INTERRUPTED CURING, RECURING, AND THE DURATION OF CURING OF PLAIN AND POZZOLANIC CONCRETES

By

MOHAMMAD SHAMIM KHAN

Bachelor of Science
Aligarh Muslim University
Aligarh, U.P., India
1980

Master of Science
University of Petroleum and
Minerals, Dhahran
Saudi Arabia
1985

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Thesis Approved:

Thesis Adviser

Dean of the Graduate College

PREFACE

An experimental study is presented on the effects of interrupted curing and recuring, and the curing requirements of pozzolanic concretes. These factors have important bearing on the short and long term performance of concrete, and influence the cost of concrete construction both directly and indirectly. The results of this study are valuable to the construction industry as they have resolved several myths associated with the curing of concrete.

This thesis is divided into six chapters. The first chapter describes the basis for the research, presents a statement of the problem, and clearly states the objectives. A detailed literature review is included in the second and third chapters to provide background information on the subject, and to highlight the significance of the present research. The fourth chapter describes the details of the experimental investigation including: materials used, mix designs, methods of casting and curing, test procedures, and data analysis techniques. The results are presented and discussed in the fifth chapter. Detailed explanations are provided for the data obtained. Additional series of experiments were conducted in several instances to verify trends in the data. The sixth chapter briefly summarizes

the overall study, and lists the conclusions and recommendations. The recommendations are made in non-technical terms so that they can be easily adopted by the construction industry.

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CHAPTER I

INTRODUCTION

Basis of the Research

A common perception regarding concrete curing is that the adverse effects of interrupted curing on the strength and durability properties of concrete are irreversible. The specifications regarding concrete curing emphasize the need for a continuous and sufficient curing. However, they do not suggest any remedial action if the curing is interrupted or discontinued prematurely. The research presented in this thesis has addressed this issue by quantifying the effects of interrupted curing and recuring in conventional concrete as well as "new generation" concretes: fly ash concrete and silica fume concrete. This research is valuable to the construction industry since it clearly demonstrates that recuring has significant beneficial effects on the strength and permeability of concrete.

Another significant aspect of this research is that it provides valuable data on the curing requirements of silica fume and fly ash concretes. The curing requirements for these concretes are still not well established. The Literature contains limited data on the curing requirements of fly ash concrete. However, the data on the curing

requirements of silica fume concrete are virtually nonexistent. The results of this research will contribute in the formulation of specifications on the curing requirements of silica fume and fly ash concretes.

Problem Statement

Concrete curing has a significant influence on the strength and durability properties of concrete. Curing is the maintenance of a satisfactory moisture content and temperature in the concrete during its early stages of hydration. It ensures sufficient hydration of cement, which consequently leads to the development of the desired strength and durability (ACI Committee 308, 1981). A significant amount of research has been conducted on the adverse effects of unsatisfactory moisture and temperature on various concrete properties (Mather, 1987; Richardson, 1991; Detwiler et al., 1991; Gardner, 1990; Senbetta & Malchow, 1987). The ACI Committee 308 (1981) report, in conjunction with other appropriate documents such as ACI Committees 305 (1977) and 306 (1978) reports on hot and cold weather concreting, serves as a guide for achieving proper curing in concrete construction.

It is unlikely that the majority of concrete curing is done strictly in accordance with the procedures set forth in the ACI documents cited above. An interruption in curing may easily occur on any project, particularly when water curing methods such as ponding, sprinkling and wet burlap covering are used, and there is insufficient job supervision

after placement of the concrete. Senbetta & Malchow (1987) stated that approximately 24% of the concrete placed in non-residential construction in the United States in 1979 received no specified curing, and as little as 26% was cured according to job specifications. They also stated that there has not been significant improvement in the past decade.

Although, it is often stated in the Literature that an interruption in concrete curing is undesirable, there is a lack of data that could quantify the adverse effects of an interrupted curing. Some of the questions that need clarification are: what will happen if the concrete is allowed to dry for some time during its specified curing period, can the losses in the properties of concrete due to this interruption in curing be regained by recuring, and how much are the strength and permeability affected by recuring? Tuthill (1991) stated that if concrete becomes dry during its initial curing period, it benefits every time it is wetted by rain, at least during its first year. Similar views have also been expressed by Mindess & Young (1981).

During the past two decades, significant emphasis has been placed on the use of pozzolanic admixtures, such as fly ash, silica fume, slag and natural pozzolans, in concrete. At present, the majority of concrete is produced with the addition of pozzolanic admixtures. Some beneficial effects of pozzolans in concrete are high strength, low permeability, high resistance to chloride and sulfate attack, and low alkali-silica reaction. The most commonly

used pozzolanic admixtures are fly ash and silica fume (ACI Committee 226, 1987a; ACI Committee 226, 1987b). Silica fume is the most recent pozzolanic material used in concrete, and its commercial application is still on a limited scale.

The introduction of fly ash and silica fume in concrete has challenged the standard mix design procedures and construction practices established for plain cement concrete. The behavior of concrete containing these admixtures is still not well understood. Several conferences and symposia have been organized on the use of fly ash and silica fume in concrete, notable among them are those periodically sponsored by The Canada Center for Mineral and Energy Technology (CANMET), and American Concrete Institute (ACI) (Malhotra, 1983; Malhotra, 1986; Malhotra, 1989a; Malhotra, 1992). ACI Committee 226 (divided into Committees 232, 233 and 234 in 1988) presented a comprehensive report on the use of fly ash in concrete and a preliminary report on the use of silica fume in concrete in 1987 (ACI Committee 226, 1987a; ACI Committee 226, 1987b).

The references cited above as well as several other publications including: Luciano et al. (1991), Mehta & Gjorv (1982), Burnett (1990), Holland & Luther (1987), and Roy (1989) focus on the mix design, properties and application of concretes incorporating fly ash and silica fume. The mechanisms that control the performance of these concretes are also addressed. The curing requirements of

these concretes is an issue which has not received sufficient attention of the researchers. Some recent studies (Thomas et al., 1989; Gopalan & Haque, 1987; Haque et al., 1988) have addressed the curing sensitivity of fly ash concretes, and indicated that fly ash concretes are more susceptible to poor curing conditions than plain cement concretes. There is a lack of similar data for silica fume concrete.

In the United States, the field application of silica fume concrete began in 1983, mostly in bridge decks and parking structures. A review of silica fume concrete use on bridge decks was presented by Luther (1988), and in parking structures by Weil (1988). From these publications, a number of similarities can be noted among various silica fume concrete projects in terms of mixing, placing and finishing. However, most of the projects differ on the curing requirements of the silica fume concrete. For example, Bunke (1988), on the basis of his experience with silica fume concrete projects at the Ohio Department of Transportation, recommends a continuous water curing of 3 days for silica fume concrete. On the other hand, Holland (1988) recommends a wet curing of 7 days as an absolute minimum.

The variations in the curing practice of silica fume concrete may largely be attributed to the lack of standard specifications, which are tied to insufficient background data on silica fume concrete, in general, and its curing in particular. The ACI Committee 308 (1981) report provides

guidelines for the curing of normal Portland cement concrete, but does not include concretes made with pozzolanic materials such as fly ash and silica fume.

Objectives

The major objectives of this research are as follows:

1. Determination of the effects of interrupted curing on the strength and permeability of mortars and concretes made with plain cement, fly ash blended cement, and silica fume blended cement.
2. Determination of the effects of recuring on the strength and permeability of mortars and concretes made with plain cement, fly ash blended cement, and silica fume blended cement.
3. Determination of the curing requirements of fly ash and silica fume mortars and concretes, and comparison with the curing requirements of plain cement mortars and concretes.

CHAPTER II

CONCRETE CURING: LITERATURE REVIEW

Curing: General

Curing is the process of maintaining satisfactory moisture content and temperature in concrete after its placement. It ensures sufficient hydration of the cement in concrete, and consequently leads to the development of desirable properties to the extent that the concrete can meet its service requirements (ACI committee 308, 1981; Carrier, 1978). The two distinct segments of this definition of curing: satisfactory moisture, and satisfactory temperature are described below.

Moisture Effects

During the production of concrete, sufficient water is added so that the desired level of hydration can be achieved. However, after placement, the mixing water has a tendency to evaporate unless preventive measures (curing) are taken. The evaporation of mixing water from concrete depends upon several factors including: air temperature, relative humidity, concrete temperature and wind velocity. The interactive effect of all these factors is shown in Figure 1 (ACI Committee 308, 1981; ACI Committee 305, 1977).

An evaporation rate of 1 $Kg/m^2/hr$ (0.2 $lb/ft^2/hr$) is considered critical and presents a situation where the curing of concrete becomes mandatory.

One of the visible effects of an excessive evaporation from the concrete surface is the development of plastic shrinkage cracks. Excessive evaporation may also lower the internal relative humidity of the concrete to the extent that the hydration reactions stop. Powers (1947) found that the hydration of cement virtually stops when the internal relative humidity of concrete drops below 80%. The cessation of hydration reactions arrests the development of strength and impermeability of concrete. The effects of different levels of moist curing on the compressive strength of concrete are shown in Figure 2 (Mindness & Young, 1981). The mixing water in concrete may also be lost to absorbent forming materials and gravitational flow. Necessary preventive measures should be taken to prevent these types of moisture losses (Carrier, 1978). However, such preventive measures are usually not considered part of the concrete curing. Concrete curing generally refers to protecting the concrete surface from evaporation of the mixing water due to environmental factors.

Temperature Effects

The hydration of cement is an exothermic process and the rate of the hydration reaction is largely a function of concrete temperature. The concrete temperature is a function of the ambient temperature, solar radiation, the

heat of hydration, and the initial temperature of the concrete ingredients. At temperatures below 5^0C (40^0F), the hydration reactions, and thus, the strength development are greatly retarded. There is negligible strength development in concretes at a temperature near or slightly below 0^0C (32^0F). The freezing of fresh concrete may cause reductions in strength and modulus of rupture by as much as 50%, and result in permanent, undesirable heaving (Carrier, 1978; ACI Committee 308, 1981).

High temperatures accelerate the hydration reactions of concrete at early stages, but may cause evaporation of the mixing water and leave a significant proportion of cement unhydrated. In addition, temperatures above 45^0C (115^0F) result in a non-uniform distribution of hydration products which may leave weak zones in the cement paste (Mindness & Young, 1981).

Carrier (1978) states that the optimum curing temperature is 23^0C (73^0F), and the concrete temperature should be maintained between 5 to 71^0C (40^0 to 160^0F). Curing at lower temperatures yields slightly higher 28-day compressive strengths. While curing at higher temperatures increases the early strength at the expense of 28-day and ultimate strength. The strengths of concretes cured at different temperatures and for different periods of time are shown in Figure 3 (Carrier, 1978).

Curing Procedures

For the maintenance of a satisfactory moisture content in concrete, the curing procedures in common use, can be classified into two broad categories: (1) water based curing methods, and (2) sheet or membrane based curing methods. In the water based curing methods, the loss of mixing water from concrete is prevented by providing a cover of water on the concrete surface. Several means to provide this water cover are: ponding, immersion, sprinkling, fog spraying, and covering the concrete surface with wet burlap, cotton mats, rugs, sand, sawdust, straw or hay. In the sheet or membrane based curing methods, the concrete is sealed against loss of moisture either by covering it with plastic sheets and reinforced papers (ASTM C-171) or spraying it with a liquid membrane-forming curing compound (ASTM C-309).

Water Based Curing Methods

Water based curing methods are the conventional, as well as the ideal, method of concrete curing. They not only prevent the loss of moisture from the concrete surface, but also provide additional water for cement hydration, particularly in the surface region of the concrete. When the concrete is in a saturated condition, the flow of water in the pore system of the cement paste is facilitated. The cement particles which hydrate rapidly, for example, fine cement particles, soon need additional water. If the water in the adjacent capillaries is consumed, water moves from

those capillaries where it is in excess (Mindness & Young, 1981). The movement of water is restricted in partially saturated concretes such as those cured with sheets or membranes (curing compounds). In these concretes (sealed concretes), as the hydration reactions proceed, there is a progressive reduction of capillary water, as the movement of water from adjacent pores is hindered.

Although water curing methods are ideal for promoting the hydration reactions in concrete, they have a number of disadvantages. These methods may significantly add to the construction costs in locations where there is a scarcity of good quality water or the water requires long haul distances. Relatively high concentrations of iron and organic matter in the curing water may cause staining of the concrete surface. High concentrations of chloride and sulfate ions in the curing water may lead to more severe deterioration mechanisms such as reinforcing steel corrosion and sulfate attack (Al-Tayyib & Khan, 1987). Curing water is acceptable if its quality is similar to that of mixing water (McCoy, 1978). ACI Building Code (1977) defines the requirements of an acceptable mixing (or curing) water.

Some additional problems associated with the water curing methods, as cited by Mather (1987), are as follows:

1. Water curing methods are difficult to maintain in a windy environment.
2. Water curing methods have high inspection costs due to round-the-clock inspection.

3. Curing personnel are usually the lowest paid and least educated construction workers and may not recognize the critical nature of the job.
4. Hoses and equipment are often stolen or the sprinklers may be inadvertently turned off by workmen.
5. Clean-up operations are difficult due to water ponding in low areas.

The above factors may contribute to an interruption in moist curing, a central issue of this thesis, and thus, necessitate the quantification of the effects of interrupted curing and recuring.

Sheet or Membrane Based Curing Methods

Although, sheet or membrane based curing methods are not as effective as water based curing methods in promoting hydration reactions, they offer several advantages such as low cost and easy handling. Liquid membrane forming curing compounds are popular in the construction industry due to these advantages. Curing compounds are chemicals which form a moisture retentive film when applied to the concrete surface, and thus prevent the evaporation of mixing water.

One of the serious drawbacks associated with curing compounds is that they are not recommended for use in concretes with water-to-cement ratios less than 0.40 (Mather, 1987). In low water-to-cement ratio concretes, the internal relative humidity of concrete may soon drop below 80% in the absence of a layer of moisture on the concrete

surface resulting in cessation of the hydration reactions. The majority of high strength concrete is produced with water-to-cement ratios less than 0.40. The introduction of high range water reducing admixtures has made the production of concretes possible with water-to-cement ratios as low as 0.25 (Malhotra, 1989b).

Other disadvantages associated with curing compounds are as follows (ACI Committee 308, 1981; Carrier, 1978; Mather, 1987; Shariat & Pant, 1985):

1. The time of application of the curing compounds is critical. It should be applied immediately after the bleed water sheen on the concrete surface disappears. If the curing compound is applied while the concrete is still bleeding, it results in scaling or map cracking of the membrane. If the curing compound is applied too long after the water sheen has disappeared, it may be absorbed into the concrete without forming a moisture retentive film.
2. The membrane formed due to the application of curing compounds has a finite porosity which allows the evaporation of some of the mixing water from the concrete.
3. The membranes pose bonding problems if the existing concrete surface receives additional layers of concrete, paint or tile at a later stage.

4. The application of curing compounds on textured surfaces is difficult. They may flow from the ridges of the texture to the sag areas.
5. It is difficult to assess the uniformity of application of curing compounds. On windy days, some of the concrete surface may not receive uniform application, particularly, when the curing compound is applied with power sprayers.

Figure 4 compares the effectiveness of water curing with that of compound curing in terms of absorptivity of mortar specimens with water-to-cement ratio of 0.5 (Senbetta & Malchow, 1987).

The water curing and sheet or membrane curing methods, described above, in addition to controlling the evaporation of mixing water from the concrete, also control the temperature of the concrete. The evaporation of curing water from the concrete surface (water-curing method) produces a cooling effect, and thus lowers the concrete surface temperature. The white pigmented curing compounds possess heat reflecting characteristics and can lower the concrete surface temperature by as much as 4.4^0C (40^0F) (Mather, 1987). In hot weather, where the evaporation of mixing water is excessive, water curing methods are preferred (ACI Committee 305, 1977).

In extremely cold weather, the evaporation of mixing water is not a serious concern, but the maintenance of a satisfactory temperature is critical. The concrete needs to be protected from freezing until it develops a compressive

strength of at least 3.4 MPa (500 psi). Depending upon the section dimensions, the concrete temperature should be maintained in the range of 5-13^{0}C (44-55^{0}F) for a period of 1 to 3 days. The time of protection depends upon the type of cement, loading and exposure conditions (ACI Committee 306, 1977). Several methods used to protect the concrete from freezing include: insulating blankets, insulated forms, heat enclosures, and internal electrical heating (ACI Committee 306, 1977; Grove, 1988).

Although, in cold weather, undesirable moisture losses in concrete are low, there may be some moisture loss when the concrete is dry heated to protect it from freezing. It is recommended that before applying dry heat, the concrete should be coated with a curing compound. Water curing methods are less preferable in cold weather because they may cause freezing problems when the heating is discontinued. If water curing is used (i.e. steam), it should be terminated 12 hours before the heat protection ends, so that the concrete is dry before it is exposed to cold weather (ACI Committee 306, 1977). When a heat source is used which produces carbon-di-oxide, the fumes should be vented outside. Otherwise, the fumes will induce a carbonation reaction in the concrete, which will result in "softening" of the surface, and reinforcing steel corrosion if the concrete contains reinforcing steel (ACI Committee 306, 1977; Proudly, 1978).

In addition to the above curing procedures, there are several specialized curing procedures in use, namely high pressure steam curing (ACI Committee 516, 1965), and atmospheric pressure steam curing (ACI Committee 517, 1980). These curing procedures are used in the production of precast concrete products such as concrete masonry units, sand lime bricks, asbestos-cement pipes, calcium silicate heat insulation products, light weight cellular concretes, and structural concrete elements (precast).

Duration of Curing

The minimum duration of concrete curing depends upon several factors including the type of cement used, and the type of concrete structure. Different cements require different curing periods due to their varying rate of strength development (Figure 5; Mindness & Young, 1981). Generally, the more rapid the strength development at early stages, the shorter the length of moist curing required. According to ACI Committee 308 (1981), the minimum lengths of moist curing required for ASTM Type I, Type II and Type III cements are 7, 14, and 3 days, respectively. This does not necessarily mean that the concretes must be water cured or compound cured for the specified periods of time. If rain, mist, high humidity or moist backfill can maintain a satisfactory moisture and temperature, they can be treated as substitutes for formal curing.

ACI Committee 308 (1981) has also specified different curing periods for different types of concrete structures.

The minimum duration of curing required for slabs on grade and load bearing structural components is 7 days or the time required to attain 70% of the specified compressive and flexural strength. Examples of slab on grade installation include: highway and airfield pavements, canal linings, parking lot slabs, driveways and walkways. Examples of load bearing structural components are: cast-in place walls, columns, beams, footings, piers, and bridge decks. In unreinforced mass concrete, such as dams, a minimum curing period of at least two weeks is recommended. The curing period of precast units which are usually cured at elevated temperatures is 12 to 72 hours.

Interrupted Curing and Recuring

Ideally, concrete should be continuously cured without any interruption during its required curing period. ACI Committee 308 (1981) states "Water curing, if used, should be continuous to avoid volume changes due to alternate wetting and drying. The need for adequate continuous curing is greatest during the first few days after placement of concrete in hot weather." Mindness & Young (1981) state "... intermittent moist curing will also subject the concrete to wetting and drying at a time when the concrete is weak enough to be susceptible to tensile stresses that may develop during drying." Carrier (1978) states "It is also important that there be no interruption in the availability of water to hydrating particles during the early curing period."

However, there are very few instances where concrete receives ideal curing. Apparently water curing methods are more susceptible to an interrupted curing. The various reasons for an interruption in curing, in the case of water curing methods, were listed earlier in this chapter. Compound curing is equal to or possibly more susceptible to interrupted curing. Improperly applied curing compounds may interrupt the curing without being noticed.

There are very few studies that have dealt with the subject of recuring even in terms of simply expressing views. Furthermore, whatever information is available, is to some extent conflicting. For example, Carrier (1978) states "If curing water is denied for a period sufficient to allow curing concrete to dry, it never again regains the strength of continuously moist cured concrete, even after long periods of subsequent moist curing." Mindness & Young (1981) state "Although it is true that resaturated concrete will resume its interrupted hydration, the amount of strength developed is not as high as it would have been if moist curing had not been interrupted." Tuthill (1991) states "When the concrete is dry or a portion becomes dry such as the important surface layer, nothing happens and the concrete is less than it should be. For at least its first year, concrete is benefitted every time it is wetted by rain, but this does not diminish the importance of job curing."

Note that the above views and statements on interrupted curing and recuring are not supported by experimental data. The present study is significant in that it quantifies the effects of interrupted curing and recuring.

CHAPTER III

FLY ASH AND SILICA FUME CONCRETES: LITERATURE REVIEW

Pozzolanic Concretes: General

Extensive investigations have been carried out on the use of pozzolans in concrete during the past two decades and have consequently lead to their widespread application in the construction industry. There are very few concretes that are produced without incorporating pozzolans, for example fly ash and silica fume. Other forms of pozzolanic materials include blast furnace slag and natural pozzolans. Pozzolans, according to ASTM C-618, are "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." The following Equation represents the pozzolanic reaction (Bentz & Garboczi, 1991):

$$1.7\ CH + S + H \rightarrow \underset{(C\text{-}S\text{-}H)}{C_{1.7}SH_{4.0}} \qquad (1)$$

In the foregoing Equation, CH represents $Ca(OH)_2$, S represents SiO_2, and H represents H_2O. $C_{1.7}SH_{4.0}$ is a complex compound known as calcium silicate hydrate (C-S-H). The reactant SiO_2 in Equation (1) is derived from the pozzolans. A high SiO_2 content is a primary characteristic of pozzolans. The reactant $Ca(OH)_2$ is a hydration product of ordinary Portland cement and water. Finally the reactant H_2O is the water present in concrete which includes both mixing and curing water. The pozzolanic reaction converts a less cementitious hydration product, $Ca(OH)_2$, into a more cementitious product, C-S-H.

It is important to note that C-S-H is the principal hydration product of Portland cement whether or not it contains pozzolans. The reactions between cement compounds: tricalcium silicate (C_3S) and dicalcium silicate (C_2S), and water in normal Portland cement concrete, that lead to the formation of C-S-H and $Ca(OH)_2$ are as follows:

$$2C_3S + 6H \rightarrow \underset{(C\text{-}S\text{-}H)}{C_3S_2H_3} + 3CH \qquad (2)$$

$$2C_2S + 4H \rightarrow \underset{(C\text{-}S\text{-}H)}{C_3S_2H_3} + CH \qquad (3)$$

In normal Portland cement concrete, C-S-H occupies 50-75% volume of the hydrated cement paste, while CH occupies 20-25% volume of the cement paste (Mindness & Young, 1981). The addition of pozzolans in concrete increases the volume of C-S-H at the expense of CH. Also, C-S-H formed as a result of pozzolanic reaction (Equation 1)

is denser than that formed due to the hydration of ordinary Portland cement (Equations 2 and 3) (Idorn, 1983).

Fly Ash Concretes

According to ACI Committee 116 (1985), fly ash is "finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gases." Investigations on the use of fly ash in concrete began as early as 1937 (Davis et al., 1937). However, major use started in the 1970's due to significantly increased production of fly ash during the oil crisis. During this period, coal was being used to fire the electric power plants and fly ash was obtained as a residue of coal combustion (ACI Committee 226, 1987a). Table I shows the production and utilization of fly ash in various countries for the year 1984 (Mehta, 1989).

Two types of fly ashes are in commercial use: ASTM Class F, and ASTM Class C. Class F fly ash is produced by burning anthracite or bituminous coal, while Class C fly ash is produced by burning lignite or sub-bituminous coal. The major difference between the two classes of fly ashes is that Class F fly ash possesses only pozzolanic characteristics, while Class C fly ash possess pozzolanic as well as some cementitious characteristics (ACI Committee 226, 1987a). The classification of fly ashes into these two classes is based upon their chemical composition. According to ASTM C-618, if the sum of SiO_2, Al_2O_3 and F_2O_3 is 70% or greater, the fly ash is regarded as Class F. If the sum of

the oxides is 50% or greater but less than 70%, the fly ash is regarded as Class C. The Class C fly ashes contain a significant proportion of CaO, usually greater than 10%. The CaO is responsible for the cementitious properties of Class C fly ash. The CaO content of Class F fly ashes is less than 10%. Table II lists some of the characteristics of these two classes of fly ashes along with those of silica fume (Roy, 1989).

The Effect of Fly Ash on the Properties

Fresh Concrete

The addition of fly ash in concrete has a significant influence on its properties in both the fresh and hardened stages. In fresh concrete, the addition of fly ash improves its workability and pumpability, and reduces segregation and bleeding. Some of the mechanisms that are believed to be responsible for this improvement in the properties of fresh fly ash concrete are as follows:

1. The spherical shape of the fly ash particles reduces the friction among the aggregate particles, and between the concrete and pump line, and thus enhances the workability and pumpability of the concrete (ACI Committee 226, 1987a).
2. A partial replacement of cement by fly ash results in a higher volume of cement paste due to the lower density of fly ash. An increase in paste volume yields a concrete with better plasticity and cohesiveness, and thus leads to a reduction in

segregation (Lane, 1983).

3. A partial replacement of cement by fly ash results in an increase in SiO_2 content at the expense of the CaO content. Fly ashes are rich in SiO_2 (45-65% in Class F) and ordinary Portland cements are rich in CaO (60-65%). An increase in the SiO_2 content relative to CaO results in a more stable dispersion of cement and fly ash particles in the cement paste (ACI Committee 226, 1987a).
4. The addition of fly ash in concrete results in a dense packing of the concrete ingredients and thus blocks the bleed-water channels (Mehta, 1989).
5. The fly ash particles have the ability to disperse the flocculated cement particles in a freshly mixed cement paste resulting in an improved workability of the cement paste (Mehta, 1989).

Another important effect of fly ash addition in fresh concrete is that it lowers the heat of hydration (Roy, 1989; Berry & Malhotra, 1980; Langley et al., 1992). The rate of heat evolution in fly ash cement pastes is contrasted with ordinary Portland cement paste in Figure 6 (Roy, 1989). This characteristic of fly ash is used advantageously in mass concrete structures such as dams where the high heat of hydration is a major cause of cracking. The low heat of hydration in fly ash concrete usually extends the initial set time of the fresh concrete, which, depending upon the environmental conditions, may be desirable or undesirable. In a hot environment, an extended setting time is usually

desirable as it provides sufficient time for placement and compaction. In cold environments, the setting time of fly ash concretes may be further extended due to low ambient temperatures which may significantly delay the finishing operations.

The Effect of Fly Ash on the Properties of Hardened Concrete

The properties of hardened concrete that are significantly influenced by the addition of fly ash are strength and permeability, and these in turn, influence several other properties. The fly ash concretes, particularly those made with Class F fly ash, are characterized by their low early strength and high ultimate strength. The low early strength of fly ash concrete is attributed to the partial replacement of a highly cementitious material, Portland cement, with a material which has no or little cementitious characteristics (fly ash). The pozzolanic reactions that contribute to the strength development in fly ash concretes (Equation 1) are relatively slow and their effect is not pronounced until 28 days or longer. The strength development in different concrete mixes made with and without fly ash is shown in Figure 7 (Samarin et al., 1983). At an age of one year, the strength of fly ash concrete is reported to be 50% higher than that at 28 days, compared to 30% in the case of concrete made without fly ash (Lane & Best, 1982). The permeability of fly ash concrete is also affected by the

pozzolanic reaction. The calcium silicate hydrate (C-S-H) formed by the reaction of $Ca(OH)_2$ and SiO_2 in the presence of moisture (Equation 1) fills the capillary pores in the cement paste and thus reduces the permeability (ACI Committee 226, 1987a). Additional properties of hardened concrete that are influenced by the addition of fly ash include:

1. The modulus of elasticity of fly ash concrete follows the trend of strength development. It is lower at early stages and higher at later stages, compared with plain cement concrete (Berry & Malhotra, 1980).
2. Creep strain in fly ash concretes is a function of the strength development. At early stages, when the strength development in fly ash concrete is low, the creep strain is higher than that in plain cement concrete. However, at later ages, the creep strain in fly ash concrete is similar or even lower than that in plain cement concrete (ACI Committee 226, 1987a; Berry & Malhotra, 1980; Sivasundaram et al., 1991).
3. There is an improvement in the bond of steel and fly ash concrete due to a reduction in bleed water which is usually collected at the steel-concrete interface (ACI Committee 226, 1987a).
4. The addition of fly ash in concrete reduces the alkali-silica reaction in concrete associated with reactive silica aggregates (Alasali & Malhotra,

1991). The reaction of silica in fly ash with the alkali hydroxides in concrete leaves little alkali hydroxide to react with the silica in the reactive aggregates.

5. The addition of fly ash in concrete improves its resistance to chloride-induced reinforcing steel corrosion due to its relatively low permeability (at later ages), and the capability of fly ash to bind some of the free chloride ions (Sivasundaram et al., 1991; Haque et al., 1992).
6. The addition of fly ash (Class F) in concrete improves its sulfate resistance by reducing the ingress of external sulfate ions. Also, a partial replacement of cement by fly ash effectively reduces the tricalcium aluminate (C_3A) component of the cement which reacts with external sulfate ions to form the expansive product, ettringite (Tikalsky & Carrasquillo, 1992).

Silica Fume Concretes

Silica fume is the most recent among the pozzolanic materials currently used in concrete. Investigations on the use of silica fume in concrete began in 1970's in several Scandinavian countries, particularly Norway and Sweden. In North America, similar investigations were undertaken in the early 1980's. Silica fume is a by-product of silicon and ferro-silicon alloys, which are produced by the reduction of high purity quartz with coal in electric arc furnaces.

Silica fume is collected from the exhaust gases of the furnaces during the reduction process (ACI Committee 226, 1987b). From Table I, it may be noted that the world production and utilization of silica fume are considerably lower than those of fly ash.

Silica fumes are characterized by their high SiO_2 content, usually in the range of 90-95% (Holland & Luther, 1987; Mehta, 1989). The CaO content in silica fumes is in the range of 0.1 to 1%. Unlike fly ash (ASTM C-618), the requirements on the physical and chemical characteristics of silica fume have not yet been developed. ASTM Committee C-9 is currently working on specifications for silica fume, and is expected to complete its task in the near future (Holland, 1988). Some typical physical and chemical characteristics of silica fume are shown in Table III.

The Effect of Silica Fume on the Properties of Fresh Concrete

The most immediate and visible effect of the addition of silica fume in concrete is a reduction in the workability. The ultra-fine silica fume particles have a surface area of approximately 20,000 m^2/kg (474,600 ft^2/lb) compared to 300-400 m^2/kg (7,119-9,492 ft^2/lb) for normal Portland cement which drastically increases the water demand. Yogendran et al. (1987) have demonstrated that 10%, 15%, 20% and 25% cement replacements by silica fume increase the water demand by 9%, 24%, 34%, and 40%, respectively. Similar results have also been obtained by Bayasi & Abifaher

(1992). To overcome this problem, the use of silica fume in concrete, particularly with high silica fume contents, is almost always accompanied with a high-range water reducing admixture (HRWA). Recently, investigations have been undertaken to determine whether the addition of certain amounts of fly ash with silica fume can overcome the workability problems of silica fume concrete (Bayasi, 1992). It may be recalled from the preceding section on fly ash concrete that the addition of fly ash in concrete improves workability. Bayasi (1992) has reported that the addition of fly ash in silica fume concrete improves the workability, but has a detrimental effect on permeability.

Like fly ash, the addition of silica fume improves the cohesiveness, and reduces the segregation of concrete. The mechanisms that improve these properties in fly ash concrete also apply in case of silica fume concrete. However, beyond a certain amount of silica fume, the concrete mix becomes sticky and poses finishing problems (Jahren, 1983).

Bleeding is another property of fresh concrete that is significantly affected by the addition of silica fume. The high affinity of silica fume particles for water leaves little free water in the concrete mix to bleed. The bleeding in silica fume concrete is significantly less than that in fly ash concrete. The bleed water serves as a buffer between the concrete surface and outside environment at early stages and prevents the development of plastic shrinkage cracks. Plastic shrinkage cracks generally develop when the rate of evaporation from the concrete

surface exceeds the rate at which water is brought to the surface by bleeding. Due to its low bleeding, if the surface of silica fume concrete is not protected at early stages, there is a higher risk of plastic shrinkage cracking (ACI Committee 226, 1987b).

As opposed to fly ash concrete, the heat of hydration generated in silica fume concrete is slightly higher than that of plain cement concrete (Roy, 1989; Bentur & Goldman, 1989). Figure 8 compares the heat liberation of silica fume blended cement pastes with that of ordinary Portland cement paste. The higher heat of hydration in silica fume concrete may shorten the setting time which may be an advantage in cold weather, and a disadvantage in hot weather.

The Effect of Silica Fume on the Properties of Hardened Concrete

The improvement in strength and permeability are the two primary reasons for the utilization of silica fume in concrete. From the standpoint of strength, there are two approaches for using silica fume in concrete. In the first approach, a portion of the cement may be replaced by a smaller portion of silica fume (for example, 3 to 4 kg or lb of cement replaced by 1 kg or lb of silica fume) so that a similar strength can be obtained. In the second approach, a portion of the cement may be replaced by an equal weight of silica fume resulting in a considerably higher strength.

In both cases, the basis for using silica fume is to increase the strength. High strength concrete and silica

fume concrete have become synonymous. In a recent mix design study, Luciano et al. (1991) suggested that 12,000 psi (82.75 MPa) concrete can be produced by adding silica fume, 8% of cement, and using a water-to-cementitious material ratio of 0.275. A silica fume concrete with 12,000 psi (82.75 MPa) 28-day strength by using a silica fume content of 8.7% by weight of cement, and a W/C ratio of 0.29 has been successfully utilized in the construction of Georgia's tallest building, One Peachtree Center (Keck & Casey, 1991). Similarly, a silica fume concrete with a 28-day strength of 13,000 psi (90 MPa) has been commercially used in Australia by incorporating a silica fume content equal to 9% of the total cementitious material content and using a water-to-cementitious material ratio of 0.29 (Burnett, 1991).

Gjorv (1983) studied the effect of the addition of silica fume on the water permeability of concrete and showed that the permeability of a concrete (cement content of 100 kg/m^3 or 168 lb/yd^3) made with 10% silica fume is 4×10^{-10} m/sec (13.12×10^{-10} ft/sec) compared to 1.6×10^{-7} m/sec (5.25×10^{-7} ft/sec) of a similar concrete made without silica fume. Figure 9 (Radjy et al., 1986) shows the effect of the addition of silica fume on the permeability of concrete. Similar reductions in the water permeability of silica fume concrete have also been reported by Ludirdja et al. (1989). A reduction in the number of large pores in silica fume-cement paste systems due to the physical and chemical effects of the silica fume addition is one of the reasons for the low permeability of silica fume

concrete. The other mechanisms that lead to an improvement in strength and permeability of silica fume concrete are discussed in Chapter V "Test Results and Discussion." Other properties of the hardened concrete that are affected by the addition of silica fume are as follows:

1. The modulus of elasticity of concrete increases with the addition of silica fume similar to the trend in compressive strength (Galeota & Giammatteo, 1989).
2. At similar water-to-cementitious material ratios, the drying shrinkage of silica fume is comparable or lower than that of plain cement concrete (Bentur & Goldman, 1989; Tazawa & Yonekura, 1986).
3. The creep deformations in silica fume concrete are 40-70% of rapid hardening (Type III) Portland cement concrete (Penttala & Rautanen, 1990).
4. The addition of silica fume in concrete improves the bond (concrete-steel) strength by 50-100% (Robins & Austin, 1986). The reduction in bleed water channels adjacent to reinforcing steel and a modified cement paste matrix are believed to be responsible for the improved bond strength.
5. Silica fume is a more effective pozzolan compared to fly ash in controlling the alkali-silica reactions in concrete (Mehta, 1989; Diamond, 1983; ACI Committee 226, 1987b). This is due to the greater effectiveness of silica fume in lowering the concentration of alkali and hydroxyl ions in

the pore solution.

