000 psi (2-.68-41.34 MPa)

Particle shape: Irregular

Typical particle size: 0.08 in. (2 mm)

Typical concrete applications: Structural concrete; precast blocks.

Granulate slag (14):

Unit weight: 55-65 lb/cu.ft. (887-1048 kg/cu.m.)

Water absorption (% by weight): 4-15

Production technique: Raw material is iron ore. Produced by rapid quench of the molten slag.

Concrete 28-day compressive strength: 3000 psi (21 MPa).

Cost ($/yd^3): 0.6-1.2 in 1972

Typical applications: Structural concrete; prestressed concrete.

Comments: It is a glassy material.

Synopal (14):

Unit weight: 65-80 lb/cu.ft. (1048-1290 kg/cu.m.)

Water absorption (% by weight): 0.7-2.0

Production technique: The origin of synopal is calcium silicate. The manufacturing of synopal consists of heating of raw material in a double kiln process in which the

materials react in the first kiln and the product is then annealed in the second kiln.

Concrete unit weight: 115-125 lb/cu.ft. (1855-2016 kg/cu.m.)

Concrete 28-day compressive strength: 3000-6000 psi (20.7-41.9 MPa)

Typical concrete applications: Structural concrete; highway pavements.

Comments: Concrete has high light reflection and skid resistance.

APPENDIX II

MIX PROPORTIONING PROCEDURES

APPENDIX II

MIX PROPORTIONING PROCEDURES

Common methods of light-weight aggregate concrete mix porportioning are presented in this Appendix. Procedures for the adjustment of mix proportions and examples of light-weight concrete mix design are also given.

As mentioned in Chapter 2, there are differences in mix proportioning of normal-weight and light-weight concretes. This is partly because light-weight aggregates have a high absorption capacity and thus the water-cement ratio of light-weight aggregate concrete cannot be fixed (13). Hence, mix proportioning of light-weight concrete is generally accomplished by the cement content-strength method (11), instead of the method based on water-cement ratio. In the "cement content-strength method" of mix proportioning, the cement content depends on the strength of light-weight aggregate concrete (which is normally specified prior to mix design). The quantity of water is decided based on the desired slump value. With the cement and water contents known, the aggregate content in the mix design is then decided. An alternative method for the mix proportioning of light-weight concrete is the "weight method".

II.1 "Cement Content" Method

The following steps should be taken in the "cement content-strength method" for the proportioning of available materials into a mix suitable for a specific job.

Step 1. Selection of slump: If slump is not specified, a value suitable for a job can be taken from Table II.1.

Table II.1. Recommended slump values (11).

Type of Construction	Slump in (mm)	
	Max.	Min.
Beam & reinforced wall	4 (100)	1 (25)
Building column	4 (100)	1 (25)
Floor slab	3 (75)	1 (25)

The slump values suggested in Table II.1 can be used where vibrators are employed for the consolidation of concrete.

Step 2. Selection of Maximum Aggregate Size: The maximum aggregate size should not exceed 1/5 of the narrowest dimension between sides of form, 1/3 the depth of the slab, or 3/4 of the minimum spacing between reinforcing bars. If concrete can be placed without voids and honeycombing these limitations can be waived.

Step 3. Calculation of Cement Content: As the cement content varies for different types of aggregate, the aggregate supplier should be consulted regarding the cement content to be used in a mix. In case information from producer/supplier are not available, the cement content can be taken from Table II.2.

At the same compressive strength, light-weight concretes typically have higher cement contents than normal-weight concretes (Table II.2).

Table II.2 Cement content of light-weight and normal-weight concretes (7).

Compressive Strength		Cement content lb/yd^3 (kg/cu.m.) Light-Weight		Normal-Weight	
lb/in^2	(MPa)				
2500	(17)	425-700	(255-420)	350-550	(210-330)
3000	(21)	475-750	(285-450)	350-600	(210-360)
4000	(28)	550-850	(330-510)	400-700	(240-420)
5000	(35)	650-950	(370-560)	500-750	(300-450)

Step 4. Water and Air Contents: Air contents in the range of 5 to 9% should be incorporated into the mix in order to avoid frost damage. Factors influencing slump are the water and air contents and the maximum aggregate size. Table II.3 presents approximate values for water requirements in air-entrained light-weight concrete, depending on the required values of slump and aggregate size. Suggestions for the required air content as a function of the exposure condition and maximum aggregate size are also presented.

Table II.3 Approximate water and air contents required in air entrained light-weight concrete (11).

Slump in inch	Water in lb/yd^3 of concrete for indicated max. size of aggregate. 3/8"	1/2"	3/4"
	Air Entrained Concrete.		
1 to 2	305	295	280
3 to 4	340	325	305
5 to 6	355	335	315
Exposure of concrete	Recommended average total air content percent.		
Mild	4.5	4.0	4.0
Moderate	6.0	5.5	5.0
Extreme	7.5	7.0	6.0

<u>Step 5. Estimation of Light-Weight Aggregate Volume</u>: Total volume of light-weight aggregate required, measured as the sum of uncombined volumes on a dry-loose basis, is typically from 28 to 34 cu.ft. per cu.yd· of concrete (1.0 to 1.2 cu.m. per cu.m. of concrete). Of this quantity, the fine aggregate volume may be from 40 to 60 percent. The aggregate producer may be consulted before making a final decision on aggregate volume. Aggregate supplier should also be consulted for first-trial mix proportions; such mix proportions may be the result of previous experience or previously established mix proportions for concrete. This first-trial mix proportion may be adjusted as necessary to change the properties of concrete.