6. Silica fume concretes are highly resistant to reinforcing steel corrosion due to their low permeability to water and chloride ions, and high electrical resistivity (Berke, 1989; Gautefall & Havdahl, 1989). In addition, the resistance of silica fume concrete to some aggressive chemicals such as acetic acid, formic acid, phosphoric acid, and sulfuric acid is better than that of normal Portland cement concrete. It is believed that the calcium silicate hydrate (C-S-H) formed in the presence of silica fume is more stable in acidic environments than that formed due to the hydration of Portland cement (Durning & Hicks, 1991).
7. The low permeability of silica fume concrete provides superior resistance to sulfate attack in the presence sodium sulfate salts. However, in the case of magnesium sulfate, the performance of silica fume concrete is questionable due to the fact that in the presence of magnesium sulfate, calcium silicate hydrate (C-S-H) may be converted to magnesium silicate hydrate (M-S-H) which is non-cementitious (Cohen & Bentur, 1988).
8. Properly air-entrained silica fume concrete provides freeze-thaw resistance which is comparable to that of properly air entrained plain cement concrete (Berke, 1988).

Curing Requirements of Fly Ash and Silica Fume Concretes

The current state of knowledge concerning various aspects of fly ash concrete is, in general, more than that of silica fume concrete. However, both fly ash and silica fume concretes, particularly silica fume concrete, lack information on their curing requirements, that is, the minimum length of moist curing required for the development of desirable properties. A brief review of the available Literature concerning the curing requirements of fly ash and silica fume concretes follows.

Curing Requirements of Fly Ash Concretes

Although, it has long been realized that the strength development in fly ash concrete is slow, the realization of the fact that the curing requirements of fly ash concrete may be significantly different than that of normal Portland cement concrete is recent. The rate of strength development and curing are closely linked. In general, the lower the rate of strength development, the longer the concrete needs to be maintained at a satisfactory moisture content and temperature. Even the ACI Committee 226 (1987a) report, published in 1987, which summarized the developments on the use of fly ash in concrete does not address the curing of fly ash concrete. The report relies on statements such as: "When fly ash concrete is properly cured, fly ash reactions help fill in the spaces between hydrating cement particles

in the cement paste fraction of concrete, thus lowering its permeability to water and aggressive chemicals....," and "Increased long-term strength through continued pozzolanic reaction is achieved with most fly ashes in concrete, if the concrete is maintained in a moist environment at moderate temperatures" (ACI Committee 226, 1987a).

The major contributions in the curing requirements of fly ash concretes are due to several Australian and Canadian researchers (Gopalan & Haque, 1987; Haque et al., 1988). A number of variables were evaluated including: the amount of cement replaced by fly ash, the type of fly ash (Class F, Class C), the water-to-cementitious material ratio, curing environment, and duration of curing. These studies demonstrated that fly ash concretes are more susceptible to substandard curing conditions than plain cement concrete. For example, the average 7-day compressive strengths of ASTM Class F fly ash concrete specimens made with fly ash contents of 20-50% and cured in the dry conditions of the laboratory are 61% of those of similar specimens continuously cured in a fog room. The corresponding strength ratio in case of plain cement concrete has been found to be 69% (Gopalan & Haque, 1987). The susceptibility of Class C fly ash concrete specimens to poor curing conditions is lower than that of Class F fly ash concrete specimens, but still higher than that of plain cement concrete specimens (Haque et al., 1988). This is due to the cementitious characteristics of Class C fly ash. The strength contribution from a Class F fly ash, as mentioned

earlier, is solely due to the pozzolanic reaction, which is long-term and requires the presence of moisture for its continuance.

A major limitation of the studies, cited above (Gopalan & Haque, 1987; Haque et al., 1988), as well as several others (Haque & Gopalan, 1987; Haque & Kayyali, 1989) is that the curing periods investigated are 7 days and above (usually 7, 28, and 91 days). In many instances, the field curing is less than 7 days, and at an age of less than 7 days, the strength development in fly ash concrete would be much lower than that indicated in these studies. Thus, it would have been more useful if curing periods less than 7 days and several intermediate curing intervals between 7 and 28 days, and 28 and 91 days were investigated. These studies are valuable that they created an awakening in the concrete community regarding the curing sensitivity of fly ash concrete. However, these studies do not provide specific data on the curing requirements of fly ash concretes to achieve desirable properties. These data could be obtained by closely monitoring the strength and other properties at close intervals and then determining the length of moist curing by the criteria of ACI 308.

In a recent study, Thomas et al. (1989) have attempted to determine the minimum length of moist curing for concretes made with several British fly ashes, by using curing periods of 1, 2, 3, 7, 14, 28 and 90 days. They concluded that, based on strength, the minimum length of moist curing for fly ash concrete is 3 days compared to

2 days for normal Portland cement concrete. Although, the minimum length of moist curing is expected to vary from one type of fly ash to other, a curing period of 3 days seems too low. It is very unlikely that most fly ash concretes would achieve a strength of 70% in 3 days. According to ACI 308, a concrete should be cured for 7 days or for a period required to attain 70% of the compressive strength or flexural strength, whichever is lower. The author could not find another study that could verify the applicability of the above conclusions for other types of fly ash or other curing environments. Thus, there is a need for a significant amount of experimental data that could determine the curing requirements of fly ash concrete and consequently lead to the formulation of standards and specifications. Note that the ACI Committee 308 (1981) report "Standard Practice for Curing Concrete" does not include the curing of any pozzolanic concrete including fly ash concrete and silica fume concrete.

Curing Requirement of Silica Fume Concretes

A thorough Literature review could not identify any study specifically dealing with the curing requirements of silica fume concrete. However, there are several studies concerning silica fume concrete that have included curing as one of the variables and thereby provide limited data on the curing sensitivity of silica fume concretes. For example, Bentur & Goldman (1989) have compared the 28 and 90-day

strengths of silica fume and plain cement concretes under two curing conditions: (1) continuous immersion in water, and (2) 7 days immersion in water followed by exposure in air (20^0C or 68^0F/60%RH). They concluded that the adverse effects of the air curing (compared to water curing) on the strength and carbonation of silica fume concrete are comparable or lower than those of plain cement concrete. Maage et al. (1990) have compared the compressive strengths of silica fume and plain cement concretes in continuous water (20^0C or 68^0F) and continuous air (20^0C or 68^0F/50%RH) curing conditions at ages of 1 day, 7 day, 28 day and above. They concluded that the adverse effects of air curing on the strength of silica fume concrete are comparable to those of plain cement concrete. They state that "Concretes with silica fume are as robust against early drying as concretes without, independent of the W/(C+S)-ratios tested" (Maage et al., 1990).

In the absence of sufficient laboratory data on the curing requirements of silica fume concretes, a significant amount of confusion exists in the construction industry regarding the curing of silica fume concrete. A number of silica fume concrete projects have been documented in the United States since 1983. These projects used different lengths of moist curing, although, they had several other features in common such as mixing, placing, and finishing. Some examples of the variable curing practices are as follows:

1. A silica fume concrete overlay with a silica fume content of 15.5% was used by the Ohio Department of Transportation in a bridge rehabilitation project. The overlay was cured with wet burlap and plastic sheets for 2 days. After 2 days, the burlap and plastic were removed, and the lane was opened to traffic on the fourth day (Luther, 1988).
2. In a silica fume concrete project constructed by the New York State Department of Transportation, the silica fume concrete was cured under wet burlap for 1 day, then the burlap was removed, and the concrete was cured under plastic sheeting for 3 additional days (Luther, 1988).
3. The Maine Department of Transportation used a 7.2% silica fume concrete overlay on two bridges. The concrete was cured with wet burlap for 7 days and opened to traffic within 9 days (Luther, 1988).
4. The Illinois Department of Transportation specifies the use of wet burlap covering for 4 days for silica fume concrete projects (Luther, 1988).
5. Silica fume concrete was used by the Ohio Department of Transportation in a full depth deck placement on a bridge. The concrete was cured with wet burlap (through soaker hoses) for 3 days with a layer of polyethylene film placed over the burlap (Bunke, 1988).

In the absence of standard specifications, the experts on silica fume concrete have acted conservatively on the issue of curing of silica fume concrete, and advocated overcuring (Holland, 1988; Holland, 1989). For example, Holland (1989) states "Over curing has been emphasized to mean that to get the maximum benefit from silica fume, more curing than would be done for conventional concrete in the same placement should be done". Holland (1989) recommends a curing equivalent to 7 days of wet curing as an absolute minimum in silica fume concrete.

The above conservatism on the curing requirements of silica fume concrete is, in part, due to the relatively high susceptibility of silica fume concrete to plastic shrinkage cracking. Silica fume concretes are prone to plastic shrinkage cracking due to their almost negligible bleeding potential. However, the protection of silica fume concrete against plastic shrinkage cracking does not necessarily mean that the concrete should be cured for an extended period of time. The first 24 hours are critical from the viewpoint of plastic shrinkage cracking. Thus the best approach seems to effectively protect the concrete during the first 24 hours, and then moist cure it for a period of time necessary for the development of desirable properties, whether it is more or less than 7 days.

Conservatism results in a higher cost in the curing of silica fume concrete, particularly for large projects. Thus, there is a need to resolve the uncertainty regarding the curing of silica fume concrete. An optimum and reliable

curing requirement for silica fume concrete can only be established through comprehensive experimental data from a wide variety of sources. The data presented in this thesis on the curing requirements of silica fume concrete will contribute in the development of such a data bank.

Interrupted Curing and Recuring of Fly Ash and Silica Fume Concretes

The effects of interrupted curing and recuring have not been formally investigated for either plain cement concrete or pozzolanic concretes including fly ash and silica fume concretes. The data presented on the effects of interrupted curing and recuring in fly ash and silica fume concretes are unique. A comprehensive investigation was required due to the fact that the effects of interrupted curing and recuring in fly ash and silica fume concretes might have been significantly different than those of plain cement concrete due to their different physical and chemical characteristics.

CHAPTER IV

EXPERIMENTAL PROCEDURES

This chapter describes the details of the experimental investigation including: the materials used, the mix designs, methods of casting and curing the specimens, test procedures, and data analysis techniques. The experimental investigation in this thesis can be broadly classified into two categories: (1) experiments performed on mortar specimens, and (2) experiments performed on concrete specimens. Detailed information regarding both categories is presented below.

Evaluation of Mortar Specimens

Materials/Equipment

The materials used in this phase of the work included: ASTM Type I Portland cement, Class F fly ash, silica fume, natural sand, and a high range water reducing admixture (HRWA). The sand had a water absorption of 0.28%, and its fineness modulus was 2.74. The gradation curve for the sand is shown in Figure 10. Note that the gradation curve of the sand is approximately in the middle of the ASTM C-33 gradation limits for fine aggregates.

The equipment used included: 50-mm (2-inch) molds, a vibrating table, an oven, and a uniaxial compressive strength testing machine meeting the requirements of ASTM C-39.

Mix Designs

A total of 6 mortar mixes including: 3 plain cement mortar mixes, 2 silica fume mortar mixes, and 1 fly ash mortar mix were investigated. Table IV shows the detailed mix designs of all mixes. The primary variable in the plain cement and silica fume mortar mixes was the water-to-cementitious (W/C) material ratio. The cementitious material ratio is based on the combined weight of cement and fly ash or silica fume. In the case of plain cement mixes, the cementitious material content is simply based on the weight of the cement.

Three different W/C ratios of 0.39, 0.44 and 0.49 were used in the plain cement mortar mixes. Two different W/C ratios of 0.44 and 0.49 were used in the silica fume mortar mixes, and a W/C ratio of 0.44 was used for the fly ash mortar mix. A silica fume mortar mix with a W/C ratio of 0.39 was not prepared due to workability considerations. The extreme fineness of silica fume particles significantly increases the water demand in the mortar mixes. This requirement could have been negated by the use of a very high dosage of HRWA, however, it was desirable to limit the number of variables in this study. Due to the availability of background Literature on the curing requirements of fly

ash concrete, only one fly ash mortar mix was included for comparison purposes.

All the mortar mixes had a cementitious material-to-sand ratio of 3 (by weight). In the silica fume or fly ash mortar mixes, a silica fume or fly ash content of 15% by weight of the total cementitious material was used. To obtain a mix of reasonable workability, a HRWA in the amount of 3 ml per 500 gm of cementitious material (9.2 fl oz per 100 lb of cementitious material) was added in the silica fume mix of W/C ratio 0.44. The second silica fume mix of W/C ratio 0.49, and all plain cement and fly ash mortar mixes were workable without HRWA. In order to eliminate variability of the mixes due to the HRWA addition, an equal amount of HRWA was added to all mixes.

Fifty-mm (2-inch) cube specimens were used in this phase of work. This specimen size is preferred and has been used in the past in other curing studies (Mather, 1987; Popovics, 1986). The effect of a particular curing environment is usually not more than 50-mm (2-inch) below the concrete surface (Senbetta & Scholer, 1984). In a large concrete specimen, the interior of the specimen may not be fully influenced by the curing environment in which it is placed.

Casting and Curing of the Mortar Specimens

The casting of the mortar specimens was done in small batches (2 kg or 4.4 lb, excluding water) which yielded

6 specimens (50-mm or 2-inch cubes). The batches were hand mixed and every effort was made to disperse large clusters of silica fume particles. Plain cement and fly ash posed little difficulty in dispersion. To assure a uniform dispersion of silica fume and fly ash particles, they were first dry mixed with cement, the blend was then dry mixed with sand, and finally water and HRWA were added in small increments during final mixing. A vibrating table was used during the casting procedure. After casting, the molds, containing the specimens, were covered with a thin plastic sheet that conformed to ASTM C-171, "Specifications for Sheet Material for Curing Concrete," and stored in normal laboratory conditions. The specimens were demolded after 24±1 hours and then subjected to different curing periods and different curing conditions, as described below:

1. After demolding, the specimens of each type of mix: plain cement mortar mixes, silica fume mortar mixes, and the fly ash mortar mix, were divided into five groups, each consisting of six specimens. Each group was moist cured, under conditions of complete immersion in water, for one of the following five time periods: 0, 3, 7, 14 or 28 days.
2. Following each moist curing period, the specimens were removed from the curing tanks and oven-dried at a temperature of 110^{0}C (230^{0}F) for 3 days. This was done to effectively stop the hydration of the specimens after each curing period. The

oven-drying of the specimens represented an interruption in moist curing. Note that the group of specimens corresponding to 0-day moist curing was placed in the oven immediately after demolding.

3. After oven-drying, the specimens were allowed to cool under laboratory conditions for a period of 24 hours, and were then divided into two sub-groups, consisting of three specimens each.
4. The first subgroup of specimens was subjected to recuring by immersing in water for a period of time, which if added to the moist curing period before interruption was equal to 28 days. Therefore, all the recured specimens had a total moist curing period of 28 days, but had an interruption in their moist curing (oven-drying at 110^0C or 230^0F for 3 days). Note that after oven-drying, the specimens were allowed to cool for 24 hours before immersing them in water for recuring.
5. The second subgroup of specimens was stored under air dry conditions in the laboratory after oven-drying. The curing of this group of specimens has been referred to as discontinuous curing in this thesis.

To further clarify the above two curing conditions, consider the group of specimens that corresponds to 7 days of moist curing. This group of 6 specimens was moist cured

for 7 days, oven-dried for 3 days, and then cooled for 1 day. After cooling, 3 specimens were reimmersed in water for 21 days (recuring), while the other 3 specimens were stored in the normal dry conditions of the laboratory (discontinuous curing). The group of specimens continuously moist cured for 28 days was treated as the control. Table V shows the casting and curing schedule of the plain cement mortar specimens, while Table VI shows the casting and curing schedule of the fly ash and silica fume mortar specimens.

Testing of the Mortar Specimens

At the end of the recuring period, the recured specimens and the corresponding specimens subjected to discontinuous curing were tested for absorptivity and compressive strength. The absorptivity was determined by using the following relationship, originally suggested by Powers & Brownyard (1947) and later used by others (Senbetta & Scholer, 1984):

$$(q/A) = (K_a t)^{1/2} \qquad (4)$$

Where q/A is the amount of water absorbed per unit area of exposed surface in time t. K_a, expressed in cm^2/sec, is the coefficient of absorptivity.

The relationship between the coefficient of absorptivity, K_a, and permeability is as follows (Powers & Brownyard, 1947):

$$k_a = [(k_2)_c \ \sigma \ S_c]/\eta \quad (5)$$

Where $(K_2)_c$ is the coefficient of permeability through the capillary system of the cement paste, σ is the surface tension of water, η is the viscosity of water, and S_c is the surface area of gel. S_c is a difficult parameter to measure, and it is suggested by Powers & Brownyard (1947) that K_a can be used as a relative measure of permeability.

In Equation (4), the amount of water absorbed (q) was determined by oven-drying the specimens at a temperature of 110^0C (230^0F) for 24 hours, cooling them in air tight desiccators for another 24 hours, and then soaking in water for 60 minutes. Equation (4) is valid for an absorption time of 30 to 60 minutes (Powers & Brownyard, 1947).

After the absorptivity test, the same specimens were used for compressive strength determination. Prior to the compressive strength tests, the specimens were oven-dried at 110^0C (230^0F) for 24 hours and then cooled in air tight desiccators for 24 hours. This was done to keep the capillary moisture of all the specimens at the same level before testing. It has been demonstrated by Popovics (1986) that small differences in the moisture content of concrete specimens cause significant difference in their compressive strength. The usual practice of testing the specimens in the moist condition was not followed in this study, because of possible changes in the hydration status of the specimens subjected to discontinuous curing. Similarly, the possible change in the hydration status was the reason for the

selection of a permeability test involving a short exposure time (60 minutes) of the specimens to water. The compressive strength determinations were essentially made according to ASTM C-109 specifications with exceptions in the curing procedure since curing was the primary variable of the present study. In this study, a strict adherence was made to the casting, curing and testing schedule of the specimens (Tables V and VI).

Evaluation of Concrete Specimens

The mortar specimens evaluated in the preceding section do not closely resemble "field placed" concrete. However, they do give an indication of the performance of concrete made with similar types of cementitious materials and water-to-cementitious material ratios. An advantage of mortar specimens, which are usually cast as 50-mm (2-inch) cubes, is that specimen-to-specimen or batch-to-batch variations are significantly reduced. Another advantage of mortar specimens is that an experimental test program can be conducted with limited resources.

In this phase of the research, concrete mix designs were selected that closely approximated those used in highway construction. The cylindrical specimens measured 100 x 200-mm (4 x 8-inch). This specimen size corresponded to the minimum size that was compatible with the size of the coarse aggregate used. Larger specimens, for example 150 x 300-mm (6 x 12-inch) cylinders, were not selected due to differential curing throughout the interior of the

specimen. The interior of a large concrete specimen may not be fully influenced by the curing environment in which it is placed.

Materials/Equipment

The materials used in this phase of the study were similar to those used in preparing the mortar specimens with the exception of limestone coarse aggregate and an air-entraining admixture. The coarse aggregate had a measured water absorption of 0.68%. The sand used in this phase of the research was from a different source than that used to prepare the mortar specimens. The sand had a measured water absorption of 0.45% and a comparable gradation to the mortar sand.

The major equipment required included 100 x 200-mm (4 x 8-inch) steel molds, and a power driven revolving drum mixer. Like the mortar specimens, a vibrating table, an oven, and an uniaxial compressive strength testing machine were used in the preparation and testing of the concrete specimens.

Mix Designs

Four Silica fume concrete mixes, one fly ash concrete mix, and one plain cement concrete mix were investigated. Table VII shows mix design data. The primary variable in the silica fume concrete mixes was the silica fume content. Silica fume contents of 5%, 10%, 15%, and 20% by weight of the total cementitious material (cement + silica fume)

content were used. In the fly ash concrete mix, the fly ash content was 15% of the total cementitious material (cement + fly ash) content.

A common feature of all the mixes was a total cementitious material content of 450 kg/m^3 (758 lb/yd^3), a water-to-cementitious material ratio of 0.38, and a coarse-to-fine aggregate ratio of 1.5. An air-entraining admixture in the amount of 35 ml per 100 kg (0.53 fl oz per 100 lb) of cementitious material was added to all the mixes. A high range water reducing admixture (HRWA) was added only when the mix was unworkable. The amount of HRWA added was the minimum required to produce reasonable workability. The plain cement concrete mix, the fly ash concrete mix, and the 5% silica fume concrete mix did not require the addition of HRWA. The HRWA in the amounts of 343 ml/100 kg (5.26 fl oz/100 lb), 1000 ml/100 kg (15.38 fl oz/100 lb), and 1478 ml/100 kg (22.67 fl oz/100 lb) of cementitious material was added to the 10%, 15%, and 20% silica fume concrete mixes, respectively. The mix designs incorporated in this study, except for the 20% silica fume concrete mix, are typical of those used in highway construction.

Casting and Curing of the Concrete Specimens

The casting of the concrete specimens was essentially done according to ASTM C-192 specifications "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." The exception being that all the specimens

were not cured according to those specifications, since curing was the primary variable in this study. All mixes were prepared in a power driven revolving drum mixer with 1.5 ft^3 capacity. Three batches of concrete were made from each mix design to obtain the required number of specimens. Forty five cylindrical specimens (100 x 200-mm or 4 x 8-inch) were cast for each mix. After casting, the molds, containing the specimens, were placed in a fog room maintained at 23^{0}C (73.4^{0}F) and 95% relative humidity, and demolded after 24±1 hours.

The curing conditions used for the concrete specimens were slightly different than those used for the mortar specimens. The specimens were cured in a fog room instead of immersion in water. This change was due, in part, to space limitations (immersion curing required large curing tanks occupying significant space), and because fog curing is closer to actual "field" curing. The curing interruptions in the concrete specimens were made after 0, 1, 3, 7 and 14 days of moist curing compared to 0, 3, 7, 14 and 28 days of moist curing for the mortar specimens. The selection of a shorter reference curing period (14 days) for the concrete specimens was based on the fact that "field" curing rarely exceeds 14 days.

Another significant difference between the curing conditions of the concrete and mortar specimens was in the method of curing interruption. In the case of the mortar specimens, the curing was interrupted by oven-drying the specimens at a temperature of 110^{0}C (230^{0}F) for 3 days. In

the case of the concrete specimens, the curing interruption was achieved by transferring the specimens from the fog room to normal dry laboratory conditions. The air dry state was determined to be a more realistic representation of curing interruption in actual practice. The schedule of interrupted curing and recuring in the concrete specimens was as follows:

1. After demolding, the specimens of each mix were divided into five groups, each of 9 specimens. Each group was then moist cured in the fog room for one of the following five time periods: 0, 1, 3, 7 or 14 days.
2. At the end of each moist curing period, the specimens were taken out of the fog room, and divided into three subgroups, each of three specimens. The first subgroup was tested immediately. The second subgroup was subjected to interrupted curing and recuring. The curing of the third subgroup was interrupted, but the specimens were not recured (discontinuous curing).
3. The interrupted curing and recuring of the second subgroup of specimens was achieved by removing the specimens from the fog room at the end of each moist curing period, placing them in the dry conditions of the laboratory for 14 days, and then recuring them in the fog room. The specimens were recured for a period of time, which if added to the curing period before interruption, was equal

to 14 days. Thus the total moist curing period of all of the recured specimens was 14 days. All specimens were subjected to a curing interruption of 14 days.

4. The specimens subjected to recuring (second subgroup) and those subjected to discontinuous curing (third subgroup) were tested at the end of the recuring period of the second subgroup. Both subgroups were tested 28 days after demolding.
5. For comparison, an additional group of specimens was prepared and subjected to 28 days of continuous fog room curing. Unlike the other group of specimens, recuring or discontinuous curing procedures were not performed. The specimens were removed from the fog room after 28 days and tested immediately.

In the above curing scheme, the first sub-group of specimens provided data on the curing requirements of different concretes: plain cement concrete, fly ash concrete and silica fume concrete. While, the second and third subgroup of specimens provided data on the effects of interrupted curing and recuring in these concretes. In order to further clarify the above three curing conditions, consider the group of specimens corresponding to 7 days of curing. After demolding, the 9 specimens were moist cured in the fog room for 7 days. Then the specimens were removed from the fog room, and 3 specimens (first sub-group) were tested immediately. The other 6 specimens were stored in

the dry conditions of the laboratory for 14 days. After 14 days in the air-dry condition, 3 specimens (second sub-group) were transferred back to the fog room for a period of 7 days (recuring), while the other three specimens (third sub-group) remained in the air dry condition (discontinuous curing).

Testing of the Concrete Specimens

Unlike the mortar mixes, the concrete mixes were subjected to slump and air content measurements in their fresh state. The slump was measured according to ASTM C-143 specification "Test Method for Slump of Portland Cement Concrete," and the air content was measured according to ASTM C-231 specification "Test Method for Air Content of Freshly Mixed Concrete." The compressive strength of the hardened concrete was measured according to ASTM C-39 specification "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." Before the compressive strength test, the specimens were capped with a sulphur mortar according to ASTM C-617 specification "Practice for Capping Cylindrical Concrete Specimens."

Data Analysis Techniques

The initial step in the data analysis procedure was to determine the scatter associated with the data. Two techniques were used to evaluate the scatter in the data including: (1) determining the acceptable range, and (2) identifying the outlying measurements. The acceptable

range was determined by applying ASTM C-670 specification "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials" in conjunction with other documents dealing with the precision data for the test under consideration. For example, ASTM C-192 specifies that the standard deviation for slump measurements should not exceed 17.8-mm (0.7-inch) if the measurements are made in the same laboratory. While, ASTM C-670 specifies that to determine the acceptable range for three measurements, the standard deviation should be multiplied by 5.7. Thus, the acceptable range for slump, according to these two specifications is 101.5-mm (3.99-inch).

The outlying measurements (also referred as "outliers") were identified according to ASTM E-178 specification "Standard Practice for Dealing with outlying Measurement," for an upper 5% significance level. The use of the upper 5% significance level is recommended for the testing of most construction materials (ASTM E-178). The T-statistic procedure used for identifying the outliers is briefly described below.

Suppose $x_1 \leq x_2 \leq x_3 \ldots\ldots\ldots \leq x_n$ is a sample of n measurements which needs to be tested for doubtful largest and smallest values. Further, assume that x is the arithmetic average and s is the standard deviation of these measurements. From this information, two parameters T_n and T_1 are calculated as follows:

$$T_n = (x_n - x)/s \quad (6)$$

$$T_1 = (x - x_1)/s \quad (7)$$

The larger of the above two T values, is compared against a critical T value. The critical T values for different significance levels and different number of measurements are documented in Table 1 of ASTM E-178. If the T value calculated and selected from Equations (6) and (7) is less than the critical T value for a particular significance level, then the measurements are considered to be within that significance level. According to ASTM E-178, the critical T value for an upper 5% significance level and a sample of 3 measurements is 1.155.

The measurements that did not meet either or both of the above criteria (acceptable range and significance level) were discarded. Note that in the case of permeability test data, the acceptable range could not be determined, since the test is not standardized and the acceptable values of standard deviation are not known. In order to supplement the significance level criteria in the permeability test, the variability of the individual measurements was checked against their average value. The individual measurements varying more than 10% from the average value were discarded. This is one of the requirements in the strength testing of mortar specimens, as specified by ASTM C-109.

After subjecting the data to the above statistical verification, they were presented in the form of average values, standard deviations, and coefficients of variation

(Yamane, 1967). The data on the curing requirements of different concretes: plain cement concrete, fly ash concrete, and silica fume concrete were subjected to regression analysis, to determine a relationship between the time of moist curing and strength development.

CHAPTER V

TEST RESULTS AND DISCUSSION

The results presented in this chapter are divided into two broad categories: (1) results of mortar specimens, and (2) results of concrete specimens. Each category includes data concerning the effects of interrupted curing and recuring, and curing requirements. These parameters constitute the major objectives of this thesis.

Results of Mortar Specimens

The compressive strength and absorptivity data for the plain cement, silica fume and fly ash mortar specimens, cured for different periods and under two different curing conditions, discontinuous curing and recuring, are presented in Tables VIII through XI. The average, standard deviation, and coefficient of variation shown in Tables VIII through XI are based on 3 specimens. As described earlier (Chapter IV, section "Data Analysis Techniques"), the individual compressive strength and absorptivity values were checked for outliers at an upper 5% significance level. In addition, the individual compressive strength and absorptivity values, were checked for 10% variability from the average. Although, the 10% variability criteria is

specified for the compressive strength of mortar specimens (ASTM C-109), it can be used in any kind of testing to improve the significance of data. The measurements that did not meet either the upper 5% significance level or the 10% variability criteria were discarded. However, there were very few measurements that did not meet these two criteria.

The Effects of Interrupted Curing and Recuring

Plain Cement Mortar Specimens. Figure 11, Figure 12 and Figure 13 show the compressive strength of the plain cement mortar specimens, of W/C ratios 0.39, 0.44 and 0.49, respectively, cured under two different curing conditions, recuring and discontinuous curing. Similar to several previous studies, the effect of W/C ratio on the quality of concrete is well pronounced. The lower the W/C ratio, the higher the strength. The 28-day compressive strengths obtained for specimens with W/C ratios of 0.39, 0.44 and 0.49 are of the order of 83 MPa (12,000 psi), 69 MPa (10,000 psi) and 62 MPa (9,000 psi), respectively.

A comparison of the compressive strength of the specimens cured under recuring and discontinuous curing conditions (Figures 11 through 13) indicates that the specimens gain strength when they are recured after an interruption in curing. The compressive strength of the specimens which were oven-dried for 3 days immediately after demolding (curing interruption after 0 days of moist curing) and then cured for 28 days is 84-92% of the strength of the

specimens that were continuously moist cured for 28 days after demolding (control specimens). Compared to this, the compressive strength of the specimens which were not cured after oven-drying (discontinuous curing) is 62-65% of the control specimens. After 3, 7 and 14 days of moist curing, the compressive strengths of the recured specimens were 86-99%, 86-100% and 100-104% of the control specimens. The compressive strengths of the corresponding specimens whose curing was discontinued after 3, 7 and 14 days were 78-85%, 81-92% and 89-99% of the control specimens.

The results presented in Figures 11 through 13 suggest that an interruption in moist concrete curing is not as damaging as was thought and that the situation can be remedied. If the moist curing of concrete is interrupted and the concrete is allowed to dry, a significant amount of strength loss can be regained if curing is recommenced and continued for a total period equivalent to the specified curing time. It should be noted that, in this study, an interruption in curing was facilitated by oven-drying the specimens at a temperature of 110^0C (230^0F) for a period of 3 days. Drying of the concrete to such an extent is unlikely in the field, because even in extremely hot climates, the ambient temperature rarely exceeds 50^0C (122^0F) (Al-Tayyib et al., 1981). In practice, the percent of concrete strength that can be regained by recuring should be at least equal to what was achieved in this study, if not more.

Although, not in the context of interrupted curing and recuring, several comments regarding the strength of the plain cement mortar specimens obtained in this study are offered. The 28-day compressive strength values in the range of 62-83 MPa (9,000-12,000 psi) for W/C ratios varying from 0.39 to 0.49 are unusually high, particularly when no strength enhancement techniques are used. These strength values are higher than those predicted by the well known Abram's relationship between W/C ratio and strength (Mindness & Young, 1981; Shilstone Sr., 1991; Kosmatka, 1991):

$$\sigma_c = A/[B^{1.5(W/C)}] \qquad (8)$$

Where σ_c is the compressive strength, and A and B are empirical constants which depend primarily on the cement properties. The values of the constants A and B are usually taken as 14,000 psi, and 4, respectively. Some of the factors that may have contributed in the higher strength of the mortar specimens are as follows:

1. All other conditions being equal, the strength of mortar is higher than that of concrete containing coarse aggregates (Gilkey, 1961).
2. The compressive strength values reported in Table VIII, and Figures 11 through 13 are for dry, plain cement mortar specimens. Dry specimens exhibit higher strength compared to wet specimens (Popovics, 1986).

3. Smaller specimens usually exhibit higher strengths. Note that the specimen size used here was 50-mm (2-inch) cubes, and Equation (8), above, is derived from standard concrete cylinders (150 x 300-mm or 6 x 12-inch). In the present investigation, the author compared the strength of 50-mm (2-inch) cubes with that of 100 x 200-mm (4 x 8-inch) cylinders. The strength of the 50-mm (2-inch) cubes was 1.65 to 1.85 times higher than that of the 100 x 200-mm (4 x 8-inch) cylinders (Table XII).
4. The quality of the sand used in the preparation of the mortar specimens may also have contributed to the improved strength development. Note that the sand used in the preparation of the plain cement mortar specimens has a very low water absorption (0.28%) and its gradation is approximately at the midpoint of the ASTM C-33 gradation limits (Figure 10).

The absorptivity data obtained for the plain cement mortar specimens (Figures 14 through 16) support the compressive strength results. The recuring of the specimens after an interruption in curing consistently resulted in a reduction in absorptivity. The coefficients of absorptivity of the recured specimens after curing interruptions at 0, 3, 7 and 14 days are 46-81%, 18-37%, 9-27%, and 6-17% lower than those of the corresponding specimens whose curing was discontinued. An examination of Table IX, and Figures 14

through 16 reveals that the specimens with lower W/C ratio benefitted more from recuring. For example, at a curing interruption of 0 days, the coefficient of absorptivity values of the recured specimens of W/C ratios 0.39, 0.44 and 0.49 are 81%, 65% and 46% lower than those of the corresponding specimens subjected to discontinuous curing. This is understandable considering the scarcity of water for cement hydration in the low W/C ratio mixes, which is further compounded when the mortar is subjected to a harsh curing environment. The evaporation of the mixing water from a low W/C ratio mix may leave a significant proportion of the cement unhydrated which is hydrated on recuring. These results suggest that the full benefits of low W/C ratio mixes cannot be fully realized until they are properly cured.

Silica Fume and Fly Ash Mortar Specimens. Figures 17 through 19 illustrate the effect of recuring on the compressive strength of silica fume and fly ash mortar specimens. Similar to the plain cement mortar specimens, the beneficial effects of recuring, are clearly indicated in case of silica fume and fly ash mortar specimens. The compressive strengths of the recured silica fume mortar specimens, after curing interruptions at 0, 3 and 7 days are 17-21%, 6-10% and 4-5%, respectively, higher than those of the corresponding specimens whose curing was discontinued after interruption. In the case of silica fume mortar specimens, where curing was interrupted after 14 days, the

strengths of the specimens subjected to recuring and discontinuous curing are approximately equal.

The strength of the recured fly ash mortar specimens is significantly higher than that of the specimens subjected to discontinuous curing, particularly at early periods of curing interruption. The strengths of the recured fly ash mortar specimens at curing interruptions of 0, 3, 7 and 14 days are 67%, 27%, 20% and 9% higher, respectively, than those of the specimens subjected to discontinuous curing. The corresponding percentages in the case of plain cement mortar specimens were found to be 41%, 18%, 9% and 2% (Figure 12).

A comparison of the plain cement, silica fume and fly ash mortar specimens, in terms of the compressive strength of the recured and discontinuously cured specimens, indicates that the beneficial effects of recuring are most pronounced in fly ash mortar specimens followed by plain cement mortar specimens, and silica fume mortar specimens. This difference can be attributed to the different rates of strength development in different mortars. As will be discussed in the following sections, the rate of strength development in silica fume mortar is the highest, while fly ash mortar has the lowest rate of strength development. Mortar specimens with high rate of strength development are expected to gain lesser strength on recuring.

The beneficial effects of recuring on the permeability of both silica fume and fly ash mortar specimens can be noted in Table XI. The coefficient of absorptivity values

of the recured silica fume and fly ash mortar specimens, whose curing was interrupted after 0 day of moist curing, are 70% lower than those of the companion specimens subjected to discontinuous curing. At the beginning of the study, there was considerable uncertainty about the permeability characteristics of the recured mortar specimens. It was suspected that the volumetric changes resulting from the hydration of the unhydrated cement particles during the recuring period may significantly stress the hardened mortar matrix resulting in cracking, and thus increasing the permeability. This condition was anticipated for all plain cement, silica fume and fly ash mortar specimens. A visual examination of the specimens and the data obtained in this study rule out this possibility.

The possible mechanism through which the hydration of the remaining unhydrated cement particles took place during the recuring period was that the hydration products occupied the capillary pores left at the time of curing interruption, and therefore did not stress the matrix to the extent that cracking would occur. The increased degree of hydration resulted in the observed strength gain, and the filling of the capillary pores resulted in the reduction in absorptivity or permeability. The formation of new hydration products during recuring may have healed the micro-cracks (discussed in the following section) developed during the curing interruption (oven-drying) of the specimens, i.e. autogenous healing.

Curing Requirements of Silica Fume and Fly Ash Mortar Specimens

The variation in the compressive strength of the silica fume and fly ash mortar specimens where moist curing was discontinued after 0, 3, 7, 14 and 28 days is illustrated in Figure 20 (W/C = 0.44) and Figure 21 (W/C = 0.49). In these Figures, the data for plain cement mortar specimens are included for comparison. The difference in the curing sensitivity of silica fume, fly ash and plain cement mortars can be clearly noticed in these Figures. The compressive strength of the silica fume mortar specimens which were oven-dried immediately after demolding (no moist curing) is found to be 79-85% (W/C = 0.44, 0.49) of the specimens continuously moist cured for 28 days. The corresponding strength in the case of fly ash mortar specimens (W/C = 0.44) is 51% and in the case of plain cement mortar specimens (W/C = 0.44, 0.49) 62-65%. The maximum compressive strength of the silica fume mortar specimens corresponds to moist curing periods of 7 to 14 days, while fly ash and plain cement mortar specimens continue to gain strength for the entire moist curing period of 28 days.

In the case of the silica fume mortar specimens, the marginal adverse effect of prolonged moist curing is, to some extent, surprising. A reduction in strength has not been commonly reported in the Literature either for plain cement concrete or concretes containing fly ash and silica fume. The usual trend is that the strength increases as the

period of moist curing increases. A possible mechanism for this behavior is the leaching of calcium hydroxide [$Ca(OH)_2$] from the specimens when they were immersed in water for curing. The basis for this hypothesis is that the clean potable water which was used for curing became saturated with $Ca(OH)_2$ during the curing period. To support this hypothesis, the curing water was chemically analyzed for pH, and concentrations of $(OH)^-$ and Ca^{++} ions (Table XIII). The significantly higher $(OH)^-$ and Ca^{++} ion concentrations of curing water compared to those of the original water confirm the leaching of $Ca(OH)_2$ from the mortar specimens. In Table XIII, Ca^{++} ions are a better indicator of $Ca(OH)_2$ leaching compared with $(OH)^-$ ions due to the fact that $Ca(OH)_2$ originally leached from the specimens might have carbonated according to the following reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (9)$$

If the leaching of $Ca(OH)_2$ was responsible for the strength reduction in the silica fume mortar specimens, the question arises as to why fly ash and plain cement mortar specimens did not suffer a similar loss in strength. When the mortar specimens were immersed in water, two mechanisms operated simultaneously; the continuing hydration of the specimens was contributing to a gain in strength, while the leaching of $Ca(OH)_2$ was causing some loss in strength. At early stages, the loss in strength, due to leaching, was probably overshadowed by the predominant strength contributing hydration reactions. After the hydration

reactions subsided in the silica fume mortar specimens in 7 to 14 days, the adverse effect of leaching was noticed. In the case of fly ash and plain cement mortar specimens, the hydration reactions seem to be predominant for the entire 28 days.

According to Roy (1989), the hydration rate of cement containing silica fume is greater than that of ordinary Portland cement, while that of cement containing fly ash is lower than that of ordinary Portland cement. Similar hydration rates, as interpreted from the strength development data, have been observed in this study. The high rate of hydration of cement containing silica fume is attributed to the fact that the silica fume particles accelerate the hydration of C_3S (Ca_3SiO_5, alite) (Equation 2), the primary cement compound responsible for strength development at early ages (Roy, 1989).

However, the strength development in silica fume mortar specimens, which lacked moist curing, is not accompanied by a proportional reduction in the permeability (Figure 20 and Figure 22). The coefficient of absorptivity of these silica fume mortar specimens is not significantly different than that of plain cement and fly ash mortar specimens. When the silica fume mortar specimens are subjected to a moist curing of 3 days, there is a significant reduction in their absorptivity compared to plain cement and fly ash mortar specimens. This implies that a harsh curing environment at early stages would not affect the strength of silica fume concrete significantly, but would have a significant effect

on its permeability.

Although, careful visual examination did not reveal any macro surface cracks in either silica fume mortar specimens or fly ash and plain cement mortar specimens, there is a possibility of micro-cracking in the specimens subjected to oven-drying (110^0C or 230^0F) immediately after demolding. One of the factors that may have resulted in micro-cracking of the specimens, particularly in the surface region, is the loss of some chemically bound water in addition to capillary water. Lankard et al. (1971) measured the loss of chemically bound water on the order of 10% in 50-mm (2-inch) cubes of neat cement and mortar after heating the specimens at a temperature of 121^0C (250^0F) for 58 days. The shrinkage associated with the loss of chemically bound water is believed to disrupt the bonding configuration between the solid hydrated cement phases, and thus causing the micro-cracking of the cement paste (Lankard et al., 1971).

The differential thermal movement of sand particles and cement paste upon heating and cooling may have also contributed in the micro-cracking of the specimens, particularly those oven-dried after demolding. This type of cracking depends upon the differences in the coefficients of thermal expansion of the various constituents (cement paste, sand, aggregate) and the tensile strength of the concrete (Venecanin, 1977; Venecanin, 1990; Sharif, 1991). Concretes with large differences in the coefficients of thermal expansion of their constituents and low tensile strength are more susceptible to this type of cracking.

Another hypothesis regarding the relatively high permeability of 0-day moist cured silica fume mortar specimens is related to the distribution of hydration products at elevated temperatures. According to Mindess & Young (1981), curing at temperatures above 45^0C (113^0F) causes a non-uniform distribution of hydration products and results in increased permeability of the paste.

The incompatibility in the strength and permeability characteristics of silica fume mortar specimens subjected to a harsh curing environment at an early stage is in agreement with the recent findings of Bentur and Jaegermann (1991). Their results indicate that the adverse effects of inadequate water curing are more on concrete permeability rather than strength. This is attributed to the fact that permeability is largely a function of the quality of the surface region of the concrete specimen, while strength is a function of the quality of the concrete specimen as a whole. The surface region of the concrete specimen is affected most by an adverse curing environment. It should be noted that even from the standpoint of permeability, the curing requirements of silica fume mortar specimens are lower than that of plain cement and fly ash mortar specimens (Figure 22).

Results of Concrete Specimens

Table XIV shows the slump and air content of the silica fume, fly ash and plain cement concrete mixes. The low scatter in the slump and air content data indicates the

uniformity of the mixes. The acceptable ranges (difference between highest and lowest values of three measurements) of slump and air content, as determined from ASTM C-192 and ASTM C-670 specifications, are 58-mm (2.3-inch), and 1.0%, respectively. All the slump and air content values shown in Table XIV are within these acceptable ranges.

The slump and air content data obtained here (Table XIV) reveal some of the known characteristics of silica fume and fly ash concretes. The addition of 5% silica fume reduced the slump from 77-mm (3-inch) to 24-mm (1-inch). The concrete mixes with silica fume contents of 10%, 15%, and 20% were completely unworkable without the addition of high range water-reducing admixture (HRWA). As the amount of silica fume was increased, higher additions of HRWA were needed to maintain a reasonably constant slump. The loss in the slump of silica fume concretes is due to their increased water demand and can be attributed to the very high specific surface area of the silica fume particles. The specific surface area of silica fume particles is approximately 20,000 m^2/kg (474,600 ft^2/lb) compared to 400-700 m^2/kg (9,492-16,611 ft^2/lb) for fly ash and 300-400 m^2/kg (7,119-9,492 ft^2/lb) for normal Portland cement. The diameter of an average silica fume particle is approximately 100 times smaller than that of an average cement particle (ACI Committee 226, 1987b).

Conversely, the fly ash used in this study (ASTM Class F) has a beneficial effect on the workability. A 15% replacement of cement by fly ash resulted in an increase in

the slump from 77-mm (3-inch) to 137-mm (5.4-inch). Therefore, a reduction in the water content was possible if a slump of 77-mm (3-inch) was maintained. These results are in agreement with previous studies. Pasko & Larson (1962) found that concrete made by substituting 20% cement with fly ash required 7.2% less water than was required for concrete without fly ash to obtain a constant slump of 63-mm (2.5-inch). The beneficial effects of fly ash in improving the workability is attributed to the essentially spherical shape of fly ash particles (Berry & Malhotra, 1980). Additional mechanisms that improve the workability of fly ash concrete are described in Chapter IV (section "Effect of Fly Ash on the Properties of Fresh Concrete").

The amount of silica fume added to concrete has a pronounced effect on entrained air. In all mixes, an equal amount of air-entraining agent was added, however, as the percentage of silica fume increased, the entrained air decreased (Figure 23). A linear relationship exists between the amount of silica fume and entrained air with an R^2 value of 0.987:

$$Y = -0.152\ X + 4.69 \qquad (10)$$

In the above Equation, Y is the percent air content, and X is the silica fume content, expressed as a percent of total cementitious material content. A similar effect of silica fume on air entrainment has been reported by Malhotra & Carette (1983). They found that in order to obtain an air content of 6±1%, a concrete made with 85% cement and 15%

silica fume, required an air-entraining agent approximately 4 times higher than that made without silica fume (100% cement). The presence of carbon in the silica fume is believed to be responsible for the inhibition of air-entrainment (ACI Committee 226, 1987b).

From Table XIV, it may be noted that an exception to the linear relationship between silica fume content and air content (Figure 23) occurs at 20% silica fume addition. The measured air content of the 20% silica fume concrete mix is slightly higher than that of the 15% silica fume concrete mix. The entrained air content is not only a function of silica fume content, but also the slump. The slump of 5%, 10%, and 15% silica fume mixes was in a narrow range of 13-25 mm (0.5-1 inch), which tended to eliminate the effect of slump on air content. In the case of the 20% silica fume mix, a slump in the range of 22-48 mm (0.9-1.9 inch) was obtained, and it is believed that the effect of this increased slump was reflected in the air content of the mix. A plot of slump versus air content for the silica fume concrete mixes shows an approximate linear relationship between the two parameters (Figure 24). The above discussion of slump and air content data shows that the specimens were prepared in accordance with standard practices.

The compressive strength data including the average, standard deviation and coefficient of variation values for each mix are documented in Tables XV through XX. As previously discussed (Chapter IV, Section "Data Analysis

Techniques"), the strength data were checked for acceptable range according to the ASTM C-670 and ASTM C-192 Specifications and for any outlying measurements according to the ASTM E-178 Specification.

The maximum allowable difference between any two compressive strength measurement of three specimens, according to ASTM C-670 and ASTM C-192, is 8 MPa (1,160 psi). In strict terms, this acceptable range is valid for specimens cast, cured and tested at an age of 7 days according to the ASTM C-192 Specification. Although, in this study, some specimens were not cured according to the ASTM C-192 Specification, and several different ages of testing were used, the above acceptable range is still a valid tool to analyze the scatter in the data, particularly when the data are further tested for outliers (ASTM E-178).

The data that were either out of the acceptable range (8 MPa or 1,160 psi), or did not meet the upper 5% significance level criteria of ASTM E-178, or both, were discarded. When a compressive strength measurement was discarded, the average, standard deviation and coefficient of variation values shown in Tables XV through XX are for two specimens. After subjecting the data to the above statistical treatments, they can be considered valid and significant.

The Effects of Interrupted Curing and Recuring

Figures 25 through 30 compare the compressive strengths of the concrete specimens subjected to discontinuous curing and recuring. Figure 25 and Figure 26 include the data for the plain cement concrete mix, and the fly ash concrete mix, respectively. Figures 27 through 30 present the data for silica fume concrete mixes with varying silica fume contents of 5%, 10%, 15%, and 20%. A cursory examination of these Figures indicates that the compressive strength of the recured specimens is comparable or marginally lower than that of the specimens subjected to discontinuous curing. These observations are in contrast with those made for mortar specimens where the strength of the recured specimens was consistently and significantly higher than those of the discontinuously cured specimens. However, a thorough analysis of the data in conjunction with supplementary data shows that the effects of recuring obtained in this phase of the work are not detrimental, but, rather, overshadowed by additional factors associated with the specimens subjected to discontinuous curing. These factors are discussed below.

The laboratory environment, which was used to interrupt the moist curing of the specimens, cannot be characterized as a harsh curing environment. The laboratory was not environmentally controlled in terms of humidity. The specimens were placed in the laboratory during the spring of 1992 (March-June) and at times, the relative humidity may

have approached 90%. Furthermore, the specimens in the laboratory were protected from wind, which is one of the elements that contribute to a harsh curing environment. The effect of these relatively moderate conditions of curing interruption are reflected in the compressive strength of the specimens subjected to discontinuous curing (Tables XV through XX, Figures 25 through 30). The strengths of the discontinuously cured silica fume concrete specimens corresponding to moist curing periods of 0, 1, 3, 7 and 14 days are on average 93%, 97%, 101%, 104%, and 109%, respectively, of the specimens subjected to continuous moist curing for 28 days. The corresponding percentages in the case of the Portland cement concrete specimens are 90%, 91%, 92%, 95% and 106%. It should be noted that all the specimens subjected to discontinuous curing were evaluated at the same age as that of reference specimens (28-day moist curing). The only difference was that the specimens subjected to discontinuous curing had different combinations of moist curing and air (room) curing. For example, the specimens corresponding to 1 day of moist curing were moist cured for 1 day and then placed in the laboratory environment for 27 days. The specimens corresponding to 3 days of moist curing were moist cured for 3 days and then placed in the laboratory environment for 25 days, and so on. The point to which this discussion leads is that when the effect of an interruption in moist curing is relatively insignificant, minimal benefits should be expected from recuring.

Furthermore, the beneficial effects of recuring, may have been overshadowed by testing the discontinuously cured specimens in the dry condition compared to saturated condition testing of the recured specimens. The recured specimens were tested immediately after their removal from the fog room along with the discontinuously cured specimens which were stored in the dry condition of the laboratory. With other parameters being similar, the measured strength of a dry concrete specimen is always higher than that of a saturated concrete specimen.

Several explanations exist in the Literature regarding the higher strength of dry concrete compared to wet concrete. One hypothesis is that when the concrete dries, the surfaces of the hardened gel come closer and a secondary bond develops between these surfaces resulting in increased strength. Another hypothesis is that when wet concrete is tested under compression, a pore pressure develops in the capillary pores of the concrete which reduces its load carrying capacity (Popovics, 1986). Popovics (1986) has shown experimentally that the 28-day compressive strengths of concrete specimens with 25-day fog curing followed by 3-day air curing are 18-25% higher than those of similar specimens continuously moist cured for 28 days. In order to obtain supportive data, the author compared the compressive strength of wet and dry concrete cubes (50-mm or 2-inch) in a limited scale experiment (Table XXI). The compressive strength of the dry concrete was 13-19% higher than that of saturated concrete at different ages of testing.

Another small series of experiments was conducted in which a harsher environment was used to interrupt the moist curing of the concrete specimens. In this series, the curing interruption was achieved by oven-drying the specimens at a temperature of 45^{0}C (113^{0}F). A single silica fume concrete mix and a single moist curing period of 0 days were used in this series of experiments. The strength of the recured silica fume concrete specimens was 18% higher than that of the discontinuously cured specimens. Note that in this series of experiments, the recured specimens and the discontinuously cured specimens were oven-dried at a temperature of 110^{0}C (230^{0}F) for 24 hours prior to testing in order to bring their moisture content at a comparable level.

Curing Requirements of Silica Fume and Fly Ash Concrete Specimens

Figures 31 through 36 show the compressive strengths of plain cement, fly ash and silica fume concrete mixes continuously moist cured for different periods of time (0, 1, 3, 7, 14, 28 days) at the laboratory temperature of 23^{0}C (73.4^{0}F). Figure 37 compares the compressive strength development of one silica fume concrete mix (15% silica fume) with a fly ash and a plain cement concrete mix. Note that these specimens were not subjected to any interruption in moist curing and were tested immediately after their removal from the fog room.

A regression analysis of the compressive strength data establishes the following relationships between compressive strength and curing time for various plain cement, fly ash, and silica fume concrete mixes:

PC Mix: $S = 11.93 \text{ Log } t + 17.53$ (11)

FY-15 Mix: $S = 17.79 \text{ Log } t + 12.28$ (12)

SF-5 Mix: $S = 13.14 \text{ Log } t + 23.23$ (13)

SF-10 Mix: $S = 13.30 \text{ Log } t + 24.41$ (14)

SF-15 Mix: $S = 16.70 \text{ Log } t + 27.28$ (15)

SF-20 Mix: $S = 18.48 \text{ Log } t + 26.62$ (16)

Where S is the compressive strength in MPa, and t is the total time of curing in days which includes the time of moist curing after demolding and the 1-day period between casting and demolding. The R^2 values for all the Equations are 0.967 or more, except for Equation (16) corresponding to 20% silica fume concrete mix where it is 0.938 (Table XXII). The agreement between the compressive strength values calculated from Equations 11 through 15, and the experimental compressive strength data is so close that in most instances the difference is less than 1 MPa (145 psi). The relatively poor correlation between the compressive strength and curing time in the case of the 20% silica fume concrete mix may be attributed to its comparatively high batch-to-batch variation in terms of slump (Table XIV).

In addition, the 20% silica fume concrete mix was highly cohesive and difficult to compact which may have caused some non-uniformity in the specimens. Due to placement difficulties, a silica fume content exceeding 15% is rarely used. The data and observations on the 20% silica fume concrete mix justify this practice.

The strengths of the 0, 1, 3, 7 and 14-day moist cured silica fume concrete specimens are 48-56%, 60-65%, 74-76%, 86-93%, and 88-93% of the specimens continuously moist cured for 28 days. The average strength values of the silica fume concrete specimens corresponding to these ranges are 53%, 63%, 75%, 88%, and 91%. The strengths of the 0, 1, 3, 7 and 14-day moist cured fly ash concrete specimens are 35%, 44%, 56%, 64%, and 87% of those continuously moist cured for 28 days (Figure 32). The corresponding strength ratios in the case of the plain cement concrete specimens are 51%, 60%, 67%, 76%, and 89% (Figure 31). These data clearly illustrate that the strength development in silica fume concrete is more rapid than that in plain cement concrete. Conversely, the strength development in fly ash concrete is slower than that in plain cement concrete.

The minimum length of moist curing required for the plain cement, fly ash, and silica fume concrete mixes used in this study can be calculated using Equations (11) through (16), and the ACI 308 guidelines on the minimum duration of concrete curing. As described in Chapter II (section "Duration of Curing"), ACI 308 (1981) recommends that concrete should be cured for a minimum period of 7 days or

the time required to attain 70% of the specified compressive strength or flexural strength, whichever period is less. The calculation of the minimum length of moist curing is illustrated below considering Equation (14) corresponding to 10% silica fume content.

Step 1: Calculate the 28-day strength

$S = 13.3 \text{ Log } 28 + 24.41 = 43.66$ MPa

Step 2: Calculate the time of curing corresponding to 70% of 28-day strength

$(0.70 \times 43.66) = 13.3 \text{ Log } t + 24.41$

Thus, $t = 2.90$ days

Step 3: Since the curing period of 2.9 days, calculated in step 2, is less than 7 days, the minimum length of curing is 2.9 days.

The minimum length of moist curing calculated for all the concrete mixes, using the above procedure, is summarized in Table XXIII. Due to the relatively poor correlation between the strength and curing time for the 20% silica fume concrete mix, no corresponding estimate is produced.

Table XXIII indicates that, on average, the minimum length of curing required for silica fume concrete mixes is 3 days, compared to 6.5 days for fly ash concrete mix and 3.75 days for plain cement concrete mix. Note that these curing requirements are calculated from Equations developed at standard laboratory temperature (23^0C or 73.4^0F). The concretes cured at different temperatures will yield different strength-time relationships and, thus, their required length of curing will be different. However, the

relative curing requirements of silica fume, fly ash and plain cement concretes are expected to be the same at other temperatures as well.

The relatively low curing requirement for silica fume concrete is in conformity with the compressive strength of discontinuously cured specimens. Figures 25 through 30 indicate that silica fume concrete specimens have a relatively low sensitivity to less-than-desirable curing conditions compared to plain cement and fly ash concrete specimens.

The data obtained in this study on the relative curing requirements of plain cement concrete and fly ash concrete are in agreement with earlier studies. It is generally agreed that fly ash concretes are more susceptible to inadequate curing conditions than plain cement concrete. Gopalan & Haque (1987) found the compressive strength of 7-day fog cured fly ash (ASTM Class F) concrete specimens to be 67-85% of 28-day fog cured specimens, compared with 80-85% in the case of plain cement concrete specimens. Various W/C ratios and fly ash contents (30-50% of total cementitious material by volume) were evaluated. The ratio of the 7-day to 28-day strengths decreased as the fly ash content was increased. Similar data were reported by Haque et al. (1988) for other types of fly ashes (ASTM Class C) and additional mix designs. In these studies, curing periods of less than 7 days were not investigated. Thomas et al. (1989) investigated curing periods of 1, 2, 3, 7, 14 and 28 days, similar to those

investigated in the present study. For a 15% fly ash concrete mix, they reported that the strengths of 1, 2, 3, 7 and 14-day water cured specimens are 18%, 40%, 49%, 70% and 86% of 28-day water cured specimens. The corresponding percentages in the case of plain cement concrete specimens are reported to be 21%, 42%, 51%, 76%, and 90% (Thomas et al., 1989).

As mentioned earlier (Chapter III, section "Curing Requirements of Silica Fume Concrete"), the Literature lacks data on the relative curing requirements of silica fume and plain cement concretes. Furthermore, whatever data are available, are to some extent conflicting. For example, Sandvick & Gjorv (1986) using a total cementitious material content of 300 kg/m^3 (505 lb/yd^3), water-to-cementitious material ratio of 0.70, and silica fume contents of 0%, 5%, 10%, and 20%, concluded that silica fume concrete mixes had strength development similar to that of plain cement concrete mix up to a curing periods of 7 day, after which they showed a higher rate of strength development. Maage (1986) showed that the strength development in a 10% silica fume concrete mix was slower than that in a plain cement concrete mix up to a curing period of 14 days and at temperatures of 5^{0}C (41^{0}F) and 20^{0}C (68^{0}F). However, at a curing temperature of 35^{0}C (95^{0}F), they found a higher strength development in silica fume concrete for curing periods equal to or greater than 3 days.

The curing of silica fume concrete in the field seems to be influenced by limited and contradictory laboratory

data. For example, Bunke (1988), recommends a continuous water curing of 3 days for silica fume concrete. On the other hand, Holland (1988), recommends a wet curing of 7 days as an absolute minimum.

Considering the above state of knowledge on the curing requirements of silica fume concrete, the data presented in this study are significant. The relatively low curing requirement of silica fume concrete, as suggested by the data in this study, can be explained by the mechanism of strength development in silica fume concrete. According to Roy (1989), the hydration of C_3A (Ca_3SiO_5), the cement compound primarily responsible for strength development at early stages, is accelerated in the presence of silica fume particles. When concrete constituents are mixed with water, Ca^{2+} ions are actively dissolved from C_3A and adsorbed on silica fume particles. The lower Ca^{2+} ion concentration in the liquid phase leads to an increased hydration rate of C_3A due to further dissolution of Ca^{2+} ions. Silica fume particles act as nucleation sites for the formation of calcium silicate hydrate, C-S-H, the hydration product primarily responsible for the strength of concrete.

The high early strength development in silica fume concrete may also be attributed to an early pozzolanic reaction. Roy (1989) states that the conversion of $Ca(OH)_2$ into C-S-H due to the pozzolanic reaction in silica fume concrete, begins as early as 10 hours and continues for up to 7 days. It has been experimentally shown by Li et al. (1985) that approximately 65% of the silica fume hydrates in

the first 3 days (90% cement + 10% silica fume) compared to 5% in the case of ASTM Class F fly ash (70% cement + 30% fly ash).

The early pozzolanic reaction in silica fume concrete is an issue often debated in the Literature. For example, Detwiler and Mehta (1989) concluded that the pozzolanic reaction has little effect on the strength of silica fume concrete up to ages of 7 days. They suggest that at early ages, silica fume contributes in the strength improvement of concrete by reducing bleeding and segregation and, thus, eliminating the local areas of weaknesses such as bleed water channels and voids under coarse aggregates. All these factors, according to Detwiler & Mehta (1989), lead to an improved interfacial zone between coarse aggregate and cement paste. Reduction in pore size (pore refinement) and grain size (grain refinement) due to the presence of silica fume are the other two physical mechanisms which are believed to contribute to the strength improvement of silica fume concrete at early stages (Detwiler & Mehta, 1989; Mehta, 1989; Delage & Aitcin, 1983). However, according to Detwiler & Mehta (1989), the contribution of these physical mechanisms in the strength development is only to the extent that they compensate for the loss of strength due to the partial replacement of cement by silica fume. The basis of their reasoning is that they found the strength of 10% silica fume concrete and plain cement concrete comparable at an age of 7 days.

The consistently higher strength of all the silica fume concrete mixes, compared with the plain cement concrete mix at all ages evaluated in this study (Tables XV through XX, Figures 25 through 37), suggests that not only the physical mechanisms, cited above, but also pozzolanic reactions contribute to the early strength development of silica fume concrete. It should be noted that the average strength of all the silica fume concrete mixes moist cured for 0 days is in the range of 23-27 MPa (3,350-4,060 psi) compared to 18 MPa (2,610 psi) for the plain cement concrete mix.

From the standpoint of compressive strength, a silica fume content of 15% seems to be optimum. There is practically no gain in strength when the silica fume content is increased from 15% to 20%. The compressive strengths of 28-day moist cured silica fume concrete mixes with silica fume contents of 5%, 10%, 15%, and 20% are 42.1 MPa (6,100 psi), 43.3 MPa (6,280 psi), 51.4 MPa (7,450 psi), and 51.3 MPa (7,440 psi), respectively. The corresponding strength in the case of plain cement concrete mix is 35.7 MPa (5,180 psi). As mentioned previously, the mix containing 20% silica fume was too sticky and posed compaction and finishing problems. Silica fume contents in excess of 15% have been found non-advantageous by other investigators as well (Yogendran et al., 1987).

Although, the strength development in fly ash concrete is slow at early stages, the strength at later stages is higher than that of plain cement concrete (Figure 37). The strength of the 28-day moist cured fly ash concrete is

39.7 MPa (5,760 psi) compared to 35.7 MPa (5,180 psi) of plain cement concrete. Note that the strength of the 0-day moist cured fly ash concrete is 13.9 MPa (2,020 psi) compared to 18.1 MPa (2,620 psi) for plain cement concrete. This behavior, which is attributed to the relatively slow pozzolanic reaction, is in conformity with earlier studies (ACI Committee 226, 1987a).

CHAPTER VI

SUMMARY AND CONCLUSIONS

The study presented in this thesis was conducted with two major objectives: determination of the effects of interrupted curing and recuring on the strength and permeability of concrete, and determination of the curing requirements of silica fume concrete in comparison with plain cement concrete and fly ash concrete. The available Literature lacked information in these areas of concrete technology which have important bearing on the short and long-term performance of concrete, and influence the cost of concrete construction directly or indirectly.

The study was begun by casting 50-mm (2-inch) mortar specimens prepared with plain cement, fly ash, and silica fume. The selection of specimen size and mortar rather than concrete was based upon several factors, including: (1) 50-mm (2-inch) cubes are more suitable for curing studies, (2) the within-batch-variations in the mortar specimens, which are prepared from small batches, are reduced, and (3) by utilizing small mortar specimens, the test program could be conducted with limited resources. The investigations were then extended to include concrete mixes typically used in highway construction. The smallest

specimen size (100 x 200-mm or 4 x 8-inch cylinders) that was capable of accommodating the concrete mix was used due to the suitability of small specimen sizes for curing studies. In the selection of concrete mixes, a large number of silica fume concrete mixes were included due to the lack of data on silica fume concrete, in general, and its curing requirements in particular.

Mortar specimens were moist cured for various periods of time (0, 3, 7, 14, 28 days), and then their moist curing was interrupted by oven-drying the specimens at a temperature of 110^0C (230^0F) for 3 days. After oven-drying, one group of specimens was stored in the dry conditions of the laboratory (discontinuous curing), and another group was recured. At the end of the recuring period, both groups of specimens were tested for compressive strength and coefficient of absorptivity. A harsh environment for curing interruption (oven-drying at 110^0C or 230^0F) was selected in order to obtain highly visible effects of interrupted curing and recuring. Given the fact that such a harsh curing environment was rare in the field (except for industrial concrete), a moderate environment was used for interrupting the moist curing of concrete specimens. In the case of the concrete specimens, the interruption in moist curing was achieved by transferring the specimens from a fog room to the dry conditions of the laboratory for a period of 14 days. At the end of the curing interruption, one group of specimens was recured, while curing of a companion group was discontinued. A third group of concrete specimens was

tested immediately at the end of each moist curing period (0, 1, 3, 7, 14 and 28 days) which provided data on the rate of strength development for different types of concretes.

To reinforce confidence in the experimental data obtained in this study, all the data were subjected to various statistical analyses. Wherever possible, the measurements were checked for an acceptable range according to appropriate standards. The individual measurements in all tests were checked for outliers at an upper 5% significance level, according to the T-statistics procedure. A 10% variability criteria, where an individual measurement is accepted only if it does not differ from the average by more than 10%, was also used in selected cases. In any case, at least two of the above three statistical techniques were used to limit the scatter of the data.

After establishing the statistical significance of the data, they were discussed in terms of the objectives of the investigation. Explanations were provided for observed behaviors, particularly those uncommon in the Literature.

Conclusions

Based upon the test results obtained in this study, and subsequent discussion, the following conclusions can be made:

1. An interruption in moist curing has a significant detrimental effect on the strength and permeability of mortars and concretes, particularly if the environment of curing

interruption is harsh, and the curing is interrupted at an early age. The compressive strengths of the plain cement mortar specimens, subjected to discontinuous curing after curing interruptions at 0, 3, 7, and 14 days of moist curing, are 62-65%, 78-85%, 81-92%, and 89-99% of the specimens continuously moist cured for 28 days. In the case of plain cement concrete specimens, where the environment of curing interruption was moderate (room-drying), the strengths of the specimens subjected to discontinuous curing after curing interruptions at moist curing periods of 0, 1, 3, 7, and 14 days were 90%, 91%, 92%, 95%, and 106% of the specimens continuously moist cured for 28 days.

2. The behavior of the two pozzolans: silica fume and fly ash, investigated in this study are in sharp contrast with regard to the adverse effects of curing interruption. The adverse effects of an interrupted curing in silica fume mortars and concretes are lower than those in plain cement mortars and concretes. The reverse is true in the case of fly ash mortars and concretes.
3. The data clearly indicate that the losses in the strength and permeability of concrete, due to an interruption in curing, are reversible. Significant regain in the lost strength and permeability of mortars and concretes is obtained

when they are recured. The compressive strengths of the recured plain cement mortar specimens, corresponding to moist curing periods of 0, 3, 7, and 14 days, are 34-48%, 11-19%, 5-15%, and 2-14% higher than those of the specimens subjected to discontinuous curing. Similarly, the coefficient of absorptivity values of the recured plain cement mortar specimens, corresponding to moist curing periods of 0, 3, 7, and 14 days are 46-81%, 18-37%, 9-27% and 6-17%, lower than those of the specimens subjected to discontinuous curing.

4. The beneficial effects of recuring are equally apparent in silica fume and fly ash mortars and concretes. The beneficial effects of recuring are highly visible in fly ash mortars and concretes which showed the most noticeable change due to an interruption in moist curing.

5. The curing requirements of silica fume mortars and concretes are lower than those of plain cement mortars and concretes. Conversely, the curing requirements of fly ash mortar and concretes are higher than those of plain cement mortars and concretes. The minimum length of curing for silica fume concretes, as determined by the Equations developed in this study at laboratory temperature, is approximately 3 days. Compared to this, the minimum length of curing for plain

cement concrete is 3.75 days, and 6.5 days for fly ash concrete.

The above conclusions are specific to the objectives of this thesis. Some other relevant observations made during this study are summarized as follows:

1. The addition of silica fume in concrete reduces the amount of entrained air. Thus, in order to maintain a required level of entrained air in silica fume concrete, a higher dosage of air-entraining agent would be needed compared to that in plain cement concrete. This is attributed to the presence of carbon in the silica fume.
2. The rate of strength development in the different concretes investigated in this study follows: silica fume concrete > plain cement concrete > fly ash concrete. The high early strength development in silica fume concrete is attributed to several factors including: aggregate-cement paste interface refinement, pore refinement, grain refinement, and early pozzolanic reaction.
3. A prolonged curing of silica fume concrete under submerged conditions may marginally reduce its long-term strength due to the leaching of calcium hydroxide.
4. The exposure of silica fume concrete to a very harsh curing environment (i.e. temperatures above 100^0C or 212^0F) at a very early stage of curing may not have a significant adverse effect on

strength, but may adversely affect permeability. This is attributed to the micro-cracking of silica fume concrete which may be due to a variety of factors including: the loss of chemically bound water, incompatible thermal movement of the concrete constituents, and the non-uniform distribution of hydration products at elevated temperatures.

5. A silica fume content in excess of 15% has proven not to be beneficial in terms of strength. The 28-day (continuous moist curing) compressive strengths of silica fume concrete mixes with silica fume contents of 0%, 5%, 10%, 15% and 20% are: 35.7 MPa (5,180 psi), 42.1 MPa (6,100 psi), 43.3 MPa (6,280 psi), 51.4 MPa (7,450 psi), and 51.3 MPa (7,440 psi), respectively.
6. All other factors being equal, the compressive strengths of 50-mm (2-inch) concrete cubes are 1.65 to 1.85 times higher than those of 100 X 200-mm (4 X 8-inch) cylinders, and the compressive strengths of dry concrete specimens are 13-18% higher than those of wet concrete specimens.
7. With few exceptions, a proportional reduction in the coefficient of absorptivity is obtained with an increase in strength. This indicates the validity of the absorptivity test, although it is not in common use. In situations where only the

relative permeability of different concretes is desired, this is a useful test due to its simplicity. The time of testing can be significantly reduced by investigating other specimen-drying techniques such as microwave drying.