The "weight method" for mix proportioning of light-weight aggregate concrete, which is an alternative to the "cement content-strength" method is described below.

II.2 "Weight" Method

This procedure for selection of mix proportions can be applied to both light-weight and semi light-weight aggregate concrete. In semi light-weight concrete, normal-weight fine aggregate is used in order to prevent floating of coarse light-weight aggregate. The specific gravity of aggregates, which is required for batch weight estimation, is determined by pycnometer method. Effective mixing water could be calculated by dry spin method.

Estimates of water-cement ratio, minimum cement content, air content, slump, maximum size of aggregate, strength and unit weight of aggregate, may be made before designing a mix for a specific job.

If the slump and maximum size of aggregate are not specified for a mix, the value of slump and aggregate size may be chosen as follows. Slump could be selected from Table 2.3. Maximum aggregate particle size should be less than 1/5 of the narrowest dimension between the sides of form (2,11,16); the supplier/producer of aggregate may have more accurate suggestions for the size of aggregates.

Estimation of mixing water and air contents: Generally, the strength of concrete determines the water-cement ratio of a mix. Durability and finishing properties of concrete are factors which can not be ignored while deciding the water-cement ratio of concrete. Relationships between water-cement ratio and strength may be developed for different types of aggregate and cement. If such relationships are not available, Table II.4 can be used for the selection of water/cement ratio.

Depending on aggregate texture and shape, mixing water requirements may be somewhat above or below the tabulated values, but the values given in the table are sufficiently accurate for the first estimates.

Table II.4 Estimated Water-Cement Ratios (11).

Compressive strength of concrete.		Approximate water-cement ratio.	
psi	MPa	Non-air entrained concrete	Air entrained concrete.
6000	41	.41	-
5000	34	.48	.40
4000	28	.57	.48
3000	21	.68	.50
2000	14	.52	.74

Cement content: Light-weight aggregates absorb water and the water-cement ratio depends on the rate of absorption of light-weight aggregates. Hence, it is difficult to use water-cement ratio for the calculation of cement content, because water-cement ratio will vary during mixing. Proportioning of light-weight concrete mixtures on the basis of cement content is thus advisable. The cement content can be selected from Table II.2.

Light-weight coarse aggregate content: The amount of light-weight coarse aggregate can be found out from Table II.5 for different types of fine aggregate having different fineness moduli. The fine aggregate content will be the difference between total weight and the sum total of the weight of water, cement and light-weight coarse aggregate.

Table II.5 Volume of coarse aggregate per unit of volume of concrete (11).

Maximum size Aggregate		Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand.			
inch	mm	2.40	2.60	2.80	3.00
3/8	10	0.50	0.45	0.46	0.44
1/2	13	0.59	0.57	0.55	0.53
3/4	19	0.66	0.64	0.62	0.60.PA

Light-weight aggregate has a high absorption capacity. The absorption of water leads to an increase in the weight of light-weight aggregate. The absorbed water by aggregate will be deducted from the mixing water added to the batch of materials to be used in concrete mixer for producing concrete.

II.3 Adjustment of mix proportions

After completion of mix proportioning for a light-weight concrete mix, some adjustments in the mix proportions are necessary either due to absorbed water in light-weight aggregate or variations in materials at field or laboratory. If these adjustments are small, rule of thumb, using guidelines of Table II.6, may be applied for adjusting the mix proportions.

Table II.6 Guidelines for Adjustment of Mixes of Light-Weight Concrete (11).

Change required	Amount of change	lb (kg) changes in "other quantities per yd^3 (m^3) of concrete.
Fineness content	+1%	+4.41 (2) water
Air content	+1%	-6.61 (3) water
Slump	+1" (+25mm)	+132 (6) water + 3% cement.

A procedure based on absolute volume method can be used for making adjustments in mix proportions. This procedure consists of calculating the quantity of light-weight aggregate in concrete which depends on the moisture content and specific gravity of aggregate. The specific gravity can be determined by pycnomenter method (11).

II.4 Examples of Mix Proportions

Typical mix proportions for light-weight aggregate concrete reported in the literature are presented below.

(a) Ref. 28

	(lb)	(kg)
Type I cement	611	277
Fly ash	97	44
Livlite coarse	350	159
Livlite medium	416	142
Livlite fine	314	142
Water	346	157
WRDA	56 oz	1.6
Vinsol Resin	44 oz	1.3

(b) Ref. 2

	(lb)	(kg)
Cement	550	34.3
Fine aggregate	895	55.5
Coarse aggregate	705	44.0
Water	485	30.3

(c) Ref. 11

	(lb)	(kg)
Cement	529	33.0
Coarse light-weight Aggregate	696	43.5
Fine aggregate	365	23.0
Water	443	27.5

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