Recommendations

Based upon the results of this study, the following recommendations can be made:

1. If the moist curing of field cured concrete is interrupted, the concrete should, at the minimum, be recured for a period of time equivalent to that during which the moist curing was interrupted. The losses in strength and permeability of concrete, due to curing interruption, can be recovered to significant extent based on the results of this study. However, this recommendation is being made with a strong word of caution. Based upon this recommendation, continuous moist curing of concrete should never be intentionally interrupted. It was noted in this study that the losses in the properties of concrete due to curing interruption are not fully recoverable through recuring. This recommendation only implies "better late than never." Also, the benefits of recuring will be better realized if it

is done before the concrete is subjected to service loads.

2. The current industry practice of over-curing silica fume concrete is unnecessary. Although, the results obtained in this study indicate that the minimum length of moist curing required for silica fume concrete is less than that for plain cement concrete, it is conservatively recommended that silica fume concretes be cured according to the requirements of the Portland cement with which they are blended. For example, if silica fume is blended with ASTM Type III cement, a curing period of 3 days is recommended, and if it is blended with Type I cement, a curing period of 7 days should be used.

The investigation of the curing requirements of silica fume mortars and concretes in this study should be treated as a first step towards establishing the curing requirement specifications of silica fume concrete. Although, compressive strength and permeability are generally used a measure of concrete performance, several other properties including tensile and flexural strength, and the resistance to chloride and sulfate attack will be useful in assessing the required minimum curing period for silica fume concrete. With the development of this type of data, it will be possible to recommend, with confidence, a shorter duration of moist curing in silica fume concrete. Note that ACI 308 (1981) recommends the determination of the minimum

length of moist curing on the basis of strength only.

It is equally important that the agencies involved in the development of specifications and standards on concrete, such as the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM) should gather similar information to expedite the formulation of specifications on the curing requirements of pozzolanic concretes including fly ash concrete and silica fume concrete. In this regard, the individuals and organizations involved in investigating the curing of pozzolanic concretes should share equal responsibility in bringing their results to the attention of the appropriate organizations. A portion of the findings of this study are in press (Khan & Ayers, 1992; Khan & Ayers, 1993), and the remaining data will be published in the near future.

The development of specifications on the curing requirement of silica fume concrete will help eliminate the existing confusion in the construction industry regarding the curing of silica fume concrete. The development of such a specification would result in a significant cost saving associated with the over-curing of silica fume concrete.

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APPENDIXES

APPENDIX A - TABLES

TABLE I

PRODUCTION AND UTILIZATION OF POZZOLANIC MATERIALS IN 1984 (MEHTA, 1989)

Country	Fly Ash Production (Tonnes x 10^6)	Fly Ash Utilization (Tonnes x 10^6)	Silica Fume Production (Tonnes x 10^3)	Silica Fume Utilization (Tonnes x 10^3)
Australia	3.50	0.25	60.00	20.00
Canada	3.30	0.80	23.00	11.00
China	35.00	7.20	none	none
Denmark	1.00	0.45	none	none
France	5.10	1.50	60.00	none
Germany FR	2.60	2.00	25.00	none
India	19.00	0.50	none	none
Japan	3.70	0.50	25.00	none
Netherlands	0.50	0.30	none	none
Norway	none	none	140.00	40.00
South Africa	12.90	0.10	43.00	none
Sweden	0.10	0.02	10.00	1.00
United Kingdom	13.80	1.30	none	none
United States	47.00	5.00	100.00	2.00

Note: The utilization data represents only the amount of material used as a pozzolanic and/or cementitious constituents of hydraulic cements and structural concrete.

Source: Mehta, P.K. (1989). Pozzolanic and cementitious by-products in concrete- another look. In V.M. Malhotra (Ed.), Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete: ACI SP-114 (p. 35). Detroit, Michigan: American Concrete Institute.

TABLE II

SOME CHARACTERISTICS OF CLASS F FLY ASH, CLASS C FLAY ASH, AND SILICA FUME (ROY, 1989)

Designation	Mineralogical and Chemical Feature	Particle Characterization
Fly Ash (Class F) (low-Ca)	(Alkali) aluminosilicate glass matrix with mulite, Fe-rich spinel, hematite, quartz, unburned carbon. Possible alkali sulfate condensates on surface.	Size partly dependent on collection efficiency. May contain hollow or thin walled spheres.
Fly Ash (Class C) (high-Ca)	Calcium-rich glass matrix with C_3A, C_4A_3S, C_4AF, C_2S, Ca-Mg silicates (e.g. merwinite).	Spherical and irregular, size according to collection efficiency.
Silica Fume	Mainly amorphous SiO_2, some unburned carbon.	Mainly extremely fine high surface spheres.

Source: Roy, D.M. (1989). Fly Ash and silica fume chemistry and hydration. In V.M. Malhotra (Ed.), Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete: ACI SP-114 (p. 130). Detroit, Michigan: American Concrete Institute.

TABLE III

TYPICAL CHEMICAL AND PHYSICAL CHARACTERISTICS OF SILICA FUME (ACI COMMITTEE 226, 1987b)

Constituent (percent)	Elkem Spigerverket A/S, Norway	North America: SKW Canada, Inc.	North America: SKW Alloys, Calvert City, KY, and Niagara Falls, NY, USA
SiO2	90.0 - 96.0	89.0 - 95.0	90.0 - 93.0
Al2O3	0.5 - 3.0	0.1 - 0.7	0.5 - 0.6
Fe2O3	0.2 - 0.8	0.1 - 3.1	3.4 - 4.5
MgO	0.5 - 1.5	0.3 - 1.0	0.3 - 0.5
CaO	0.1 - 0.5	0.1 - 1.0	0.5 - 0.8
Na2O	0.2 - 0.7	0.1 - 0.2	0.1 - 0.3
K2O	0.4 - 1.0	0.5 - 1.4	1.0 - 1.2
C	0.5 - 1.4	2.1 - 4.2	1.3 - 3.6
S	0.1 - 0.4	0.1 - 0.2	0.1 - 0.2
Loss on ignition	0.7 - 2.5	2.3 - 4.4	1.4 - 3.8
SO3	-	0.1 - 0.6	0.4 - 1.3
Free Moisture	0.0 - 0.0	0.0 - 0.6	0.0 - 4.8

Typical Physical Characteristics:

Color: Light to dark gray
Specific Gravity: 2.2
Bulk Loose Density: 250-300 kg/m3 (15.6-18.7 lb/ft^3)
Surface Area: 20,000 m^2/kg (474,600 ft^2/lb)

Source: ACI Committee 226 (1987). Silica fume in concrete. ACI Materials Journal, 84(2), 160.

TABLE IV

MIX DESIGNS OF THE MORTAR MIXES
(SIX 50-MM OR 2-INCH CUBES)

Mix Design-ation*	Concrete Constituents (gm)					HRWA (ml)
	Cement	S.F.	F.A.	Water	Sand	
PC-0.39	500.0	-	-	195.8	1504.2	3
PC-0.44	500.0	-	-	220.8	1504.2	3
PC-0.49	500.0	-	-	245.8	1504.2	3
SF-0.44	425.0	75.0	-	220.8	1504.2	3
SF-0.49	425.0	75.0	-	245.8	1504.2	3
FY-0.44	425.0	-	75.0	220.8	1504.2	3

* PC, SF, and FY mean plain cement mortar, silica fume mortar, and fly ash mortar, respectively; the second part of the specimen designation indicates the water-to-cementitious material (W/C) ratio.

Note: S.F., and F.A., denote silica fume, and fly ash, respectively; HRWA is high-range water reducing admixture; 1 lb = 453.592 gm; 1 fl oz = 29.574 ml

TABLE V

CASTING AND CURING SCHEDULE OF THE PLAIN CEMENT MORTAR SPECIMENS

Specimen Designation*	Schedule (Month/Day of Year 1991)						
	Casting	Demolding	Curing (moist)	Oven Drying (110°C)	Recuring (moist)	Absorptivity Test	Compressive Strength Test
PC-0.39-0-D	5/27	5/28	-	5/28-5/31	-	6/29-7/1	7/1-7/3
PC-0.39-0-R	5/27	5/28	-	5/28-5/31	6/1-6/29	6/29-7/1	7/1-7/3
PC-0.39-3-D	5/27	5/28	5/28-5/31	5/31-6/3	-	6/29-7/1	7/1-7/3
PC-0.39-3-R	5/27	5/28	5/28-5/31	5/31-6/3	6/4-6/29	6/29-7/1	7/1-7/3
PC-0.39-7-D	5/27	5/28	5/28-6/4	6/4-6/7	-	6/29-7/1	7/1-7/3
PC-0.39-7-R	5/27	5/28	5/28-6/4	6/4-6/7	6/8-6/29	6/29-7/1	7/1-7/3
PC-0.39-14-D	5/28	5/29	5/29-6/12	6/12-6/15	-	6/30-7/2	7/2-7/4
PC-0.39-14-R	5/28	5/29	5/29-6/12	6/12-6/15	6/16-6/30	6/30-7/2	7/2-7/4
PC-0.39-28	5/28	5/29	5/29-6/26	6/26-6/29	-	6/30-7/2	7/2-7/4
PC-0.49-0-D	5/30	5/31	-	5/31-6/3	-	7/2-7/4	7/4-7/6
PC-0.49-0-R	5/30	5/31	-	5/31-6/3	6/4-7/2	7/2-7/4	7/4-7/6
PC-0.49-3-D	5/30	5/31	5/31-6/3	6/3-6/6	-	7/2-7/4	7/4-7/6
PC-0.49-3-R	5/30	5/31	5/31-6/3	6/3-6/6	6/7-7/2	7/2-7/4	7/4-7/6
PC-0.49-7-D	5/30	5/31	5/31-6/7	6/7-6/10	-	7/2-7/4	7/4-7/6
PC-0.49-7-R	5/30	5/31	5/31-6/7	6/7-6/10	6/11-7/2	7/2-7/4	7/4-7/6
PC-0.49-14-D	5/31	6/1	6/1-6/15	6/15-6/18	-	7/3-7/5	7/5-7/7
PC-0.49-14-R	5/31	6/1	6/1-6/15	6/15-6/18	6/19-7/3	7/3-7/5	7/5-7/7
PC-0.49-28	5/31	6/1	6/1-6/29	6/29-7/2	-	7/3-7/5	7/5-7/7
PC-0.44-0-D	6/1	6/2	-	6/2-6/5	-	7/4-7/6	7/6-7/8
PC-0.44-0-R	6/1	6/2	-	6/2-6/5	6/6-7/4	7/4-7/6	7/6-7/8
PC-0.44-3-D	6/1	6/2	6/2-6/5	6/5-6/8	-	7/4-7/6	7/6-7/8
PC-0.44-3-R	6/1	6/2	6/2-6/5	6/5-6/8	6/9-7/4	7/4-7/6	7/6-7/8
PC-0.44-7-D	6/1	6/2	6/2-6/9	6/9-6/12	-	7/4-7/6	7/6-7/8
PC-0.44-7-R	6/1	6/2	6/2-6/9	6/9-6/12	6/13-7/4	7/4-7/6	7/6-7/8
PC-0.44-14-D	6/2	6/3	6/3-6/17	6/17-6/20	-	7/5-7/7	7/7-7/9
PC-0.44-14-R	6/2	6/3	6/3-6/17	6/17-6/20	6/21-7/5	7/5-7/7	7/7-7/9
PC-0.44-28	6/2	6/3	6/3-7/1	7/1-7/4	-	7/5-7/7	7/7-7/9

* The first part of specimen designation (0.39, 0.44, 0.49) denotes the W/C ratio of the specimens, the second part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding, and the third part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

TABLE VI

CASTING AND CURING SCHEDULE OF FLY ASH AND SILICA FUME MORTAR SPECIMENS

Specimen Designation*	Schedule (Month/Day of Year 1991)						
	Casting	Demolding	Curing (moist)	Oven Drying (110^{0}C)	Re-Curing (Moist)	Absorptivity Test	Compressive Strength Test
SF-0.44-0-D	6/20	6/21	-	6/21-6/24	-	7/23-7/25	7/25-7/27
SF-0.44-0-R	6/20	6/21	-	6/21-6/24	6/25-7/23	7/23-7/25	7/25-7/27
SF-0.44-3-D	6/20	6/21	6/21-6/24	6/24-6/27	-	7/23-7/25	7/25-7/27
SF-0.44-3-R	6/20	6/21	6/21-6/24	6/24-6/27	6/28-7/23	7/23-7/25	7/25-7/27
SF-0.44-7-D	6/21	6/22	6/22-6/29	6/29-7/2	-	7/24-7/26	7/26-7/28
SF-0.44-7-R	6/21	6/22	6/22-6/29	6/29-7/2	7/3-7/24	7/24-7/26	7/26-7/28
SF-0.44-14-D	6/21	6/22	6/22-7/6	7/6-7/9	-	7/24-7/26	7/26-7/28
SF-0.44-14-R	6/21	6/22	6/22-7/6	7/6-7/9	7/10-7/24	7/24-7/26	7/26-7/28
SF-0.44-28	6/21	6/22	6/22-7/20	7/20-7/23	-	7/24-7/26	7/26-7/28
SF-0.49-0-D	6/23	6/24	-	6/24-6/27	-	7/26-7/28	7/28-7/30
SF-0.49-0-R	6/23	6/24	-	6/24-6/27	6/28-7/26	7/26-7/28	7/28-7/30
SF-0.49-3-D	6/23	6/24	6/24-6/27	6/27-6/30	-	7/26-7/28	7/28-7/30
SF-0.49-3-R	6/23	6/24	6/24-6/27	6/27-6/30	7/1-7/26	7/26-7/28	7/28-7/30
SF-0.49-7-D	6/23	6/24	6/24-7/1	7/1-7/4	-	7/26-7/28	7/28-7/30
SF-0.49-7-R	6/23	6/24	6/24-7/1	7/1-7/4	7/5-7/26	7/26-7/28	7/28-7/30
SF-0.49-14-D	6/24	6/25	6/25-7/9	7/9-7/12	-	7/27-7/29	7/29-7/31
SF-0.49-14-R	6/24	6/25	6/25-7/9	7/9-7/12	7/13-7/27	7/27-7/29	7/29-7/31
SF-0.49-28	6/24	6/25	6/25-7/23	7/23-7/26	-	7/27-7/29	7/29-7/31
FY-0.44-0-D	6/25	6/26	-	6/26-6/29	-	7/28-7/30	7/30-8/1
FY-0.44-0-R	6/25	6/26	-	6/26-6/29	6/30-7/28	7/28-7/30	7/30-8/1
FY-0.44-3-D	6/25	6/26	6/26-6/29	6/29-7/2	-	7/28-7/30	7/30-8/1
FY-0.44-3-R	6/25	6/26	6/26-6/29	6/29-7/2	7/3-7/28	7/28-7/30	7/30-8/1
FY-0.44-7-D	6/25	6/26	6/26-7/3	7/3-7/6	-	7/28-7/30	7/30-8/1
FY-0.44-7-R	6/25	6/26	6/26-7/3	7/3-7/6	7/7-7/28	7/28-7/30	7/30-8/1
FY-0.44-14-D	6/26	6/27	6/27-7/11	7/11-7/14	-	7/29-7/31	7/31-8/2
FY-0.44-14-R	6/26	6/27	6/27-7/11	7/11-7/14	7/15-7/29	7/29-7/31	7/31-8/2
FY-0.44-28	6/26	6/27	6/27-7/25	7/25-7/28	-	7/29-7/31	7/31-8/2

* The first part of the specimen designation (SF, FY) denotes whether the mix is of silica fume (SF) or fly ash (FY); the second part (0.44, 0.49) denotes the W/C ratio of the specimens; the third part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding; and the fourth part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

TABLE VII

MIX DESIGNS OF THE CONCRETE MIXES

Mix Design-ation*	Concrete Constituents (kg/m^3)							
	Cement	S.F.	F.A.	Water	C.Ag.	F.Ag.	HRWA	AEA
PC	450.0	-	-	171	1052.4	701.6	0	35
FY-15	382.5	-	67.5	171	1052.4	701.6	0	35
SF-5	427.5	22.5	-	171	1052.4	701.6	0	35
SF-10	405.0	45.0	-	171	1052.4	701.6	343	35
SF-15	382.5	67.5	-	171	1052.4	701.6	1003	35
SF-20	360.0	90.0	-	171	1052.4	701.6	1478	35

* PC, FY, and SF mean plain cement concrete, fly ash concrete, and silica fume concrete, respectively; the second part of the specimen designation in FY and SF series indicates the fly ash or silica content (%).

Note: S.F., F.A., C.Ag., and F.Ag., denote silica fume, fly ash, coarse aggregate, and fine aggregate, respectively; HRWA is high-range water reducing admixture in ml/100 kg of cementitious material; AEA is air-entraining admixture in ml/100 kg of cementitious material; 1 kg/m^3 = 1.68 lb/yd^3.

TABLE VIII

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR PLAIN CEMENT MORTAR SPECIMENS

Specimen Designation	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
PC-0.39-0-D	49.6 (7,190)	1.78 (257)	3.58
PC-0.39-0-R	66.8 (9,680)	4.18 (606)	6.26
PC-0.39-3-D	61.9 (8,970)	1.18 (172)	1.91
PC-0.39-3-R	68.9 (9,980)	4.03 (585)	5.86
PC-0.39-7-D	64.7 (9,380)	1.69 (245)	2.61
PC-0.39-7-R	68.3 (9,910)	3.58 (519)	5.24
PC-0.39-14-D	76.7 (11,230)	1.40 (203)	1.82
PC-0.39-14-R	83.2 (12,060)	3.58 (519)	4.30
PC-0.39-28	79.7 (11,560)	1.94 (281)	2.43
PC-0.44-0-D	45.2 (6,560)	1.25 (181)	2.76
PC-0.44-0-R	63.9 (9,270)	2.54 (368)	3.97
PC-0.44-3-D	58.3 (8,450)	4.62 (670)	7.94
PC-0.44-3-R	69.0 (10,000)	2.33 (337)	3.37
PC-0.44-7-D	64.1 (9,290)	0.81 (117)	1.26
PC-0.44-7-R	69.6 (10,100)	2.58 (374)	3.71
PC-0.44-14-D	68.6 (9,950)	0.67 (97)	0.98
PC-0.44-14-R	70.3 (10,190)	2.96 (429)	4.21
PC-0.44-28	69.8 (10,120)	2.47 (358)	3.54
PC-0.49-0-D	38.4 (5,560)	0.67 (97)	1.75
PC-0.49-0-R	56.7 (8,220)	1.47 (213)	2.59
PC-0.49-3-D	52.3 (7,590)	1.78 (257)	3.39
PC-0.49-3-R	59.2 (8,580)	1.25 (181)	2.11
PC-0.49-7-D	53.7 (7,790)	2.37 (343)	4.41
PC-0.49-7-R	61.5 (8,920)	1.18 (172)	1.93
PC-0.49-14-D	55.0 (7,980)	1.34 (195)	2.44
PC-0.49-14-R	62.5 (9,060)	2.13 (309)	3.41
PC-0.49-28	61.6 (8,930)	1.66 (241)	2.70

* The first part of the specimen designation (PC) denotes plain cement mortar; the second part (0.39, 0.44, 0.49) denotes the W/C ratio of the specimens; the third part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding; and the fourth part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

TABLE IX

A SUMMARY OF THE ABSORPTIVITY DATA FOR PLAIN CEMENT MORTAR SPECIMENS

Specimen Designation	Coefficient of Absorptivity Average x 10^{-6} (cm^2/sec)	Standard Deviation x 10^{-6} (cm^2/sec)	Coefficient of Variation
PC-0.39-0-D	3.26	0.124	3.81
PC-0.39-0-R	1.80	0.017	0.93
PC-0.39-3-D	2.80	0.084	2.99
PC-0.39-3-R	2.04	0.094	4.62
PC-0.39-7-D	2.68	0.218	8.14
PC-0.39-7-R	2.14	0.095	4.41
PC-0.39-14-D	2.40	0.067	2.78
PC-0.39-14-R	2.05	0.082	4.00
PC-0.39-28	2.32	0.068	2.91
PC-0.44-0-D	3.98	0.139	3.48
PC-0.44-0-R	2.41	0.118	4.87
PC-0.44-3-D	3.50	0.117	3.34
PC-0.44-3-R	2.78	0.000	0.00
PC-0.44-7-D	3.56	0.094	2.64
PC-0.44-7-R	2.81	0.075	2.68
PC-0.44-14-D	3.31	0.068	2.04
PC-0.44-14-R	3.03	0.057	1.89
PC-0.44-28	3.23	0.067	2.06
PC-0.49-0-D	4.67	0.188	4.04
PC-0.49-0-R	3.19	0.102	3.20
PC-0.49-3-D	4.05	0.261	6.44
PC-0.49-3-R	3.44	0.180	5.24
PC-0.49-7-D	4.05	0.114	2.82
PC-0.49-7-R	3.70	0.086	2.34
PC-0.49-14-D	3.99	0.099	2.48
PC-0.49-14-R	3.77	0.087	2.30
PC-0.49-28	4.19	0.146	3.49

* The first part of the specimen designation (PC) denotes plain cement mortar; the second part (0.39, 0.44, 0.49) denotes the W/C ratio of the specimens; the third part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding; and the fourth part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

Note: 1 cm^2/sec = 0.155 in^2/sec

TABLE X

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR SILCA FUME AND FLY ASH MORTAR SPECIMENS

Specimen Designation	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
SF-0.44-0-D	58.5 (8,480)	0.39 (56)	0.66
SF-0.44-0-R	71.0 (10,300)	3.13 (454)	4.41
SF-0.44-3-D	67.6 (9,800)	2.13 (309)	3.16
SF-0.44-3-R	74.0 (10,730)	5.21 (756)	7.04
SF-0.44-7-D	75.3 (10,920)	1.75 (253)	2.32
SF-0.44-7-R	78.5 (11,390)	3.92 (568)	4.99
SF-0.44-14-D	74.3 (10,770)	2.72 (395)	3.66
SF-0.44-14-R	74.3 (10,770)	3.52 (510)	4.73
SF-0.44-28	74.1 (10,740)	2.93 (426)	3.96
SF-0.49-0-D	55.3 (8,020)	0.81 (117)	1.46
SF-0.49-0-R	64.7 (9,380)	0.39 (56)	0.60
SF-0.49-3-D	58.9 (8,540)	0.39 (56)	0.66
SF-0.49-3-R	62.1 (9,010)	3.25 (471)	5.23
SF-0.49-7-D	59.8 (8,670)	3.30 (478)	5.51
SF-0.49-7-R	62.9 (9,120)	1.25 (181)	1.98
SF-0.49-14-D	66.9 (9,700)	3.13 (454)	4.68
SF-0.49-14-R	64.7 (9,380)	3.08 (446)	4.75
SF-0.49-28	65.0 (9,430)	2.07 (300)	3.18
FY-0.44-0-D	36.0 (5,230)	1.03 (149)	2.84
FY-0.44-0-R	60.3 (8,750)	1.61 (234)	2.67
FY-0.44-3-D	53.7 (7,790)	0.81 (117)	1.50
FY-0.44-3-R	68.4 (9,920)	1.21 (175)	1.77
FY-0.44-7-D	58.5 (8,480)	1.03 (149)	1.75
FY-0.44-7-R	70.4 (10,210)	1.61 (234)	2.29
FY-0.44-14-D	66.0 (9,570)	2.13 (309)	3.23
FY-0.44-14-R	72.0 (10,440)	1.62 (236)	2.26
FY-0.44-28	70.1 (10,160)	3.61 (523)	5.15

* The first part of the specimen designation (SF, FY) denotes whether the mix is of silica fume (SF) or fly ash (FY); the second part (0.44, 0.49) denotes the W/C ratio of the specimens; the third part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding; and the fourth part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

TABLE XI

A SUMMARY OF THE ABSORPTIVITY DATA FOR SILICA FUME AND FLY ASH MORTAR SPECIMENS

Specimen Designation	Coefficient of Absorptivity Average x 10^{-6} (cm^2/sec)	Standard Deviation x 10^{-6} (cm^2/sec)	Coefficient of Variation
SF-0.44-0-D	3.73	0.291	7.80
SF-0.44-0-R	2.17	0.055	2.54
SF-0.44-3-D	1.81	0.077	4.25
SF-0.44-3-R	1.40	0.091	6.51
SF-0.44-7-D	1.74	0.114	6.58
SF-0.44-7-R	1.62	0.016	0.98
SF-0.44-14-D	1.79	0.083	4.61
SF-0.44-14-R	1.63	0.058	3.52
SF-0.44-28	2.11	0.167	7.91
SF-0.49-0-D	3.59	0.163	4.54
SF-0.49-0-R	2.14	0.095	4.41
SF-0.49-3-D	2.62	0.100	3.82
SF-0.49-3-R	2.05	0.031	1.50
SF-0.49-7-D	2.60	0.053	2.04
SF-0.49-7-R	2.22	0.067	3.00
SF-0.49-14-D	2.58	0.020	0.77
SF-0.49-14-R	2.04	0.064	3.15
SF-0.49-28	3.05	0.117	3.84
FY-0.44-0-D	4.59	0.138	3.01
FY-0.44-0-R	2.70	0.108	4.01
FY-0.44-3-D	3.87	0.135	3.50
FY-0.44-3-R	2.54	0.151	5.93
FY-0.44-7-D	3.84	0.222	5.77
FY-0.44-7-R	2.56	0.140	5.45
FY-0.44-14-D	3.47	0.069	2.00
FY-0.44-14-R	2.58	0.122	4.71
FY-0.44-28	3.23	0.086	2.65

* The first part of the specimen designation (SF, FY) denotes whether the mix is of silica fume (SF) or fly ash (FY); the second part (0.44, 0.49) denotes the W/C ratio of the specimens; the third part (0, 3, 7, 14, 28) denotes the period of moist curing after demolding; and the fourth part (D,R) indicates whether the specimens were subjected to discontinuous curing (D) or recuring (R).

Note: 1 cm^2/sec = 0.155 in^2/sec

TABLE XII

A COMPARISON OF THE COMPRESSIVE STRENGTH OF 50-MM (2-INCH) CUBES AND 100 x 200-MM (4 x 8-INCH) CYLINDERS

Time of Moist Curing (Days)	Compressive Strength 50-mm Cubes Average (MPa)	S.D. (MPa)	C.O.V. (%)	100 x 200-mm Cylinders Average (MPa)	S.D. (MPa)	C.O.V. (%)
3	63.9	1.40	2.19	34.5	1.60	4.62
7	71.3	3.74	5.24	43.1	1.35	3.13
28	83.7	2.01	2.41	48.6	0.81	1.67

Note: S.D. denotes standard deviation; C.O.V. denotes coefficient of variation

TABLE XIII

CHEMICAL ANALYSIS OF THE CURING WATER

Sample Designation*	pH	$(OH)^-$ ions (mg/l)	$CaCO_3$ (mg/l)	Ca^{++} ions (mg/l)
CW-SF/FY - #1	9.3	0.339	1788	715.2
CW-SF/FY - #2	9.1	0.214	1748	699.2
CW-PC - #1	9.3	0.339	3000	1200.0
CW-PC - #2	9.4	0.427	2820	1128.0
CW-Reference	7.1	0.002	137	54.8

* CW-SF/FY means the curing water for silica fume and fly ash mortar specimens (cured in the same container); CW-PC means the curing water for plain cement mortar specimens; CW-Reference means the potable water which was originally used for curing.

TABLE XIV

SLUMP AND AIR CONTENT OF THE CONCRETE MIXES

Mix Designation*	Slump mm (inch)	Air Content (percent)
PC		
Batch #1	76 (3.0)	4.0
Batch #2	89 (3.5)	5.3
Batch #3	66 (2.6)	4.5
Average	77 (3.0)	4.6
FY-15		
Batch #1	135 (5.3)	7.6
Batch #2	140 (5.5)	7.9
Batch #3	135 (5.3)	7.0
Average	137 (5.4)	7.5
SF-5		
Batch #1	22 (0.9)	4.0
Batch #2	25 (1.0)	3.9
Batch #3	25 (1.0)	4.3
Average	24 (1.0)	4.1
SF-10		
Batch #1	13 (0.5)	3.4
Batch #2	16 (0.6)	3.0
Batch #3	13 (0.5)	2.8
Average	14 (0.5)	3.1
SF-15		
Batch #1	16 (0.6)	2.7
Batch #2	22 (0.9)	2.4
Batch #3	22 (0.9)	2.2
Average	20 (0.8)	2.4
SF-20		
Batch #1	22 (0.9)	2.9
Batch #2	48 (1.9)	3.0
Batch #3	38 (1.5)	2.7
Average	36 (1.4)	2.9

* PC, FY, and SF mean plain cement concrete, fly ash concrete, and silica fume concrete, respectively; the second part of the specimen designation in FY and SF series indicates the fly ash or silica content (%).

TABLE XV

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR THE PLAIN CEMENT CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
PC-0-C	18.1 (2,620)	1.98 (287)	10.93
PC-0-D	32.1 (4,660)	1.58 (229)	4.92
PC-0-R	32.4 (4,700)	1.89 (274)	5.84
PC-1-C	21.4 (3,100)	1.75 (254)	8.18
PC-1-D	32.4 (4,700)	1.16 (168)	3.56
PC-1-R	30.9 (4,480)	2.61 (379)	8.46
PC-3-C	24.0 (3,480)	0.82 (119)	3.41
PC-3-D	33.0 (4,780)	2.48 (359)	7.52
PC-3-R	29.5 (4,280)	1.01 (147)	3.42
PC-7-C	27.2 (3,940)	0.78 (113)	2.86
PC-7-D	33.8 (4,910)	1.74 (252)	5.14
PC-7-R	29.8 (4,330)	4.08 (591)	13.66
PC-14-C	31.8 (4,600)	2.51 (364)	7.91
PC-14-D	37.8 (5,480)	2.10 (304)	5.54
PC-28-C	35.7 (5,180)	1.73 (251)	4.84

* The first part of the mix designation (PC) means plain cement concrete; the second part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the third part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XVI

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR THE 15% FLY ASH CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
FY-15-0-C	13.9 (2,020)	1.28 (185)	9.16
FY-15-0-D	31.2 (4,520)	2.05 (297)	6.57
FY-15-0-R	31.2 (4,530)	3.13 (454)	10.02
FY-15-1-C	17.3 (2,510)	3.64 (528)	21.02
FY-15-1-D	32.5 (4,710)	1.63 (236)	5.01
FY-15-1-R	29.0 (4,210)	3.71 (538)	12.78
FY-15-3-C	22.3 (3,230)	0.46 (67)	2.06
FY-15-3-D	29.4 (4,260)	0.51 (75)	1.75
FY-15-3-R	28.5 (4,130)	0.27 (39)	0.95
FY-15-7-C	25.2 (3,660)	2.66 (386)	10.55
FY-15-7-D	31.2 (4,530)	2.94 (426)	9.41
FY-15-7-R	30.1 (4,370)	1.86 (269)	6.16
FY-15-14-C	34.3 (4,980)	2.95 (428)	8.60
FY-15-14-D	37.2 (5,390)	1.17 (169)	3.14
FY-15-28-C	39.7 (5,750)	2.68 (389)	6.76

* The first part of the mix designation (FY) means fly ash concrete; the second part of the mix designation indicates fly ash content (%); the third part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the fourth part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XVII

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR THE 5% SILICA FUME CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
SF-5-0-C	23.1 (3,350)	1.31 (189)	5.66
SF-5-0-D	41.6 (6,030)	2.61 (379)	6.28
SF-5-0-R	38.2 (5,540)	0.71 (103)	1.86
SF-5-1-C	26.6 (3,850)	2.61 (379)	9.84
SF-5-1-D	40.2 (5,830)	1.01 (147)	2.51
SF-5-1-R	38.4 (5,570)	2.94 (426)	7.65
SF-5-3-C	31.6 (4,580)	1.08 (157)	3.42
SF-5-3-D	44.0 (6,380)	1.49 (216)	3.39
SF-5-3-R	40.2 (5,820)	2.37 (343)	5.89
SF-5-7-C	36.4 (5,280)	1.71 (248)	4.70
SF-5-7-D	41.3 (5,990)	3.44 (499)	8.33
SF-5-7-R	40.4 (5,850)	3.21 (466)	7.96
SF-5-14-C	38.0 (5,510)	3.32 (482)	8.75
SF-5-14-D	45.5 (6,590)	0.90 (131)	1.98
SF-5-28-C	42.1 (6,110)	0.71 (103)	1.68

* The first part of the mix designation (SF) means silica fume concrete; the second part of the mix designation indicates silica fume content (%); the third part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the fourth part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XVIII

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA
FOR THE 10% SILICA FUME CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
SF-10-0-C	24.1 (3,490)	1.75 (254)	7.27
SF-10-0-D	40.5 (5,880)	1.36 (197)	3.36
SF-10-0-R	42.5 (6,170)	2.63 (382)	6.19
SF-10-1-C	28.3 (4,100)	2.87 (416)	10.14
SF-10-1-D	45.0 (6,520)	3.01 (436)	6.69
SF-10-1-R	41.9 (6,070)	3.51 (509)	8.40
SF-10-3-C	32.8 (4,750)	0.99 (144)	3.02
SF-10-3-D	45.9 (6,660)	3.69 (535)	8.04
SF-10-3-R	48.4 (7,020)	2.96 (429)	6.11
SF-10-7-C	37.0 (5,360)	2.12 (307)	5.73
SF-10-7-D	49.4 (7,160)	4.37 (634)	8.86
SF-10-7-R	45.2 (6,550)	3.26 (472)	7.21
SF-10-14-C	40.2 (5,830)	2.75 (399)	6.85
SF-10-14-D	48.3 (7,000)	0.77 (111)	1.59
SF-10-28-C	43.3 (6,270)	1.45 (210)	3.35

* The first part of the mix designation (SF) means silica fume concrete; the second part of the mix designation indicates silica fume content (%); the third part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the fourth part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XIX

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA FOR THE 15% SILICA FUME CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
SF-15-0-C	27.3 (3,960)	0.45 (66)	1.65
SF-15-0-D	44.9 (6,510)	2.53 (367)	5.64
SF-15-0-R	46.8 (6,780)	2.05 (297)	4.38
SF-15-1-C	30.7 (4,460)	1.82 (264)	5.92
SF-15-1-D	45.0 (6,530)	1.56 (226)	3.46
SF-15-1-R	44.7 (6,480)	1.55 (225)	3.47
SF-15-3-C	38.3 (5,550)	2.97 (431)	7.77
SF-15-3-D	49.7 (7,210)	4.16 (603)	8.37
SF-15-3-R	53.9 (7,810)	3.24 (470)	6.02
SF-15-7-C	45.0 (6,530)	1.86 (269)	4.12
SF-15-7-D	48.8 (7,070)	3.47 (503)	7.11
SF-15-7-R	50.1 (7,270)	2.28 (330)	4.55
SF-15-14-C	45.2 (6,554)	1.26 (183)	2.79
SF-15-14-D	53.7 (7,780)	3.75 (544)	7.00
SF-15-28-C	51.4 (7,450)	0.45 (65)	0.88

* The first part of the mix designation (SF) means silica fume concrete; the second part of the mix designation indicates silica fume content (%); the third part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the fourth part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XX

A SUMMARY OF THE COMPRESSIVE STRENGTH DATA
FOR THE 20% SILICA FUME CONCRETE MIX

Mix Designation*	Compressive Strength Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
SF-20-0-C	24.5 (3,560)	1.52 (220)	6.19
SF-20-0-D	47.5 (6,890)	2.24 (325)	4.72
SF-20-0-R	51.2 (7,420)	1.13 (164)	2.21
SF-20-1-C	32.0 (4,640)	0.19 (28)	0.61
SF-20-1-D	51.7 (7,490)	4.01 (581)	7.76
SF-20-1-R	53.8 (7,800)	1.62 (235)	3.01
SF-20-3-C	39.0 (5,650)	1.35 (195)	3.46
SF-20-3-D	49.9 (7,230)	2.79 (405)	5.60
SF-20-3-R	50.0 (7,260)	0.83 (121)	1.67
SF-20-7-C	47.9 (6,940)	2.32 (336)	4.84
SF-20-7-D	55.9 (8,110)	0.18 (26)	0.32
SF-20-7-R	50.3 (7,300)	3.06 (444)	6.08
SF-20-14-C	47.2 (6,850)	1.13 (164)	2.40
SF-20-14-D	48.1 (6,970)	2.25 (326)	4.68
SF-20-28-C	51.3 (7,430)	3.39 (492)	6.61

* The first part of the mix designation (SF) means silica fume concrete; the second part of the mix designation indicates silica fume content (%); the third part of the mix designation (0, 1, 3, etc.) indicates the time of moist curing; the fourth part of the mix designation indicates whether the specimens were continuously cured (C), discontinuously cured (D), or recured (R).

TABLE XXI

A COMPARISON OF THE COMPRESSIVE STRENGTH OF WET AND DRY CONCRETE SPECIMENS (50-MM or 2-INCH CUBES)

Time of Moist Curing (Days)	Compressive Strength					
	Wet Specimens			Dry Specimens		
	Average (MPa)	S.D. (MPa)	C.O.V. (%)	Average (MPa)	S.D. (MPa)	C.O.V. (%)
3	63.9	1.40	2.19	72.3	1.83	2.53
7	71.3	3.74	5.24	85.1	3.80	4.47
28	83.7	2.01	2.41	95.7	2.74	2.86

Note: S.D. means standard deviation; C.O.V. means coefficient of variation

TABLE XXII

CORRELATION COEFFICIENTS FOR
REGRESSION EQUATIONS

Mix Designation*	Equation**	Correlation Coefficient (R^2)
PC	S = 11.93 Log t + 17.53	0.987
FY-15	S = 17.79 Log t + 12.28	0.967
SF-5	S = 13.14 Log t + 23.23	0.989
SF-10	S = 13.30 Log t + 24.41	0.996
SF-15	S = 16.70 Log t + 27.28	0.968
SF-20	S = 18.48 Log t + 26.62	0.938

* PC, FY, and SF mean plain cement concrete, fly ash concrete, and silica fume concrete, respectively; the second part of the specimen designation in FY and SF series indicates the fly ash or silica content (%).

** S is the strength in MPa; t is the time of curing in days which includes the period of moist curing and the 1-day period between casting and demolding of the specimens.

TABLE XXIII

MINIMUM CURING REQUIREMENTS FOR VARIOUS CONCRETES

Type of Concrete	Minimum Length of Curing (Days)*
Plain Cement Concrete (PC)	3.73
15% Fly Ash Concrete (FY-15)	6.40
5% Silica Fume Concrete (SF-5)	3.04
10% Silica Fume Concrete (SF-10)	2.90
15% Silica Fume Concrete (SF-15)	3.33

* Includes the period of moist curing and the 1-day period between casting and demolding of the specimens

APPENDIX B - FIGURES

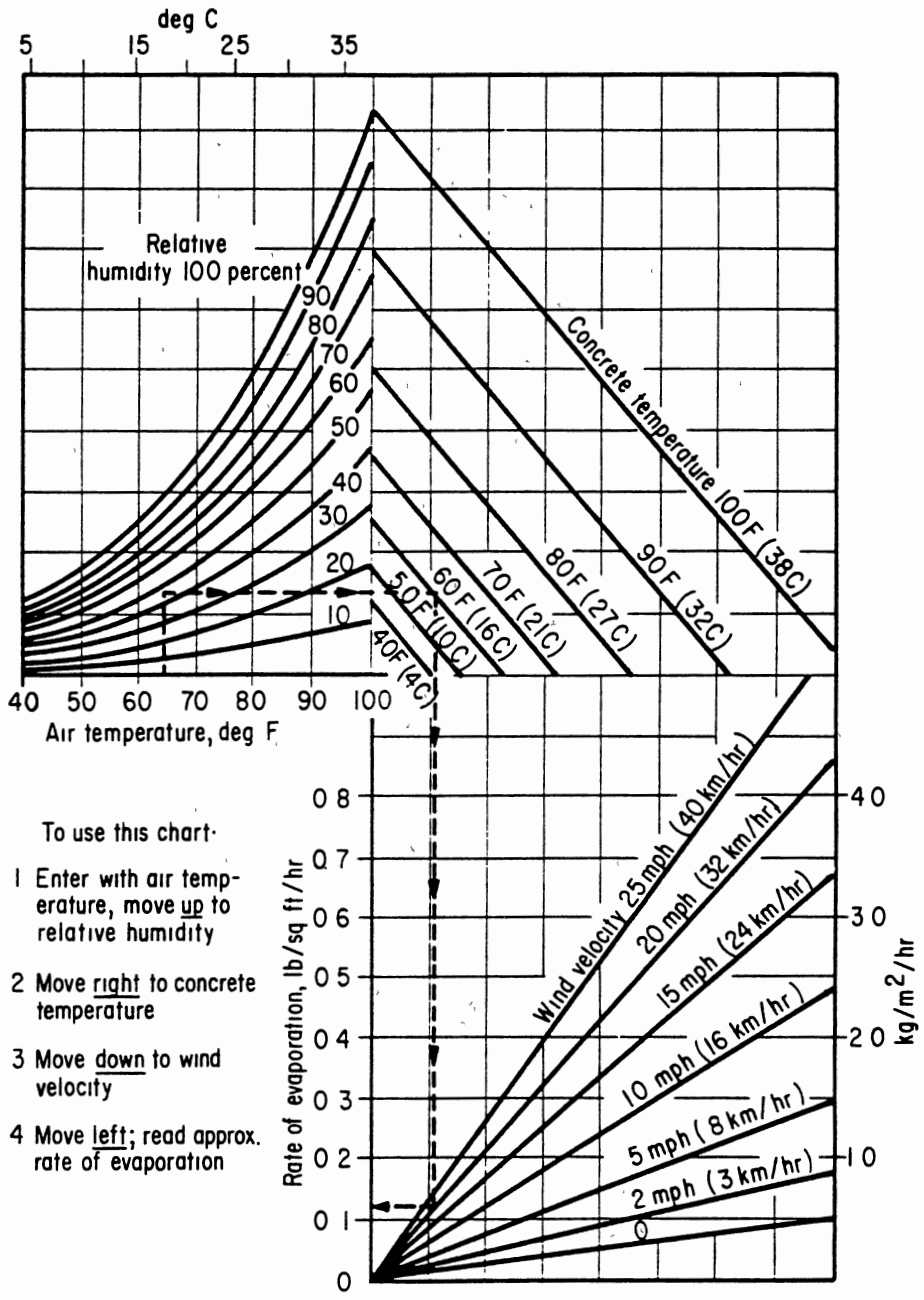

Figure 1. A Chart for Estimating the Loss of Surface Moisture in Concrete (ACI Committee 308, 1981)

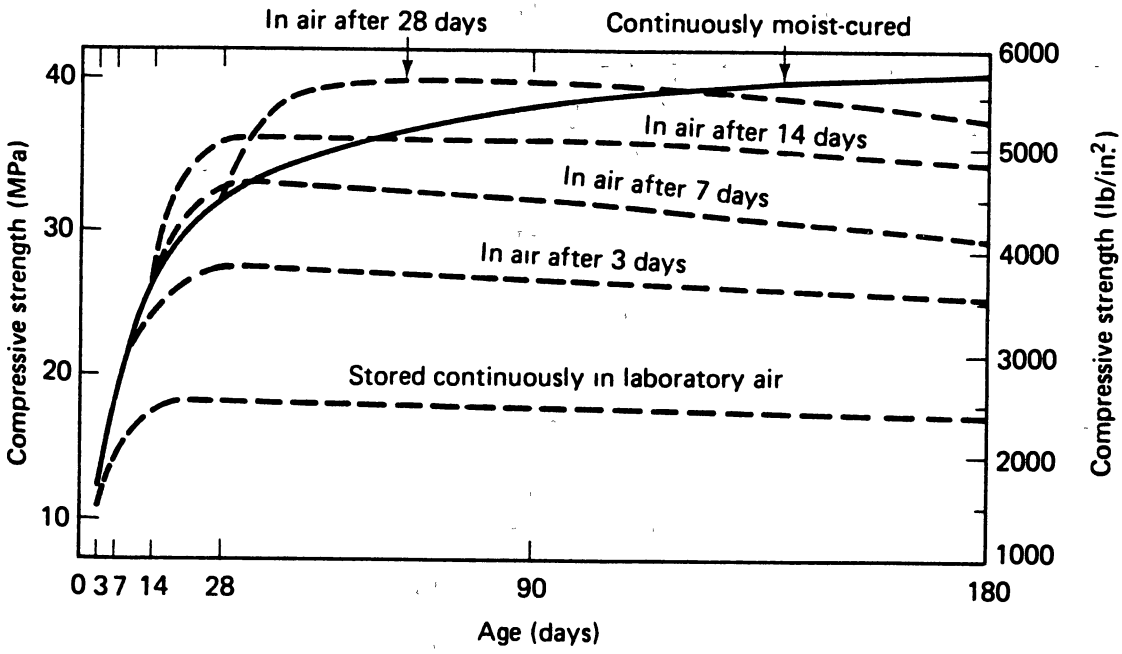

Figure 2. The Effect of Different Levels of Moist Curing on the Strength of Concrete (Mindess & Young, 1981)

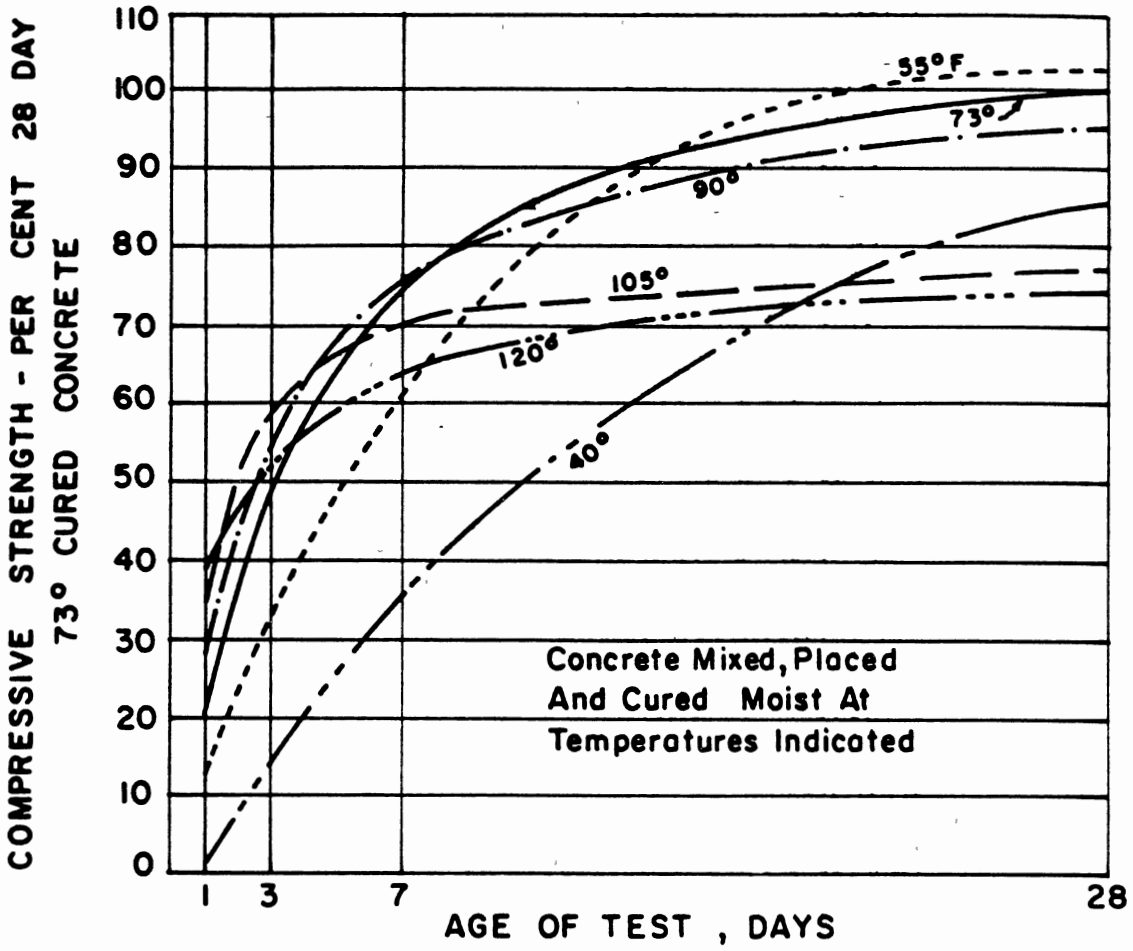

Figure 3. The Effect of Curing Temperature on the Strength of Concrete (Carrier, 1978)

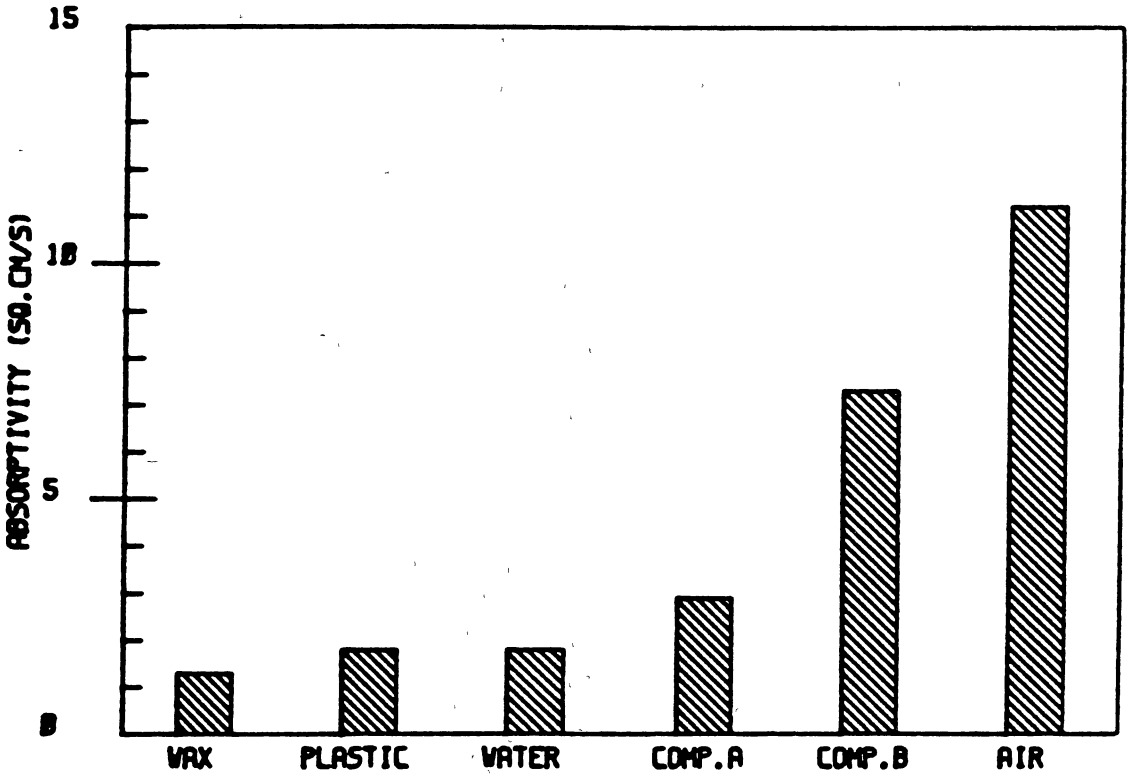

Figure 4. A Comparison of the Effectiveness of Water Curing and Compound Curing (Senbetta & Malchow, 1987)

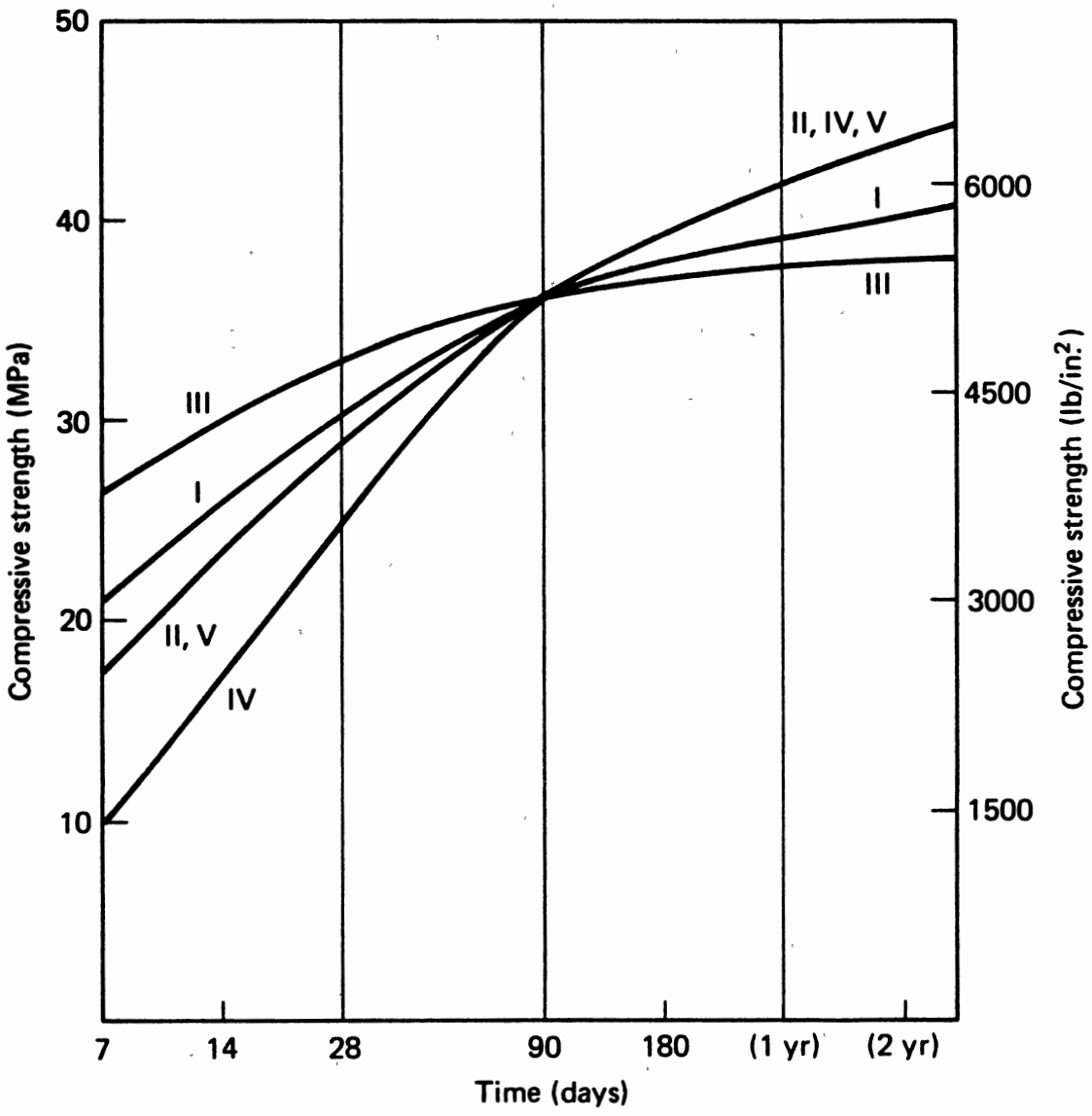

Figure 5. Strength Development in Concretes Made With Different Type of Cements (Mindess & Young, 1981)

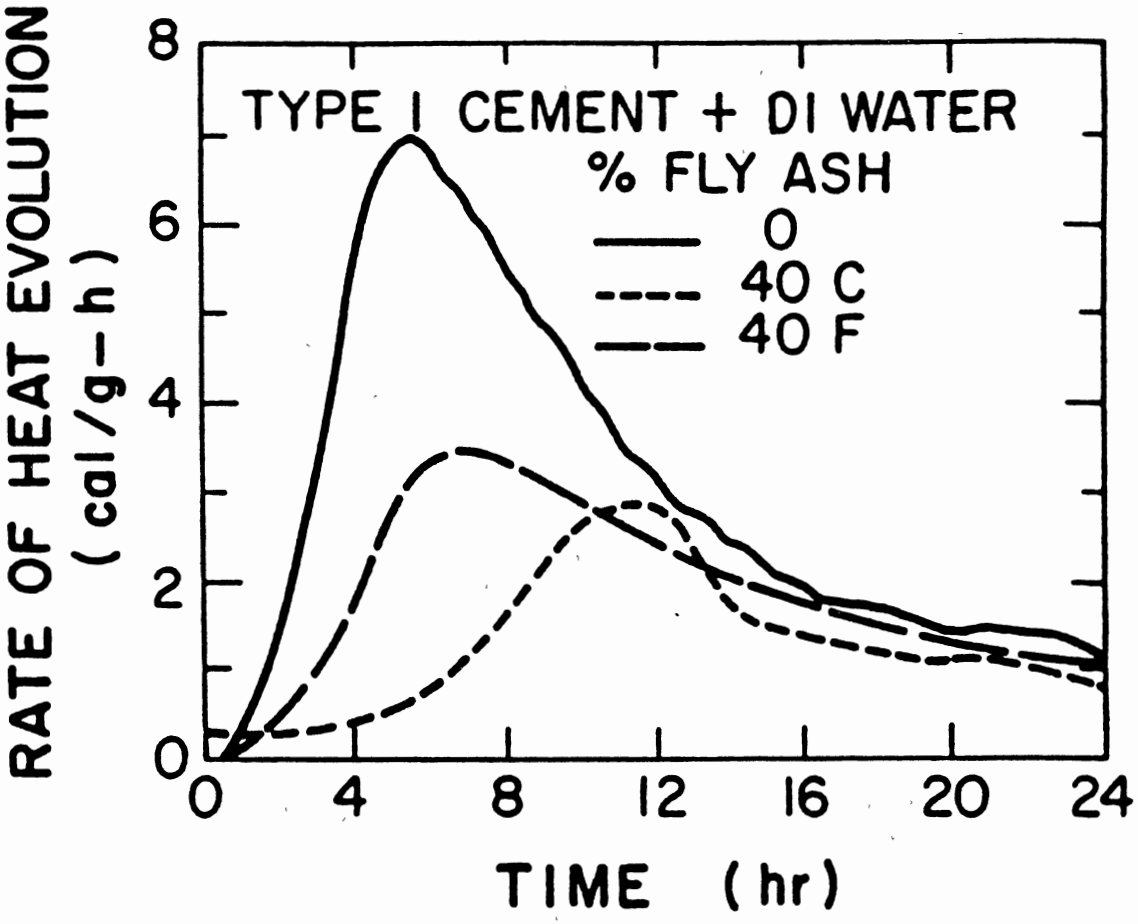

Figure 6. Heat of Hydration in Fly Ash-Cement Paste in Comparison to Normal Portland Cement Paste (Roy, 1989)

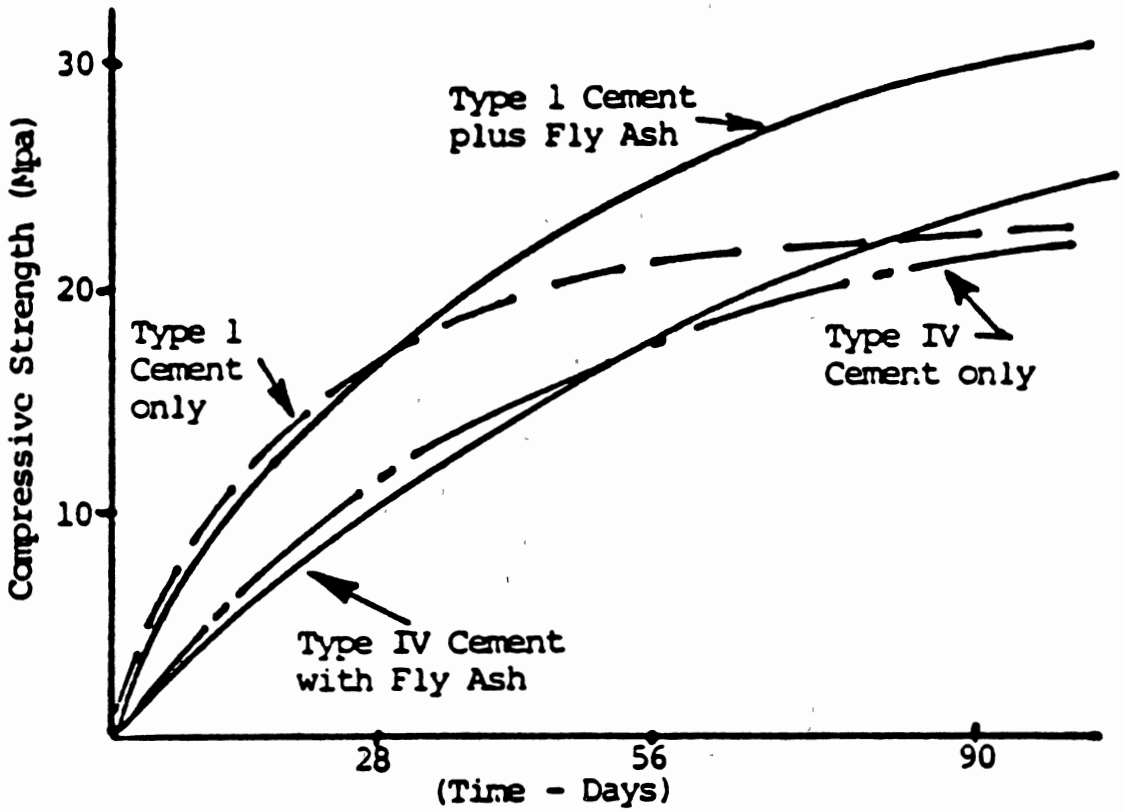

Figure 7. Strength Development in Different Concrete Mixes Made With and Without Fly Ash (Samarin & Munn, 1983)

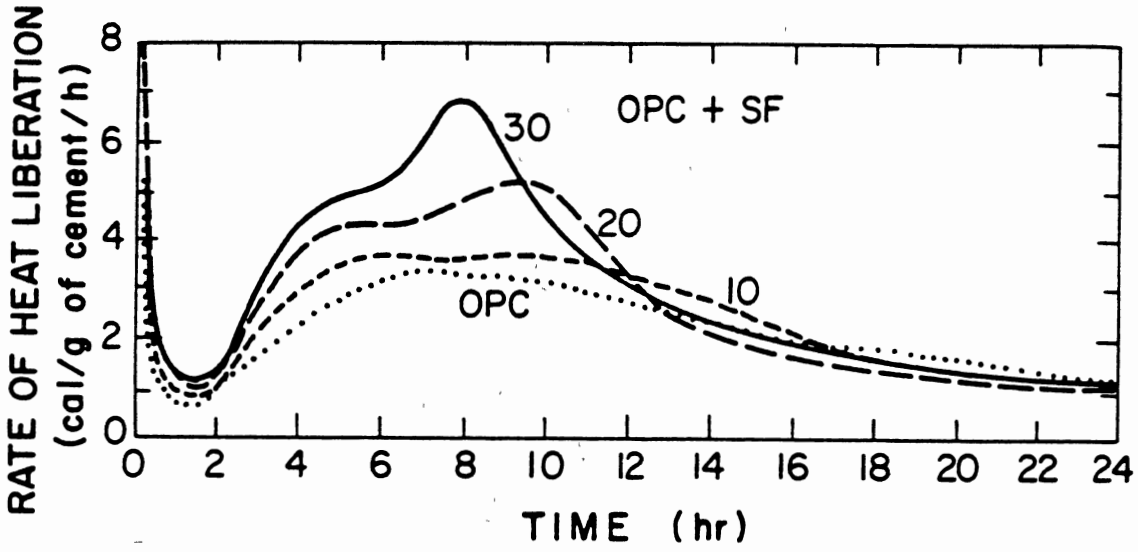

Figure 8. Heat of Hydration in Silica Fume-Cement Paste in Comparison to Normal Portland Cement Paste (Roy, 1989)

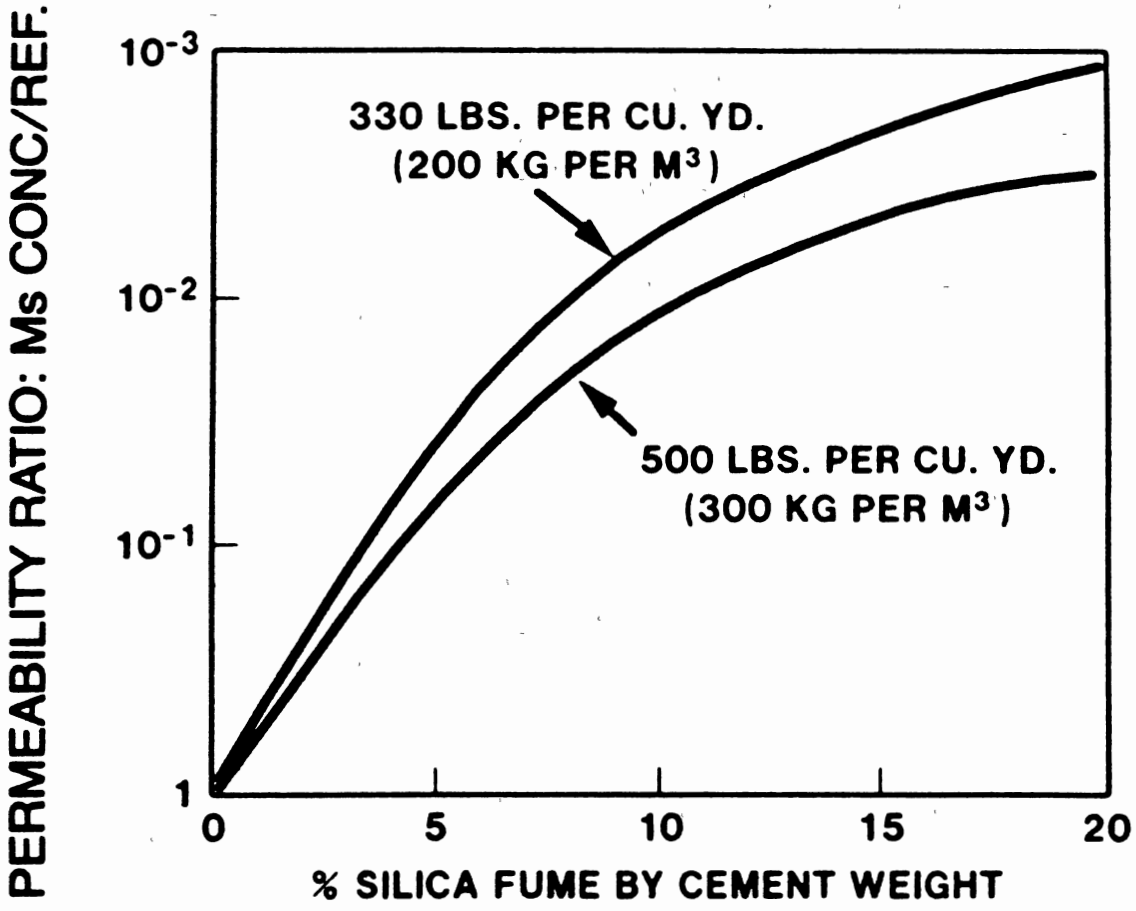

Figure 9. The Effect of Silica Fume Addition on the Water Permeability of Concrete (Radjy et al., 1986)

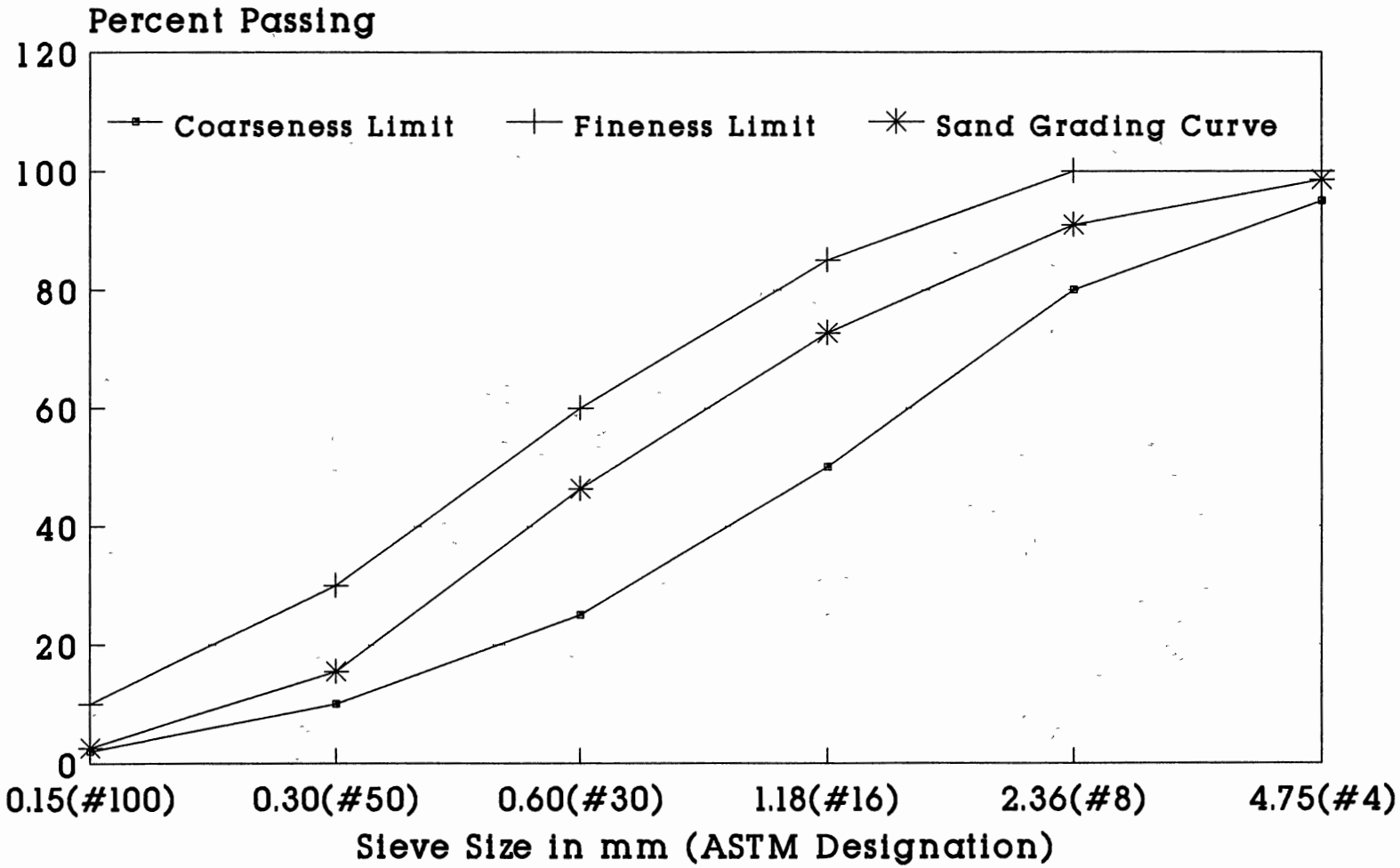

Figure 10. Gradation Curve and ASTM C-33 Specification Limits for the Sand Used to Prepare the Mortar Specimens

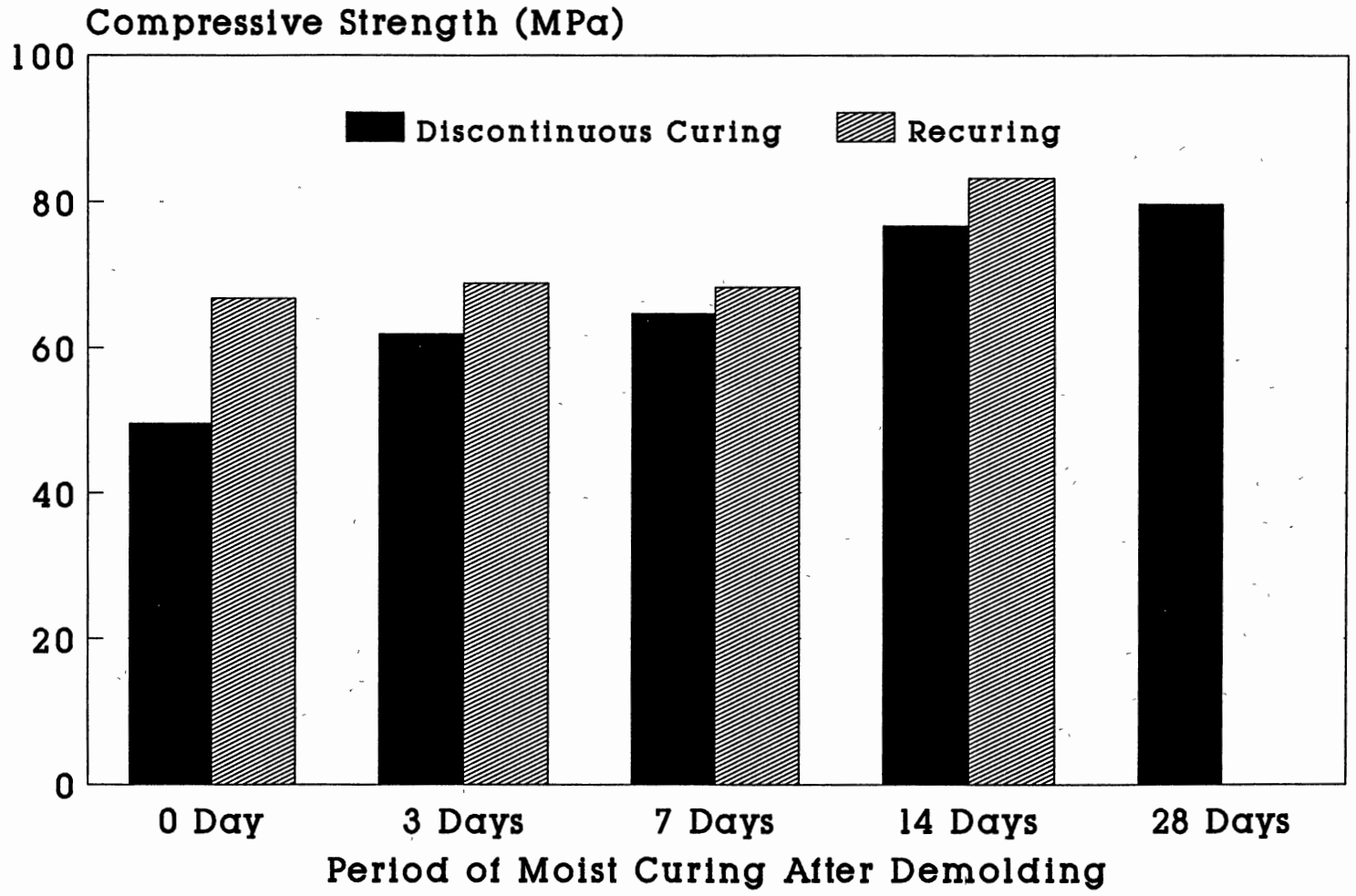

Figure 11. Compressive Strength of Plain Cement Mortar Specimens, of W/C Ratio 0.39, Subjected to Recuring and Discontinuous Curing

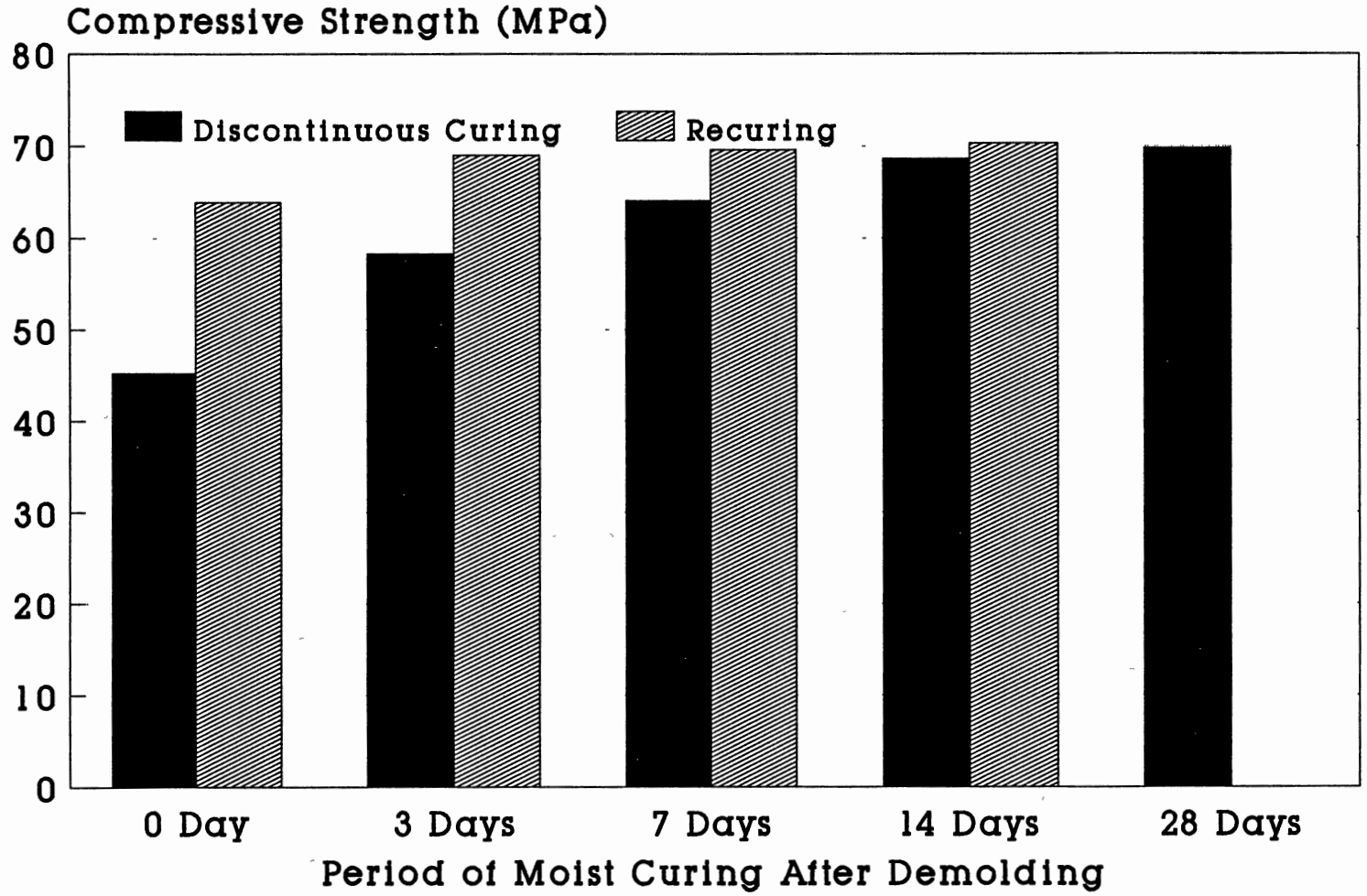

Figure 12. Compressive Strength of Plain Cement Mortar Specimens, of W/C Ratio 0.44, Subjected to Recuring and Discontinuous Curing

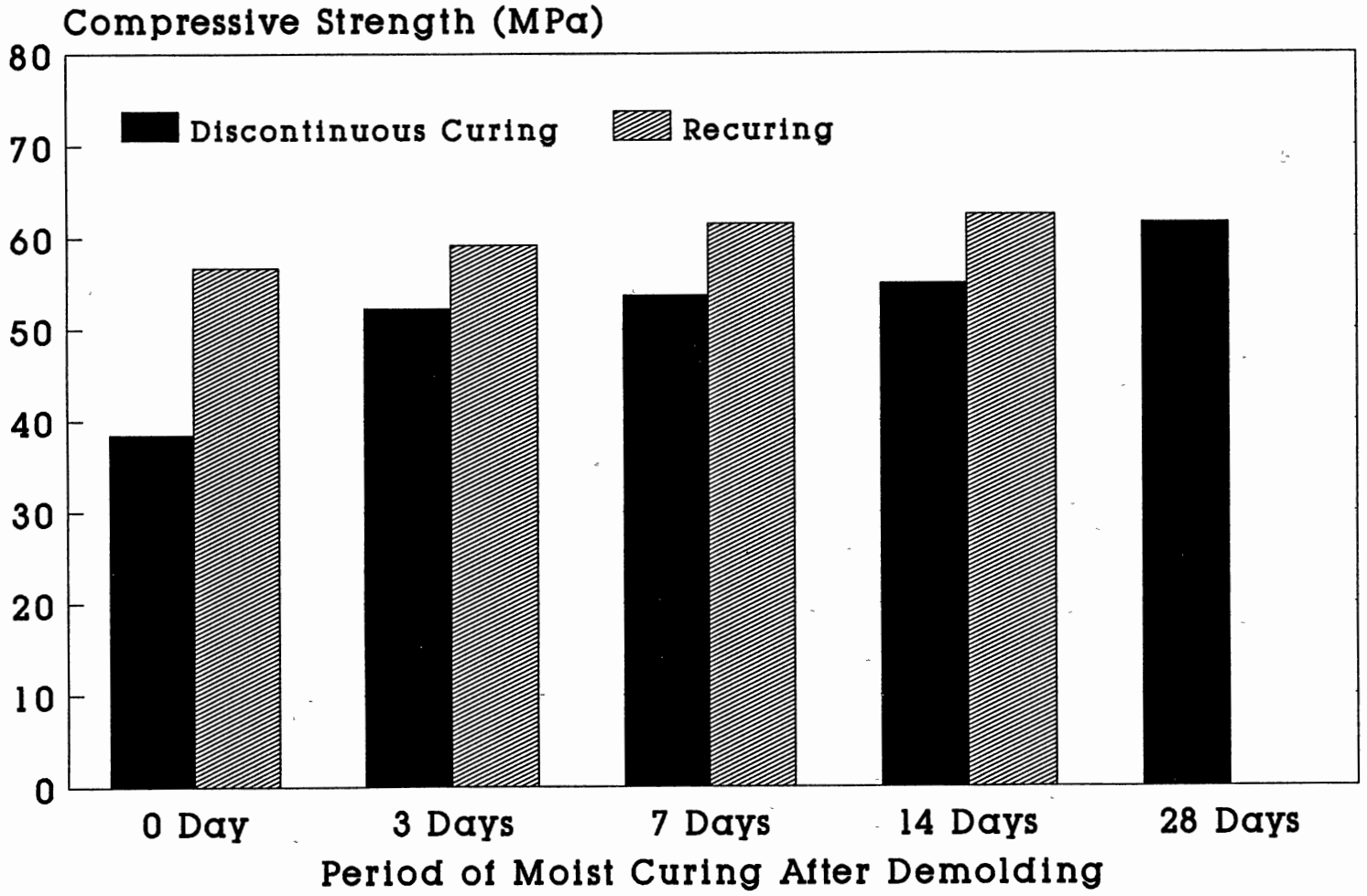

Figure 13. Compressive Strength of Plain Cement Mortar Specimens, of W/C Ratio 0.49, Subjected to Recuring and Discontinuous Curing

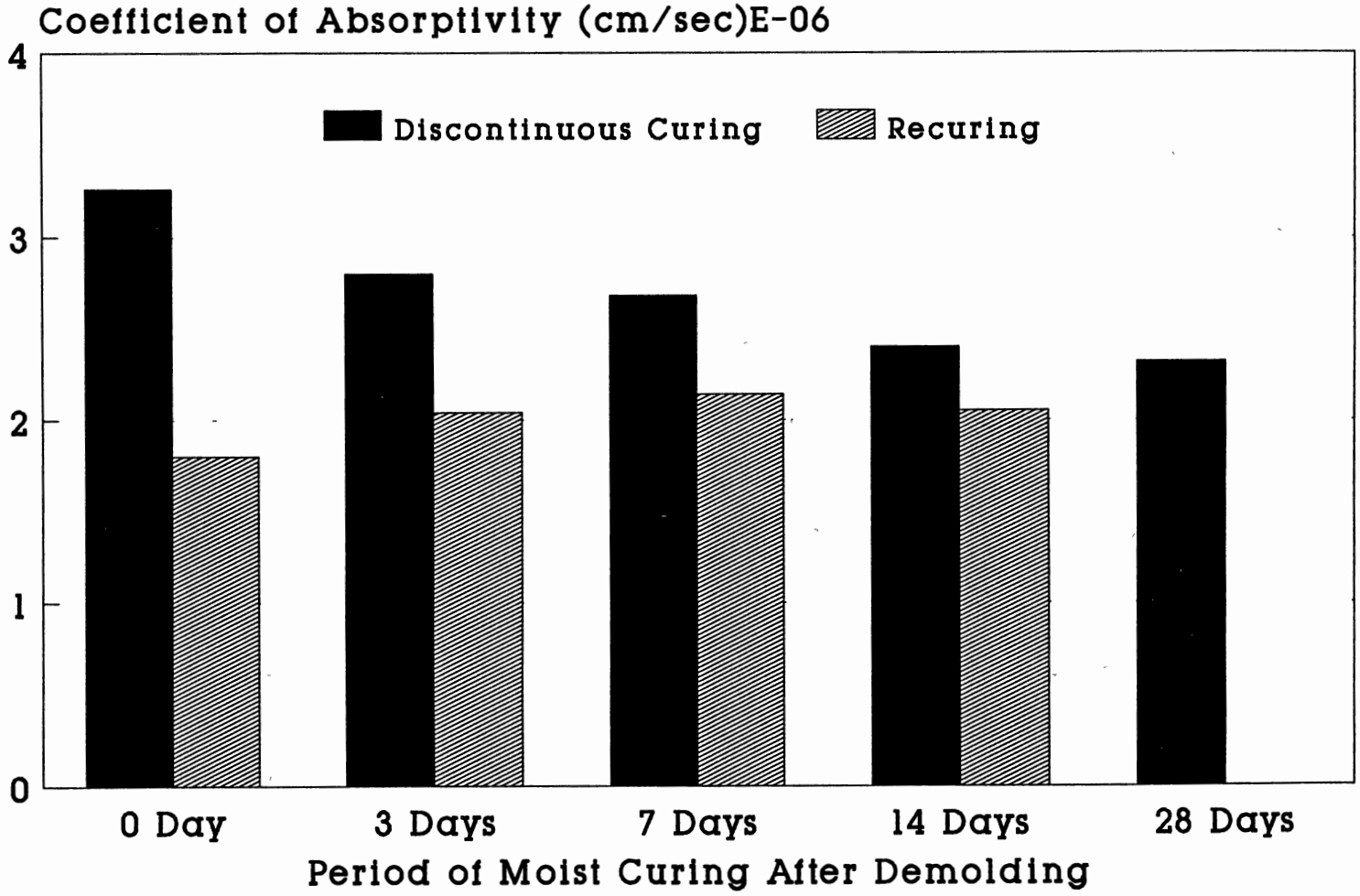

Figure 14. Coefficient of Absorptivity of Plain Cement Mortar Specimens, of W/C Ratio 0.39, Subjected to Recuring and Discontinuous Curing

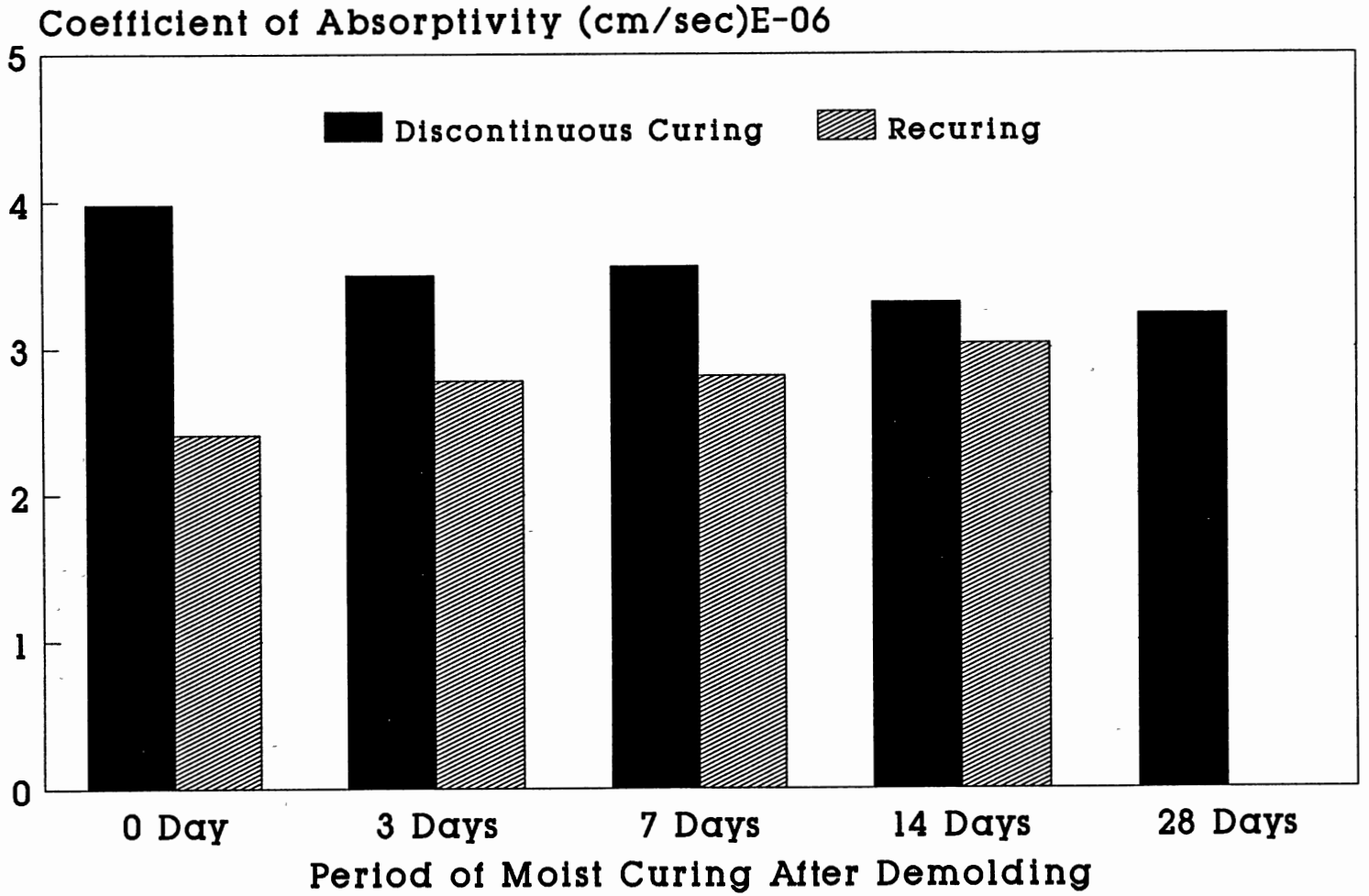

Figure 15. Coefficient of Absorptivity of Plain Cement Mortar Specimens, of W/C Ratio 0.44, Subjected to Recuring and Discontinuous Curing

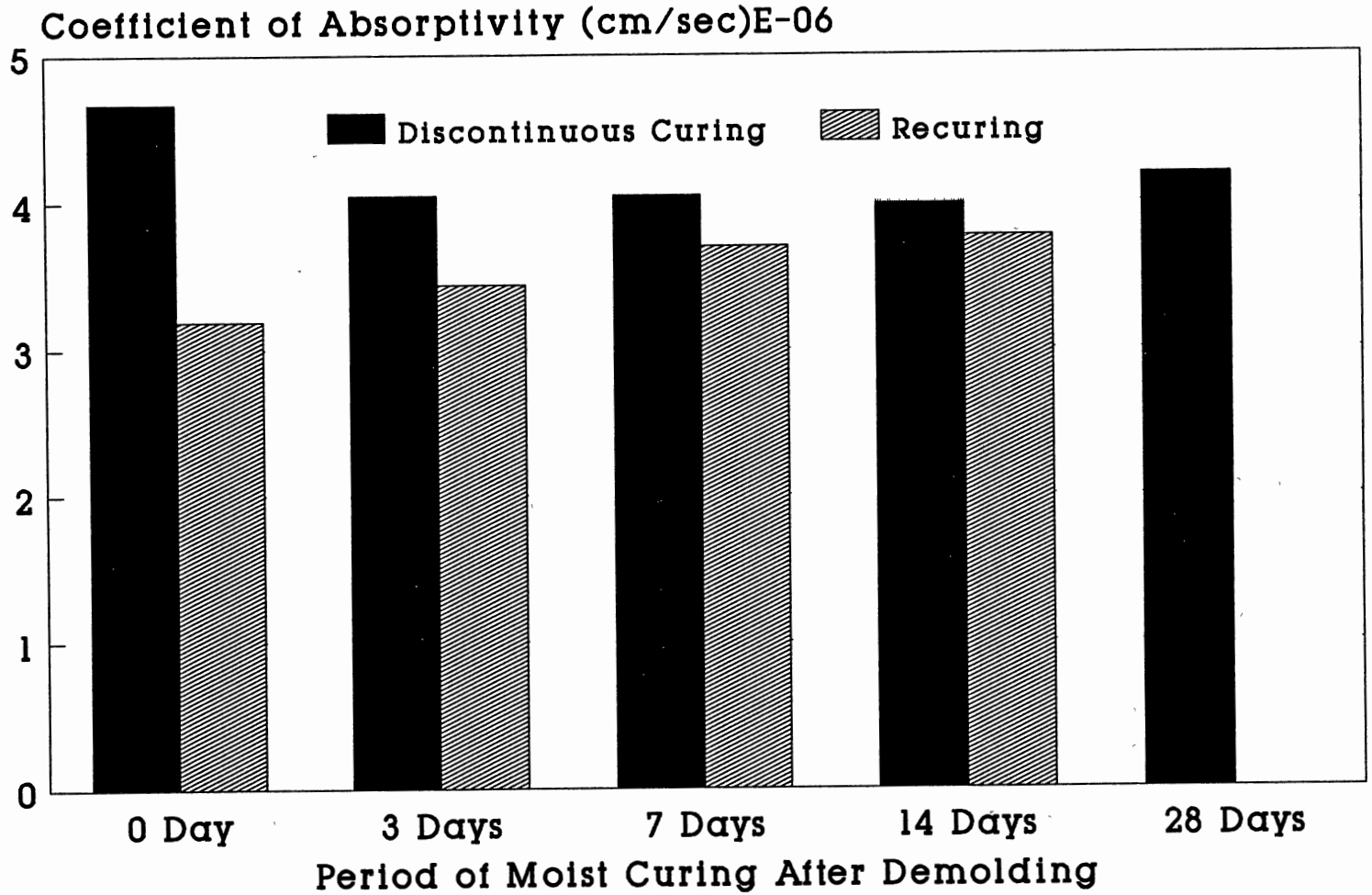

Figure 16. Coefficient of Absorptivity of Plain Cement Mortar Specimens, of W/C Ratio 0.49, Subjected to Recuring and Discontinuous Curing

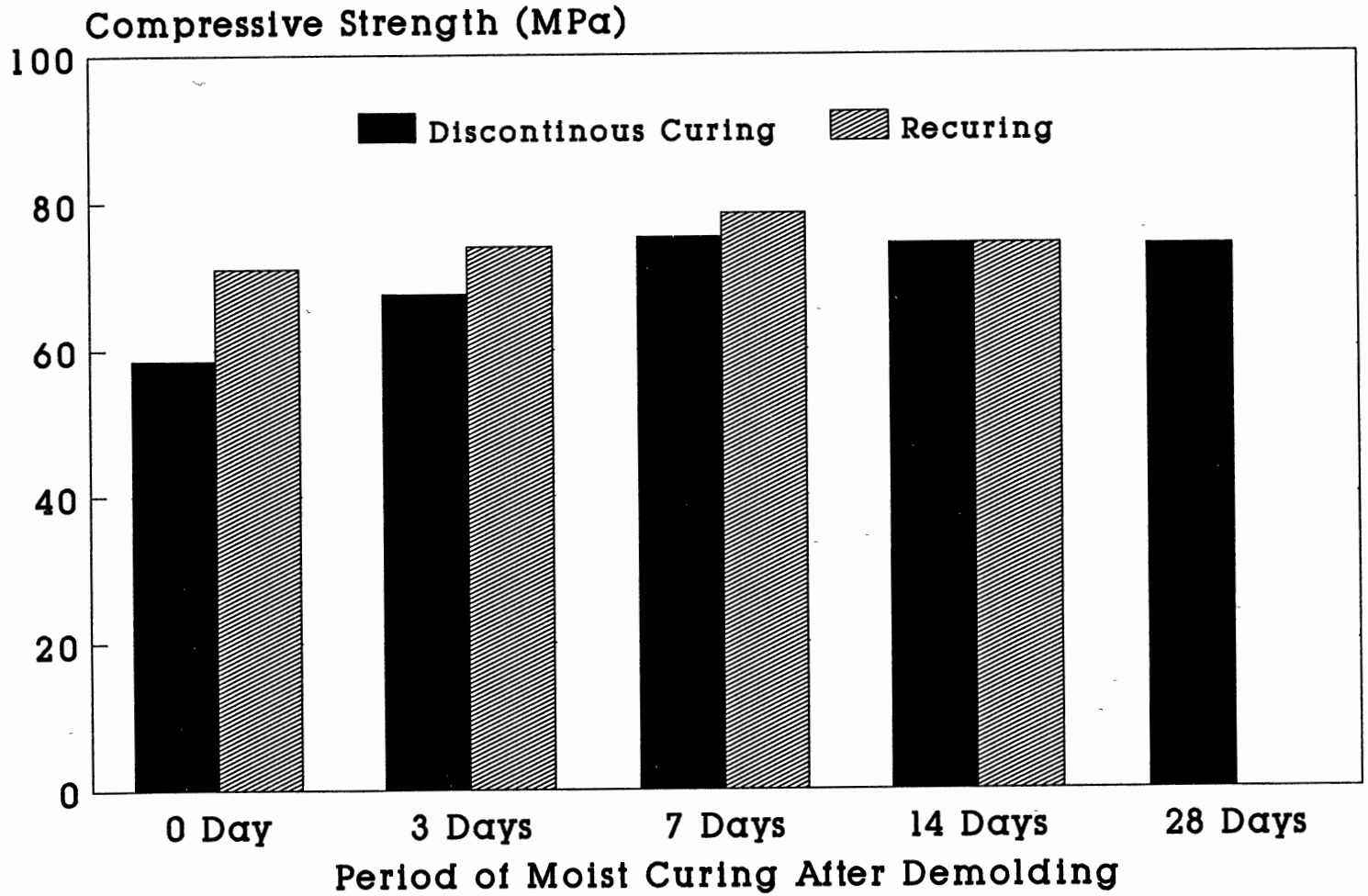

Figure 17. Compressive Strength of Silica Fume Mortar Specimens, of W/C Ratio 0.44, Subjected to Recuring and Discontinuous Curing

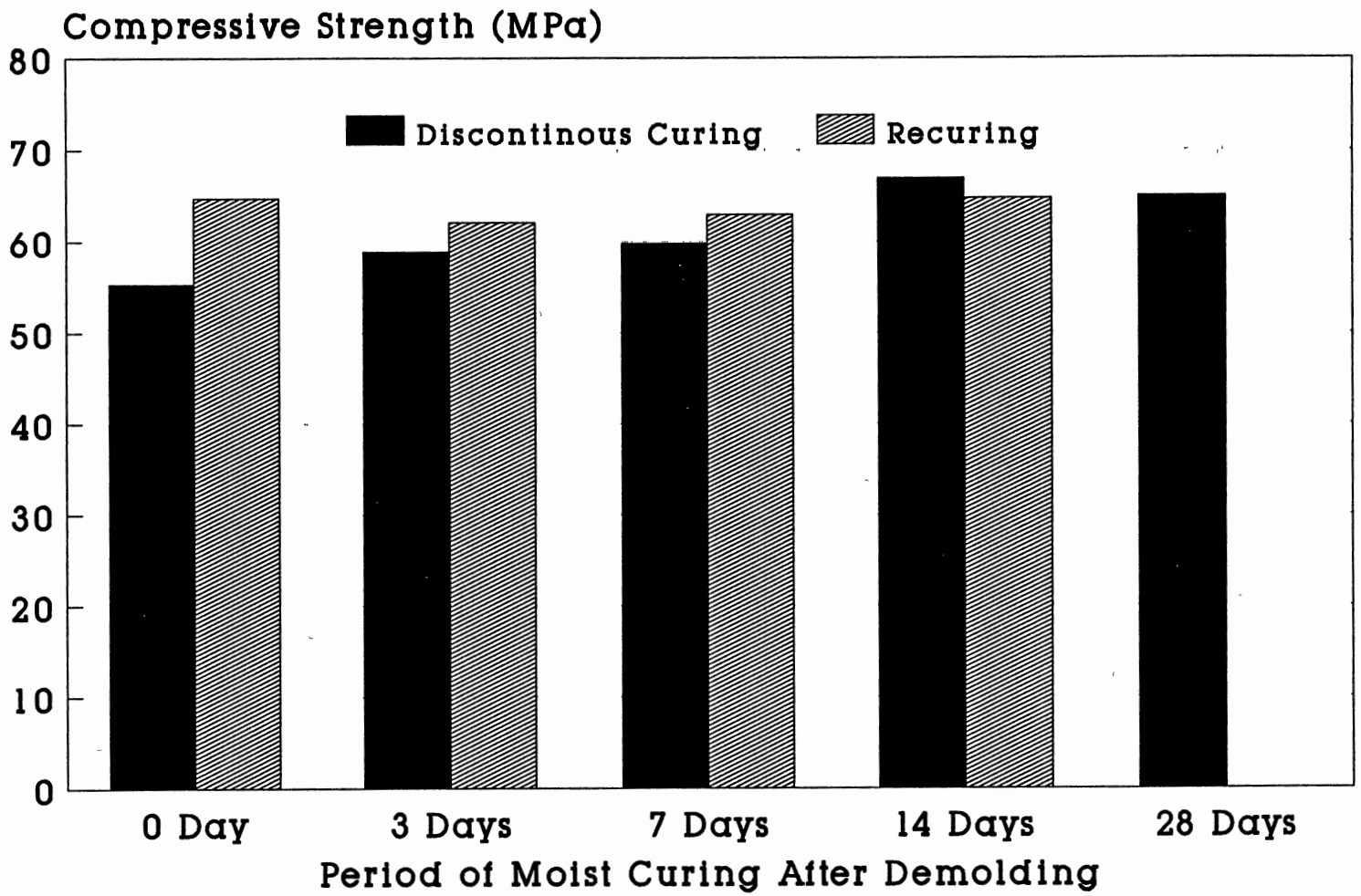

Figure 18. Compressive Strength of Silica Fume Mortar Specimens, of W/C Ratio 0.49, Subjected to Recuring and Discontinuous Curing

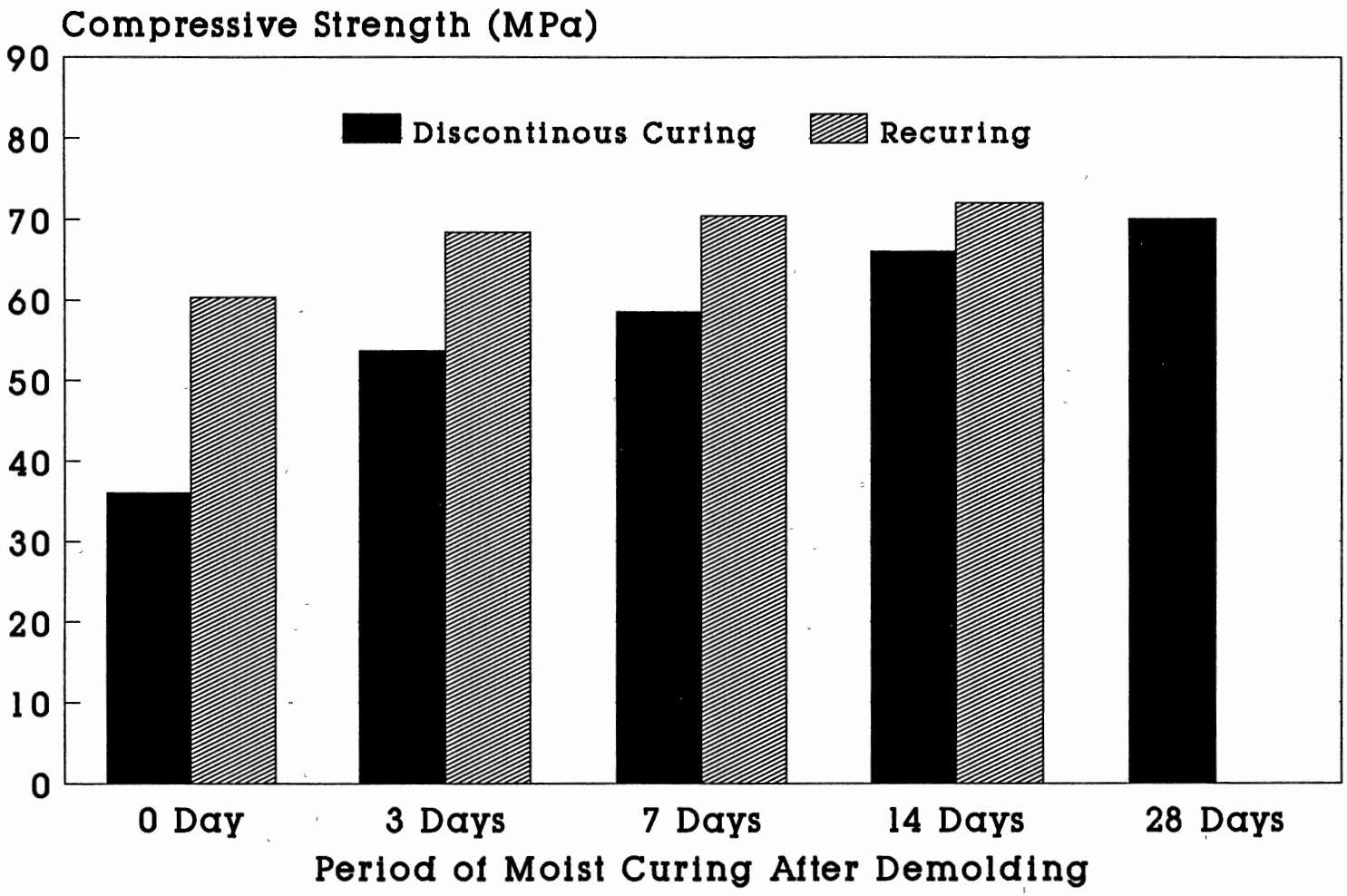

Figure 19. Compressive Strength of Fly Ash Mortar Specimens, of W/C Ratio 0.44, Subjected to Recuring and Discontinuous Curing

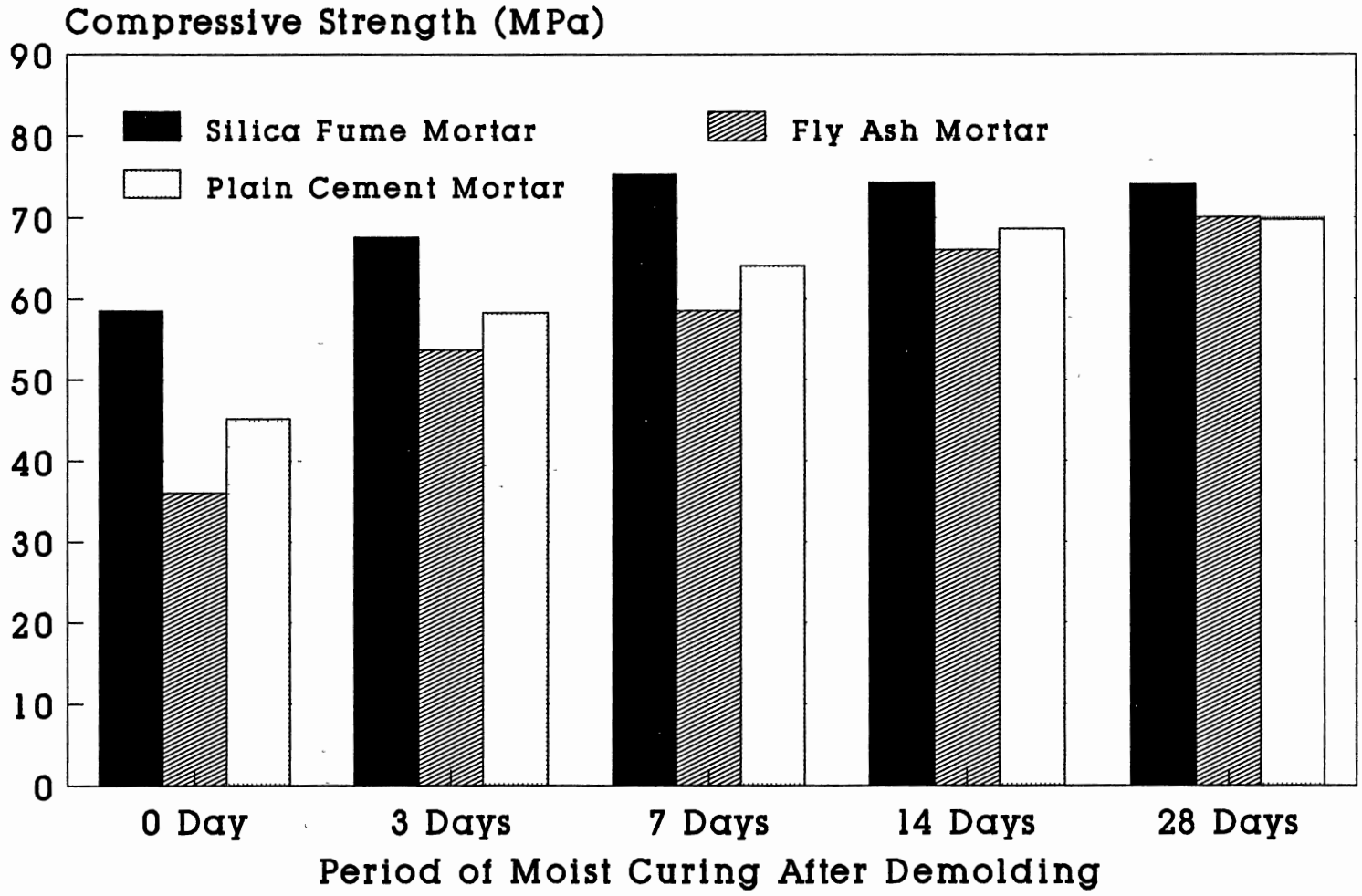

Figure 20. Compressive Strength of Silica Fume, Fly Ash, and Plain Cement Mortar Specimens, of W/C Ratio 0.44, for Different Periods of Moist Curing

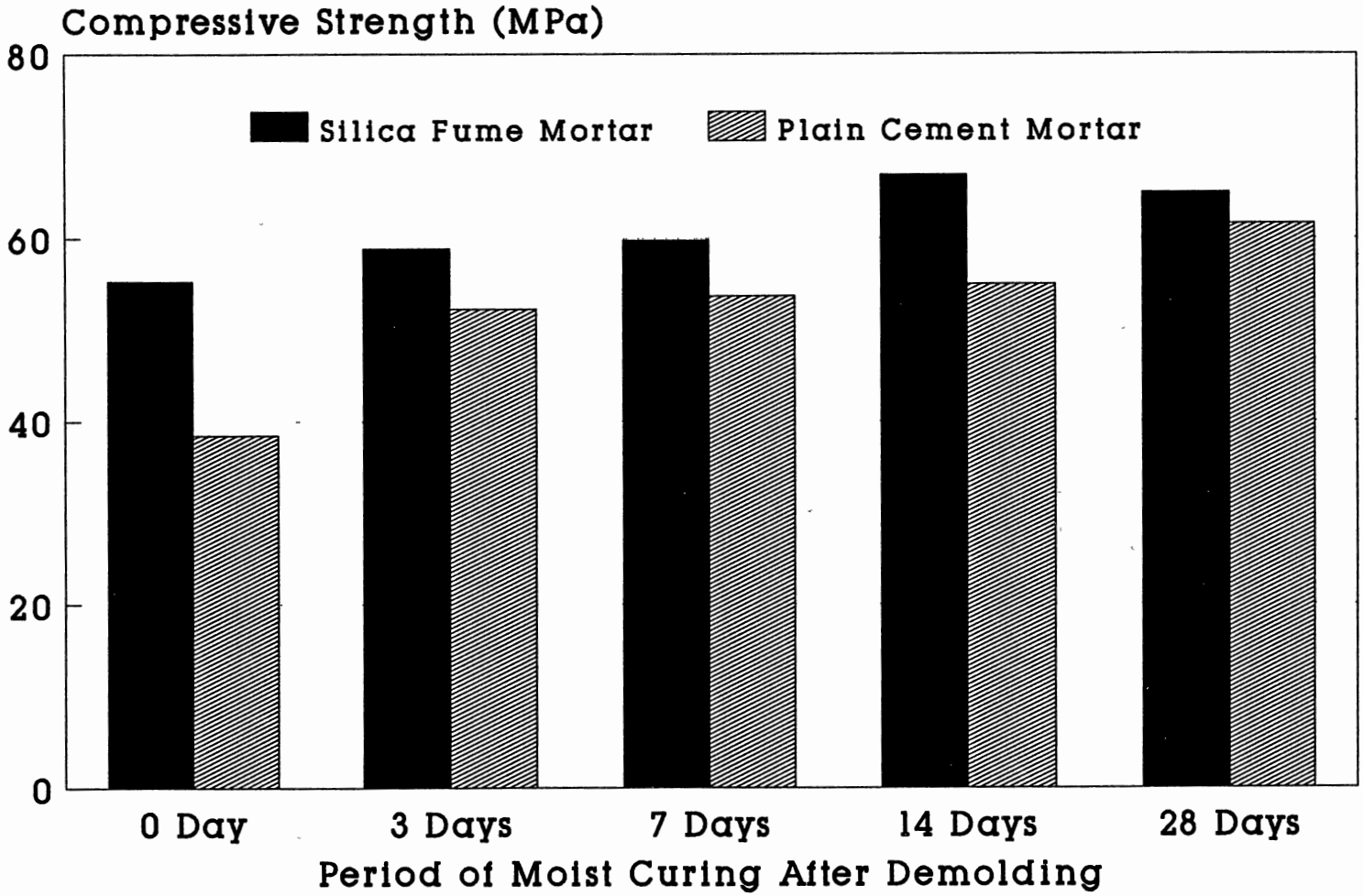

Figure 21. Compressive Strength of Silica Fume, and Plain Cement Mortar Specimens, of W/C Ratio 0.49, for Different Periods of Moist Curing

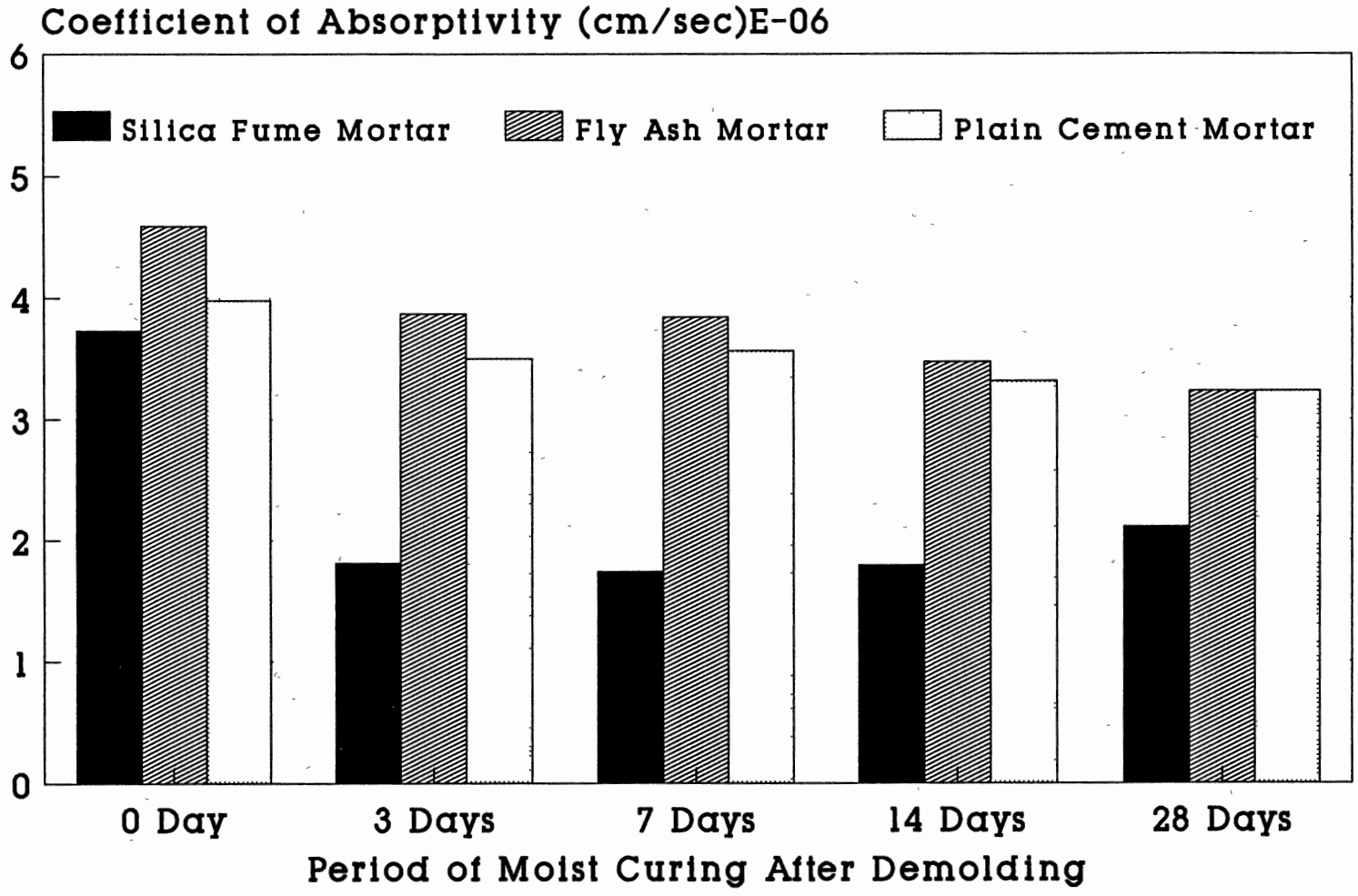

Figure 22. Coefficient of Absorptivity of Silica Fume, Fly Ash, and Plain Cement Mortar Specimens, of W/C Ratio 0.44, for Different Periods of Moist Curing

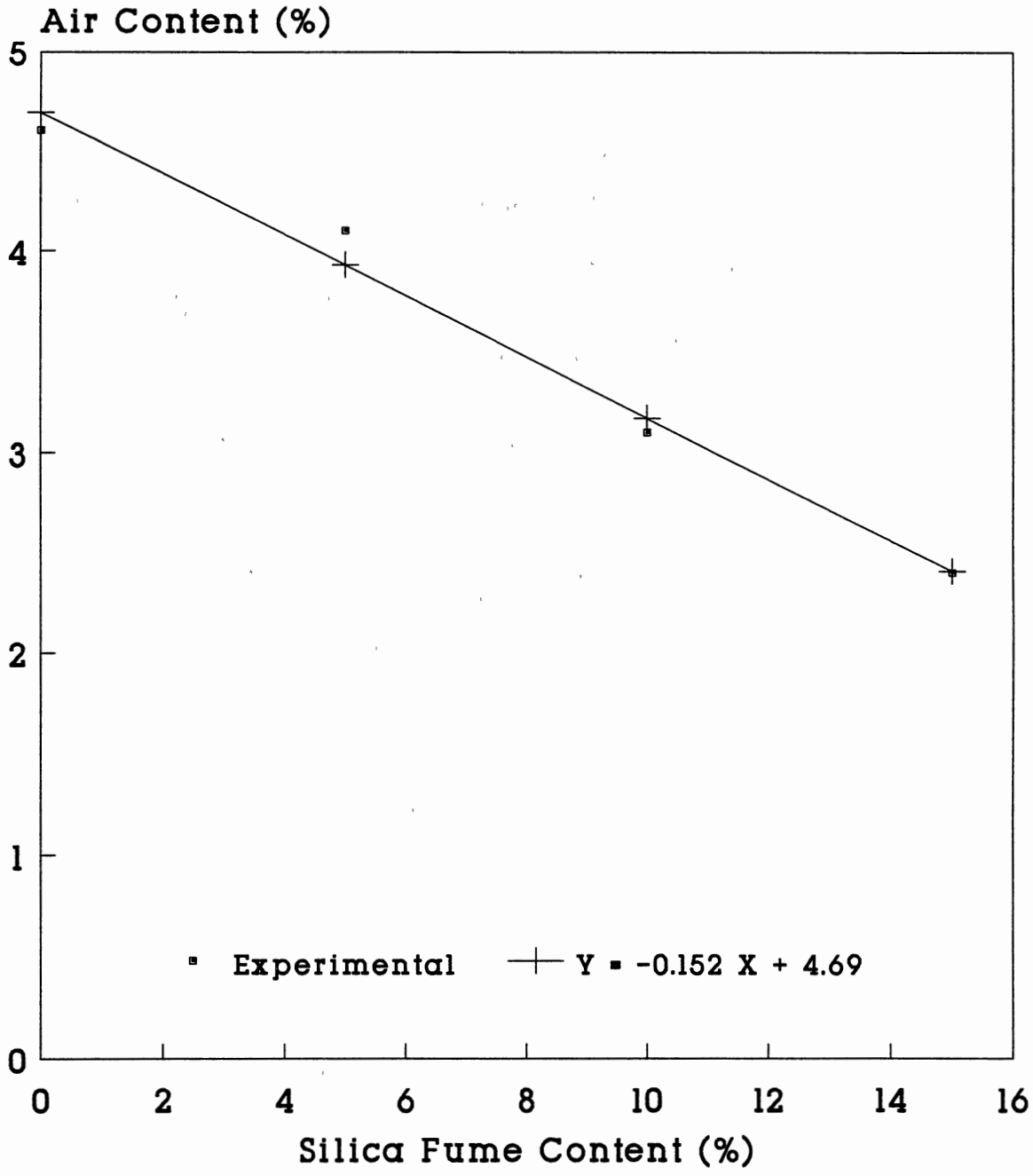

Figure 23. Relationship Between the Amount of Silica Fume and Air Content in Silica Fume Concrete Mixes

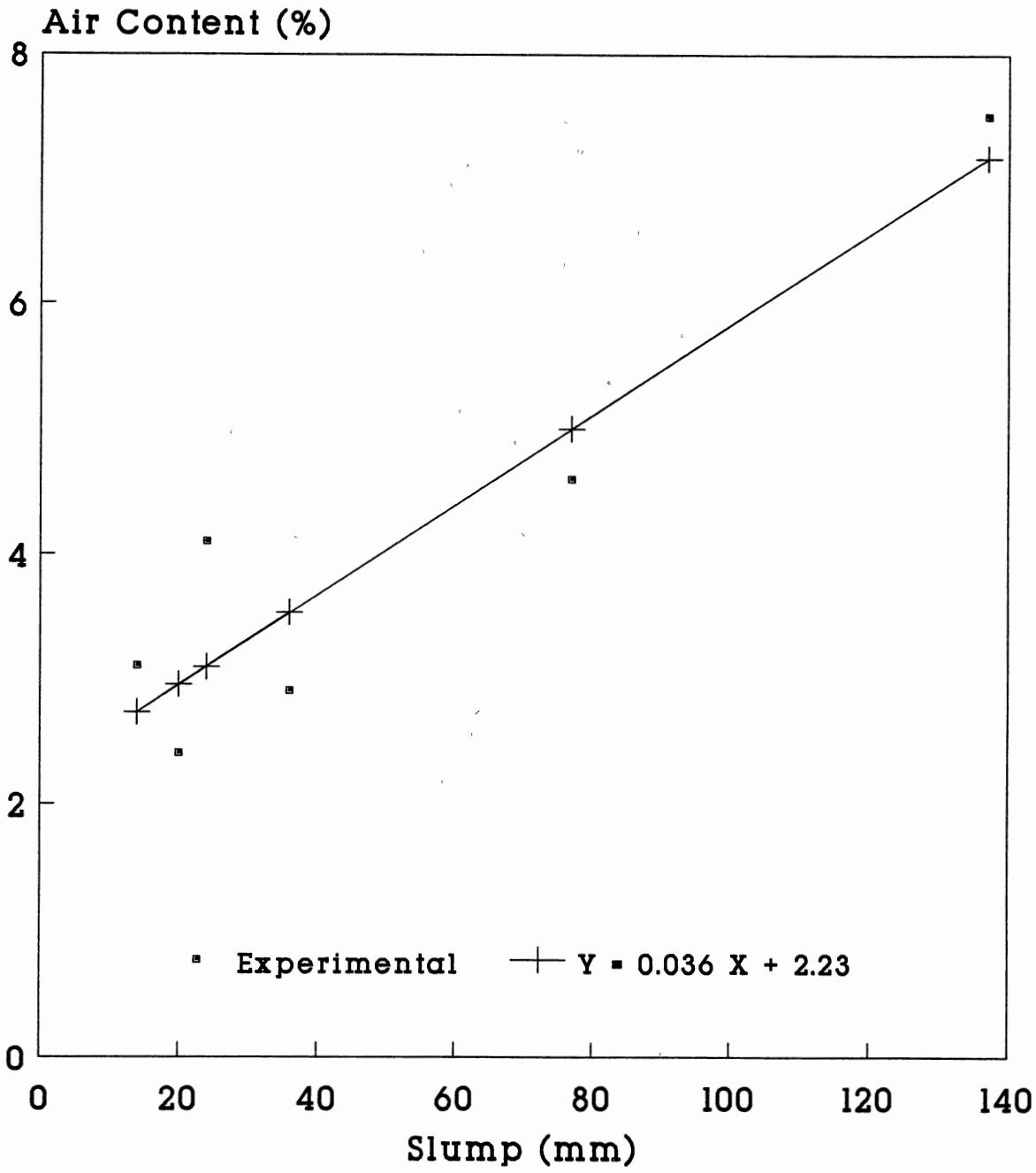

Figure 24. Relationship Between Slump and Air Content in Silica Fume Concrete Mixes

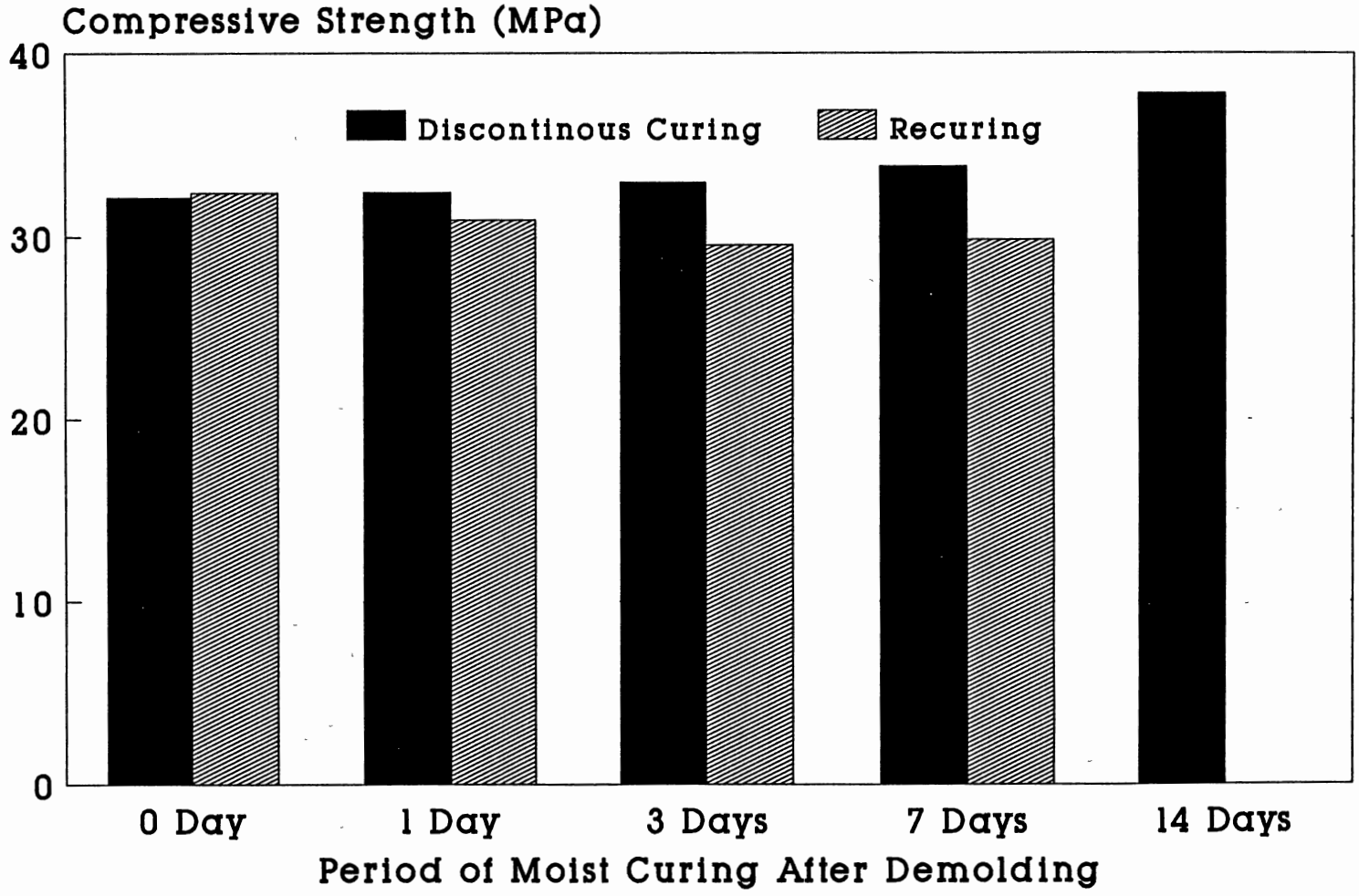

Figure 25. Compressive Strength of the Plain Cement Concrete Mix Subjected to Recuring and Discontinuous Curing

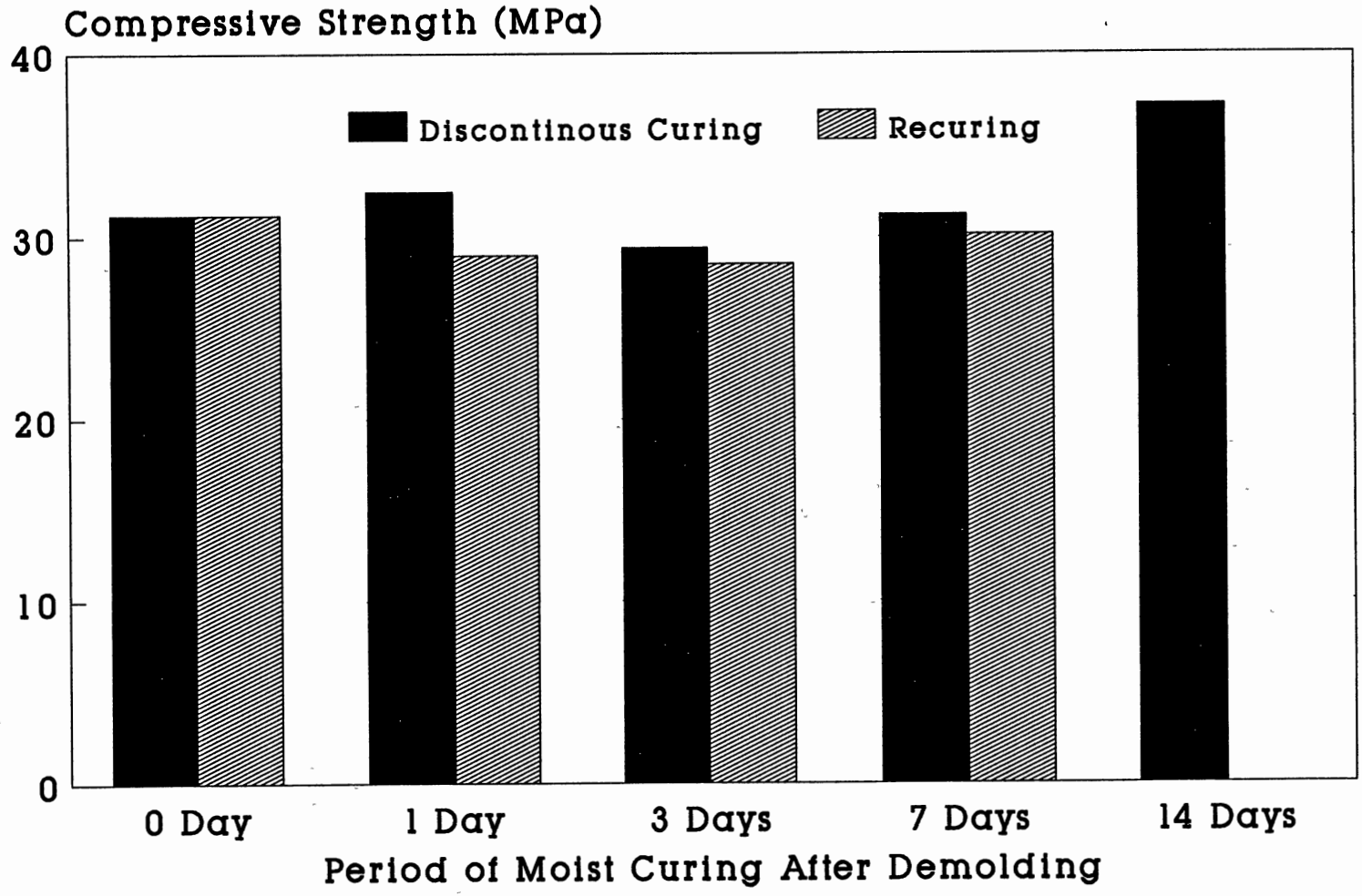

Figure 26. Compressive Strength of the 15% Fly Ash Concrete Mix Subjected to Recuring and Discontinuous Curing

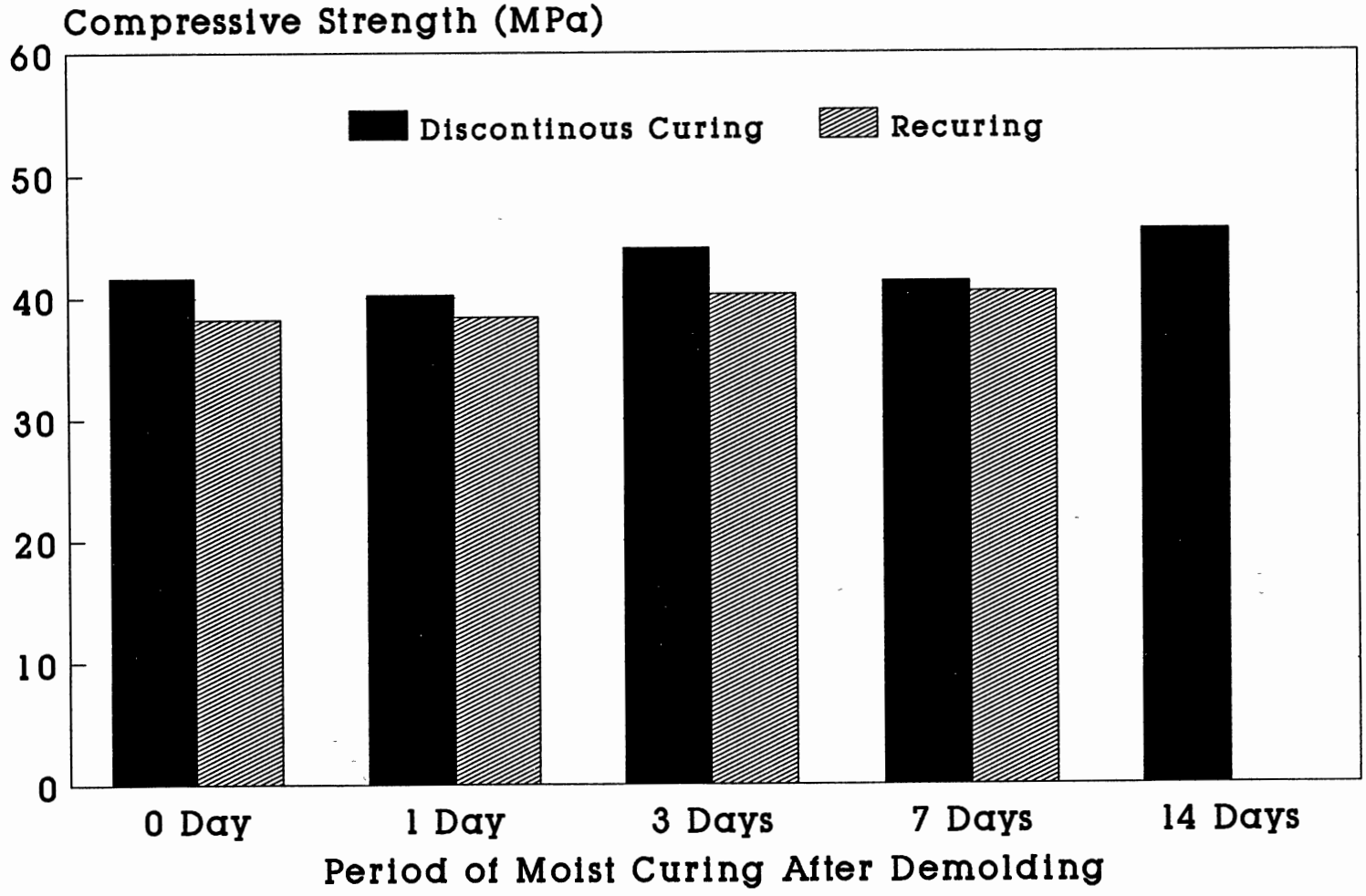

Figure 27. Compressive Strength of the 5% Silica Fume Concrete Mix Subjected to Recuring and Discontinuous Curing

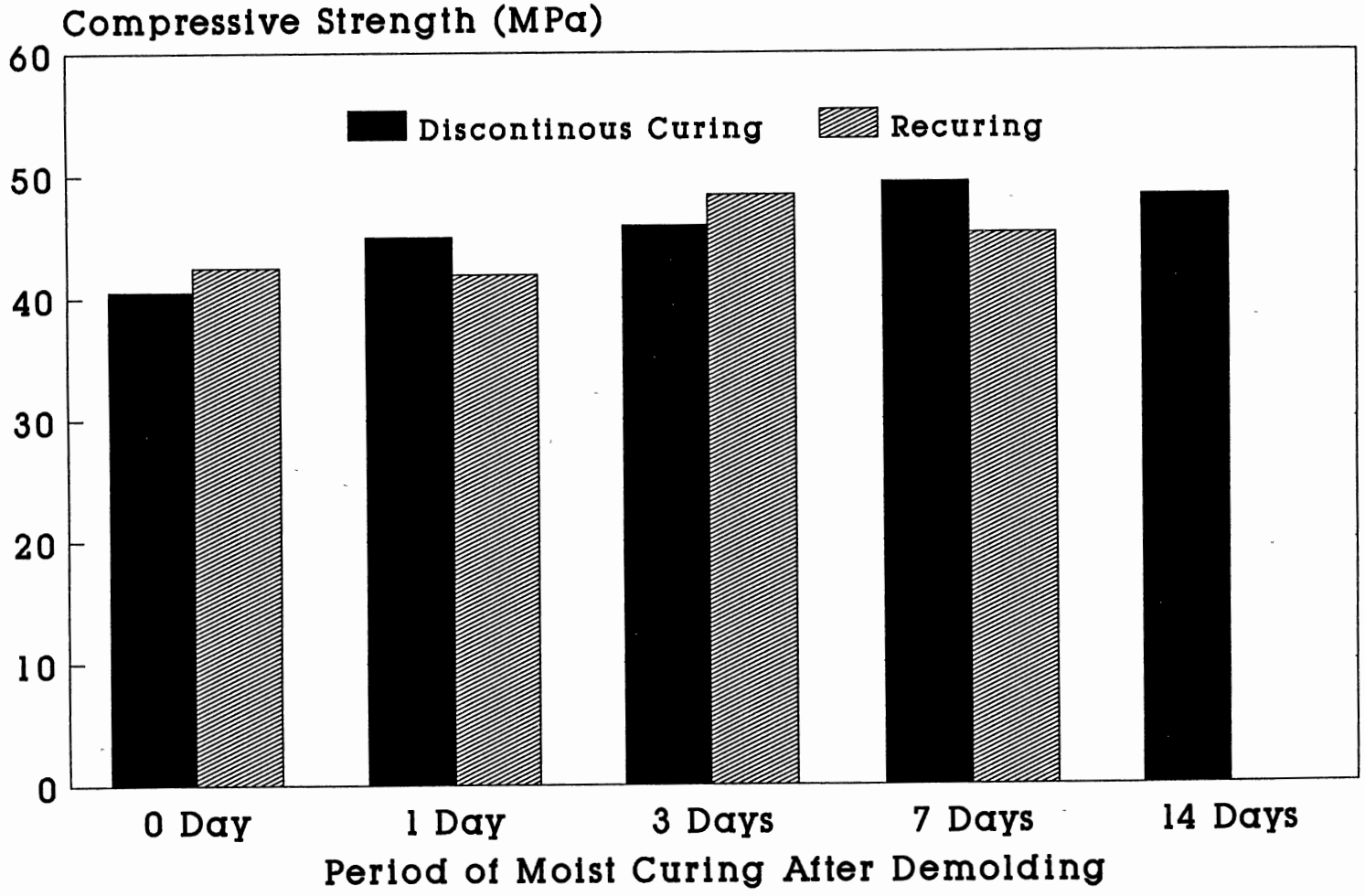

Figure 28. Compressive Strength of the 10% Silica Fume Concrete Mix Subjected to Recuring and Discontinuous Curing

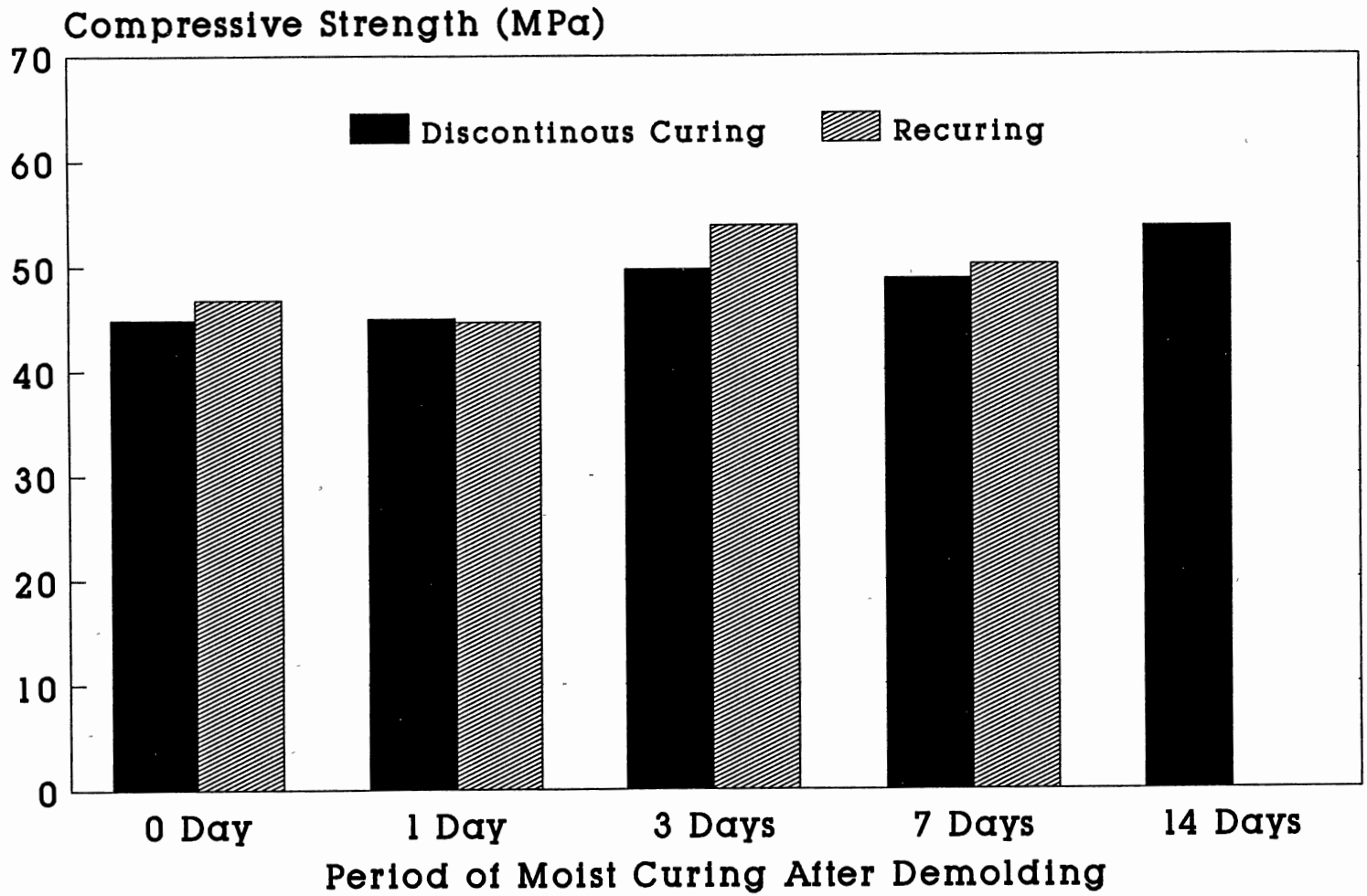

Figure 29. Compressive Strength of the 15% Silica Fume Concrete Mix Subjected to Recuring and Discontinuous Curing

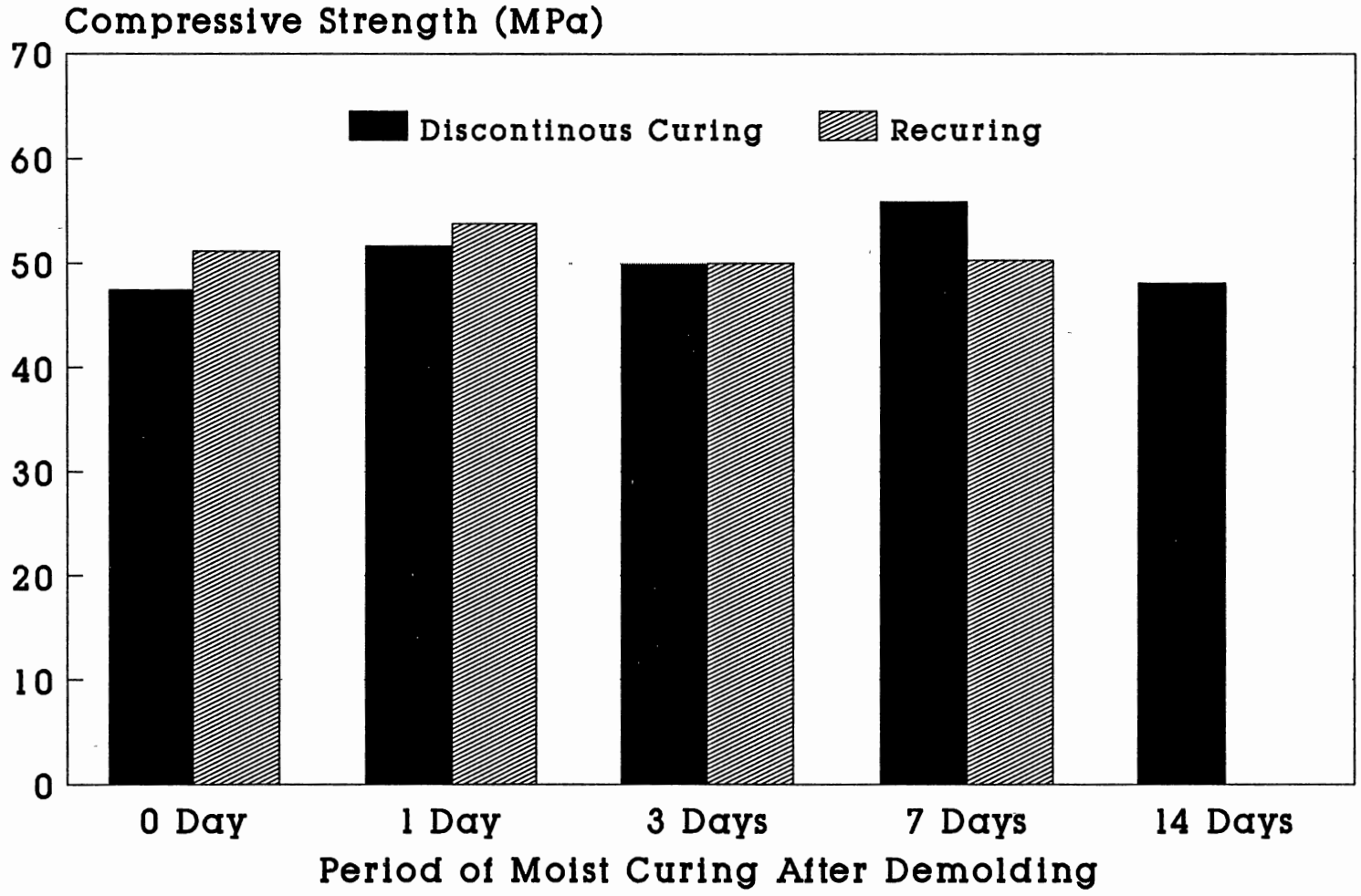

Figure 30. Compressive Strength of the 20% Silica Fume Concrete Mix Subjected to Recuring and Discontinuous Curing

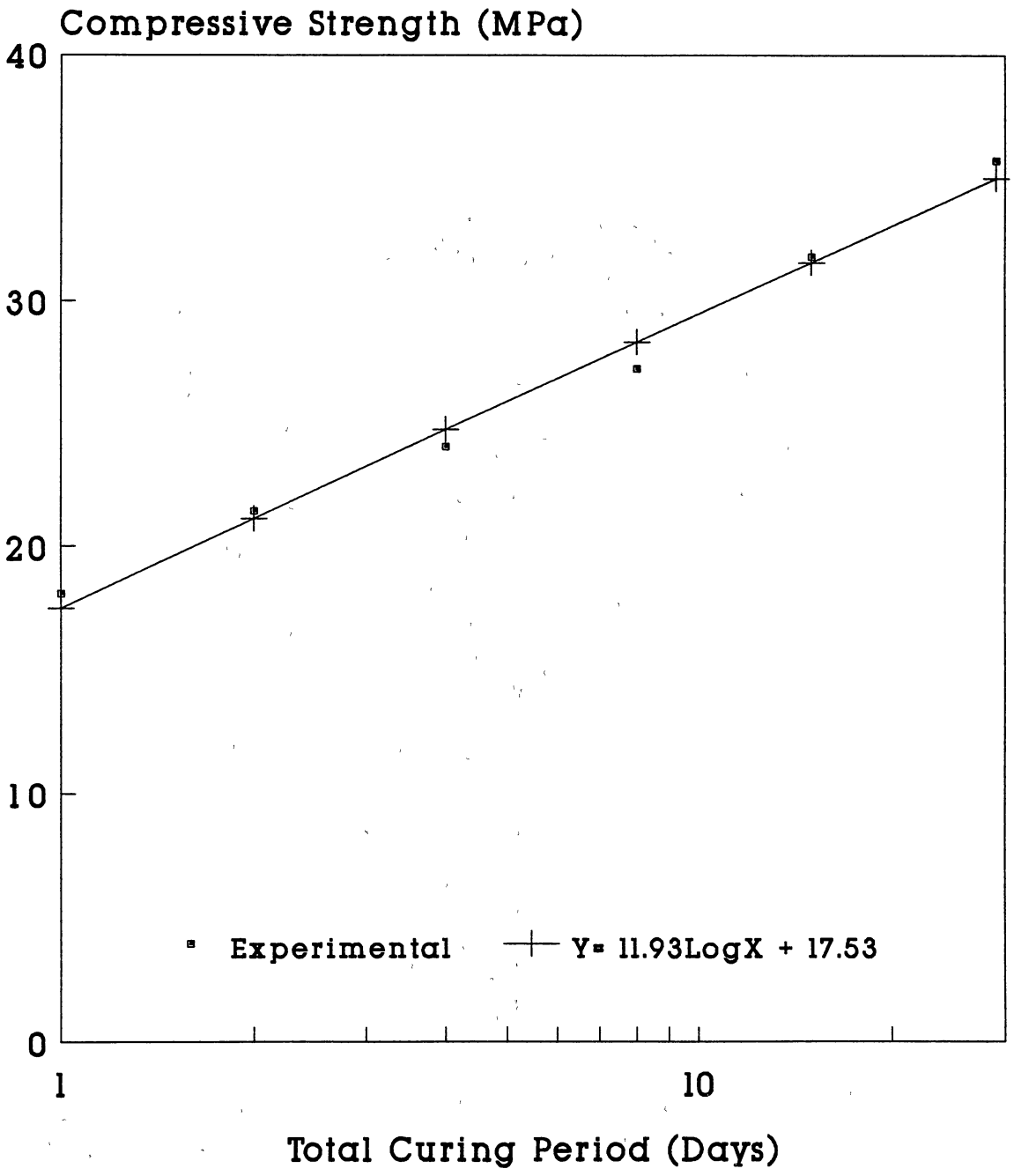

Figure 31. Rate of Compressive Strength Development in the Plain Cement Concrete Mix

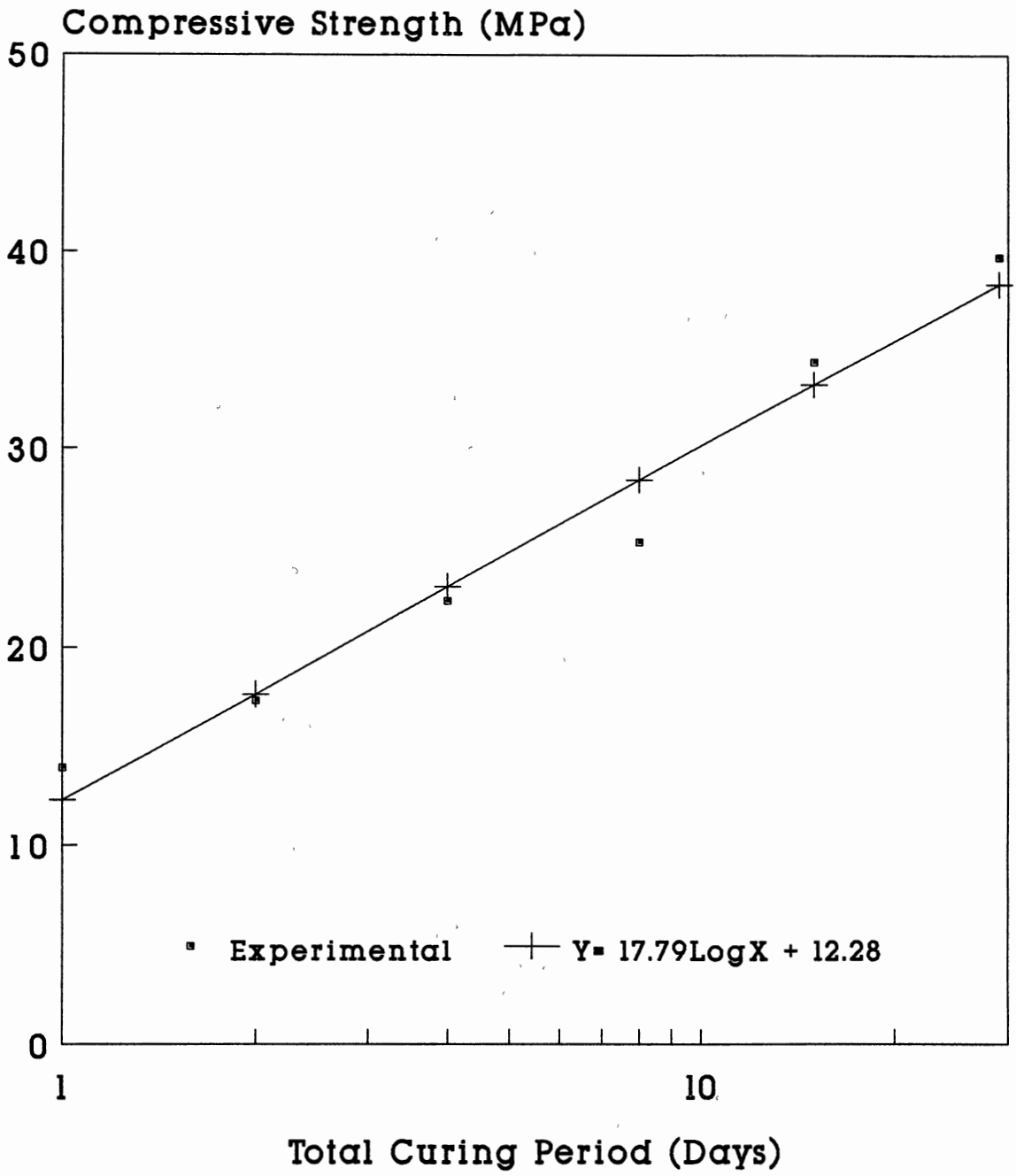

Figure 32. Rate of Compressive Strength Development in the 15% Fly Ash Concrete Mix

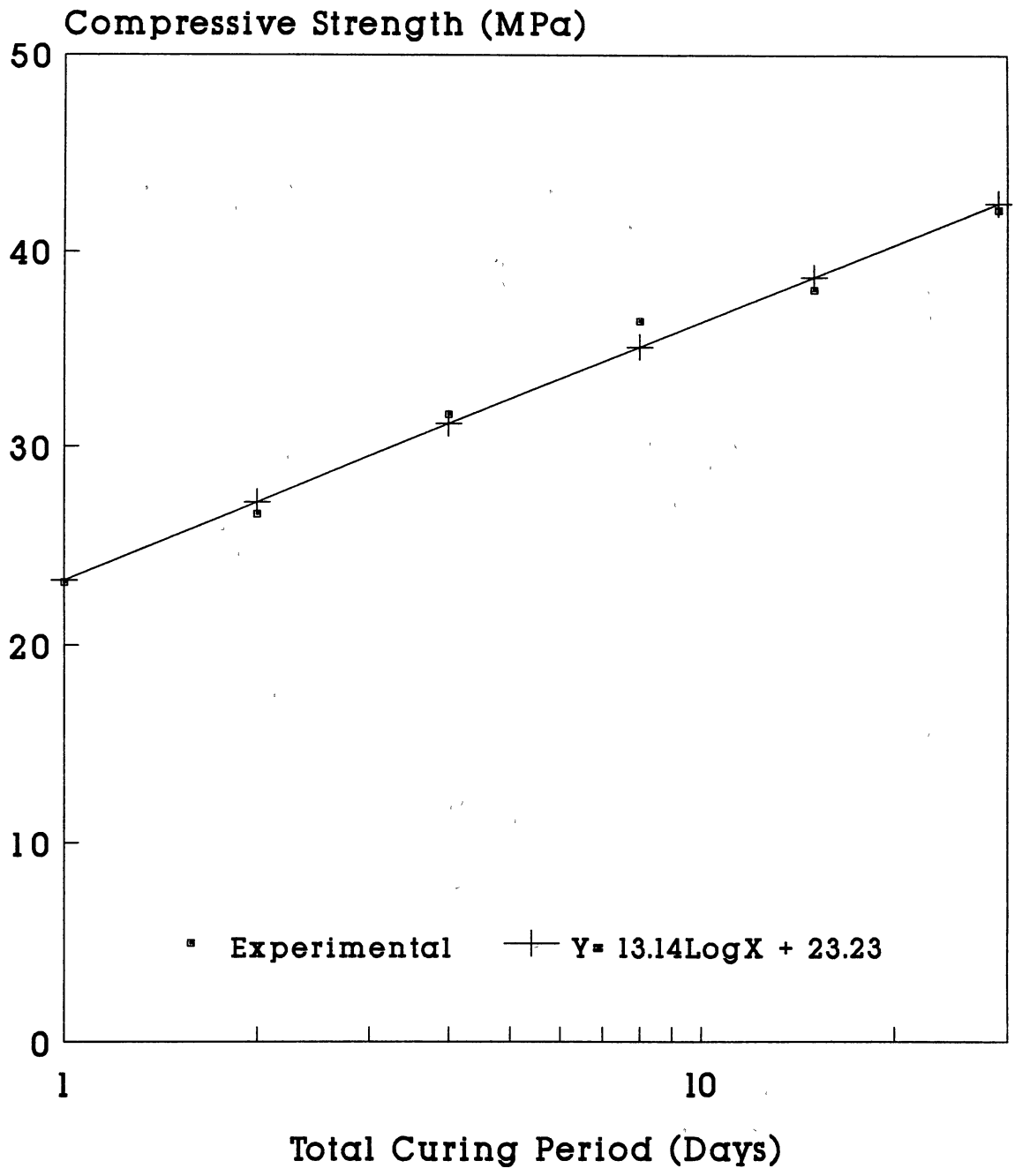

Figure 33. Rate of Compressive Strength Development in the 5% Silica Fume Concrete Mix

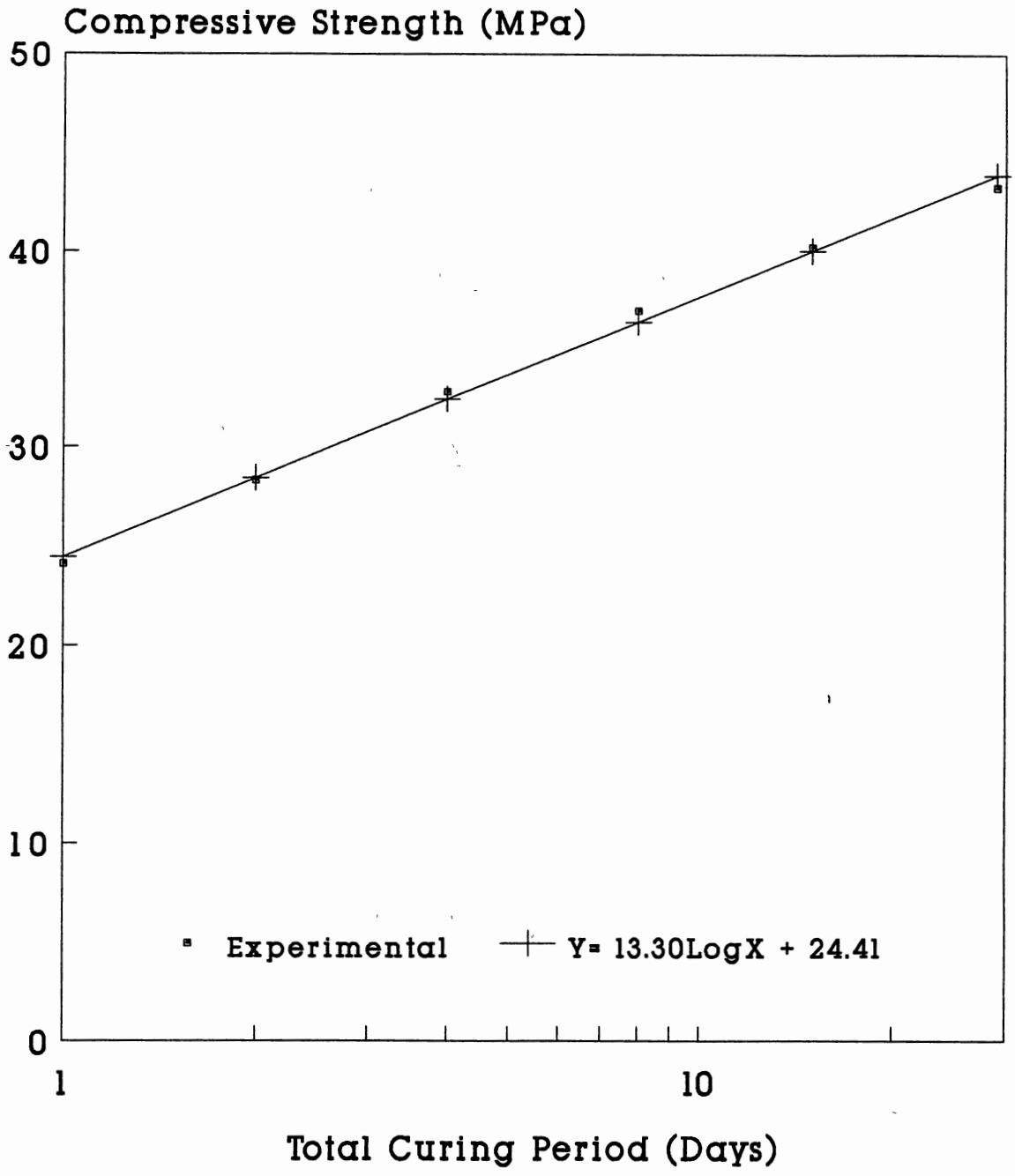

Figure 34. Rate of Compressive Strength Development in the 10% Silica Fume Concrete Mix

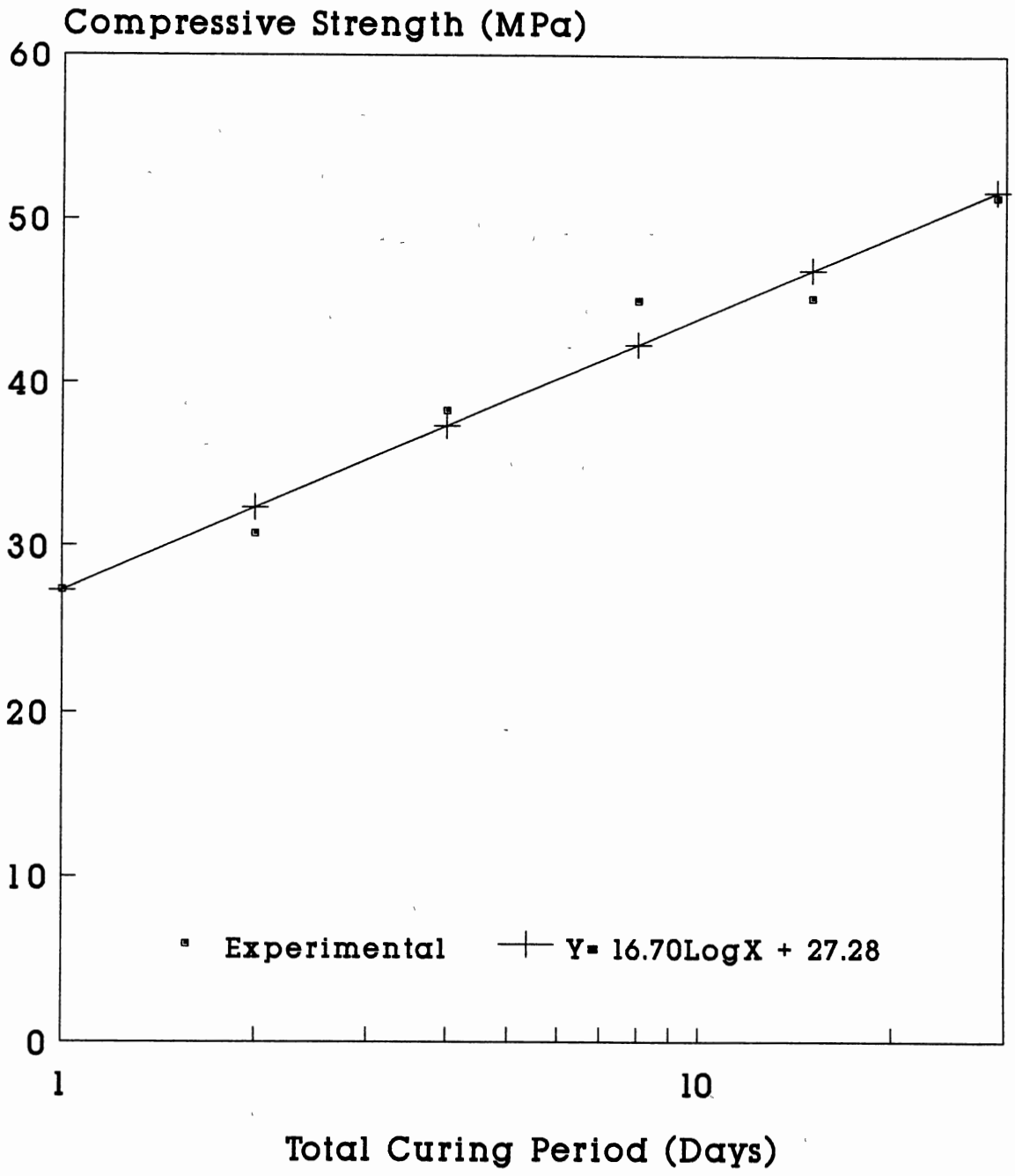

Figure 35. Rate of Compressive Strength Development in the 15% Silica Fume Concrete Mix

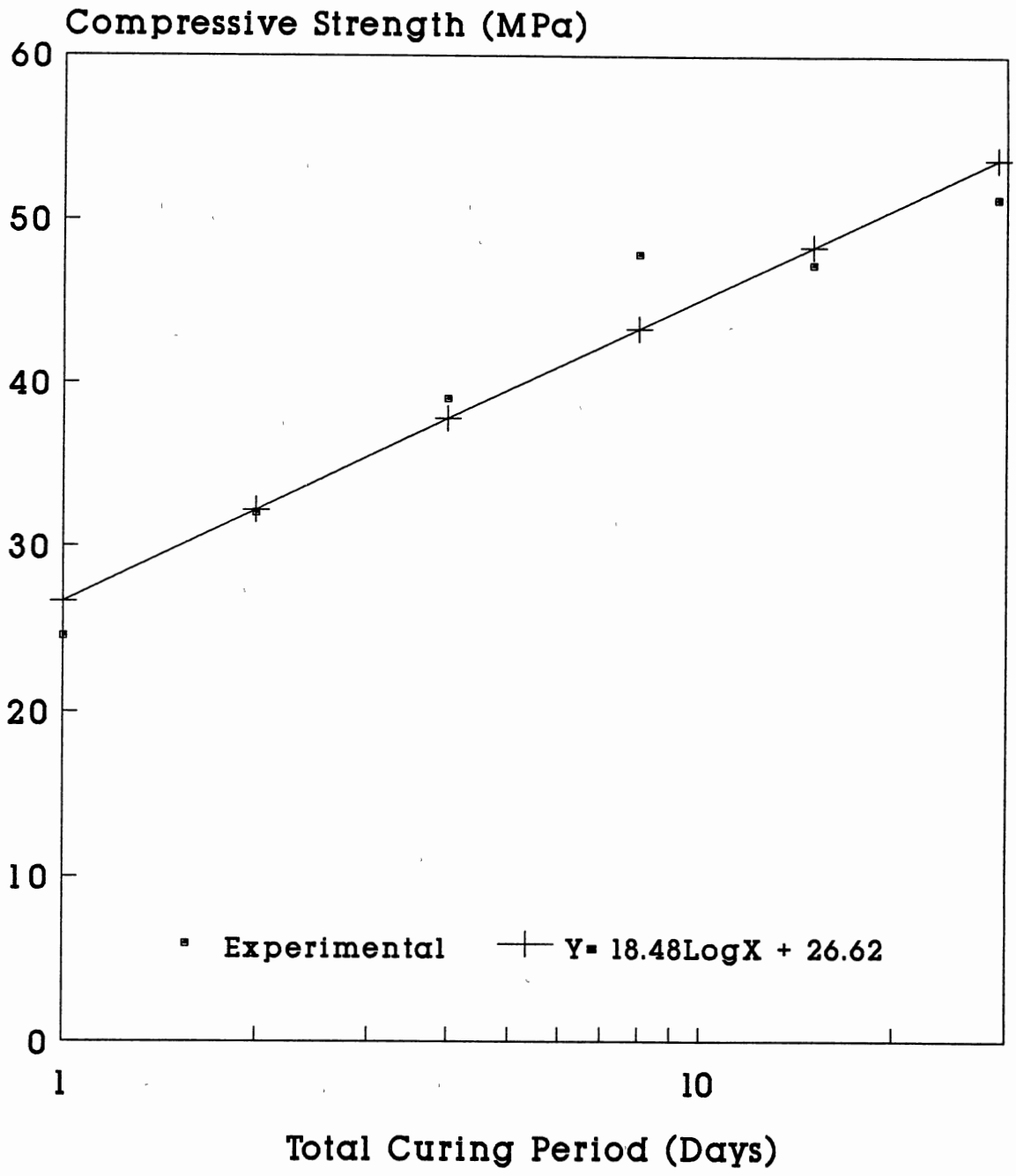

Figure 36. Rate of Compressive Strength Development in the 20% Silica Fume Concrete Mix

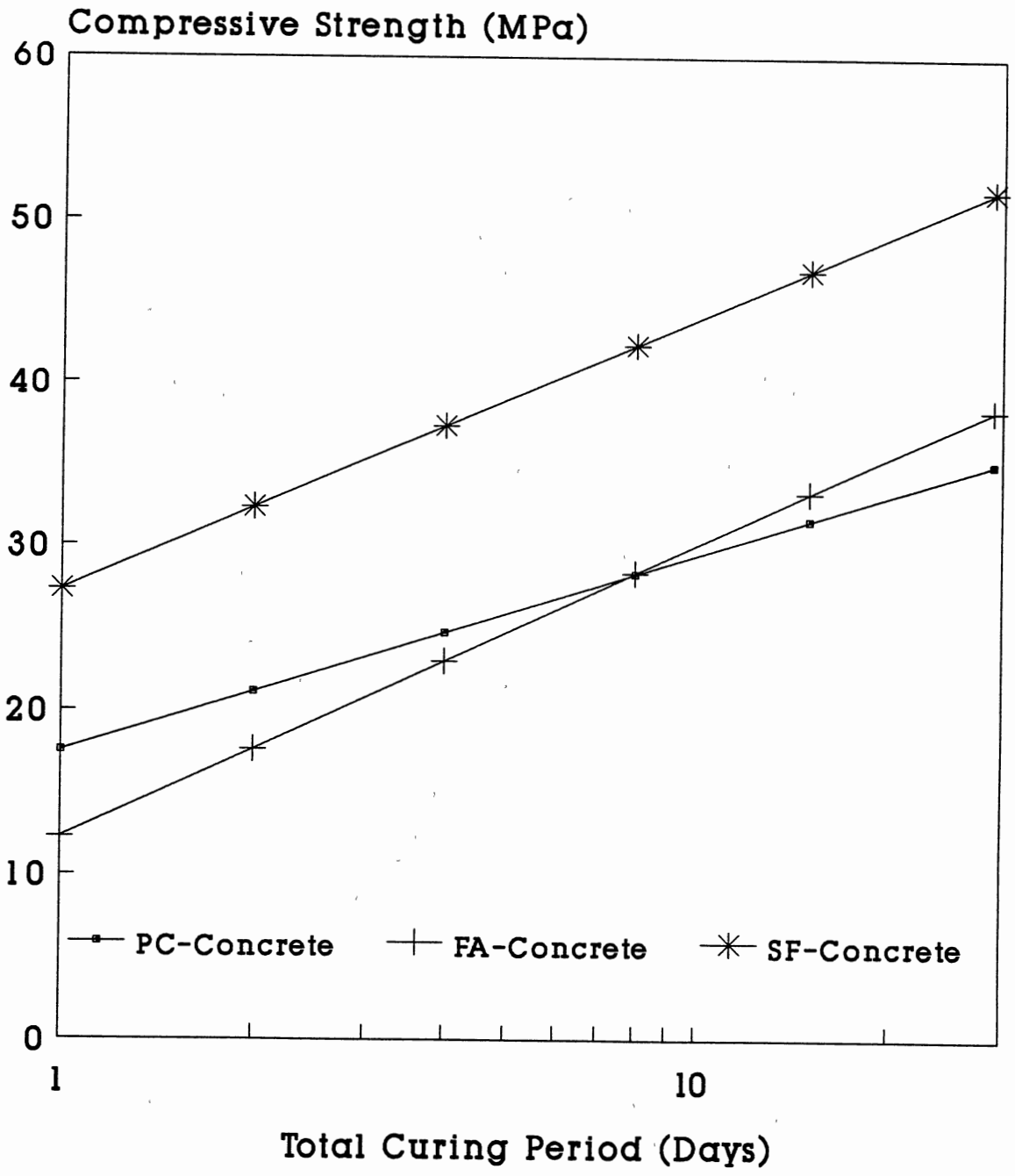

Figure 37. A Comparison of Compressive Strength Development in Plain Cement Concrete, Fly Ash Concrete (15%), and Silica Fume Concrete (15%)

2

VITA

Mohammad Shamim Khan

Candidate for the Degree of

Doctor of Philosophy

Thesis: INTERRUPTED CURING, RECURING, AND THE DURATION OF CURING OF PLAIN AND POZZOLANIC CONCRETES

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Gorakhpur, U.P., India, February 1, 1957, the son of Mohammad I. and Nagina Khan.

Education: Graduated (High School) from Dayanand Intermediate college, Gorakhpur, U.P., India in June 1973; received Bachelor of Science Degree in Civil Engineering from Aligarh Muslim University, Aligarh, U.P., India in October 1980; received Master of Science Degree in Civil Engineering from University of Petroleum and Minerals, Dhahran, Saudi Arabia in August 1985; completed requirements for the Doctor of Philosophy Degree at Oklahoma State University in December 1992.

Professional Experience: Research-Teaching Associate, School of Civil Engineering, Oklahoma State University, January 1991 to December 1992; Research Engineer, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, October 1985 to December 1990 (from October 1985 to August 1990 as Engineer-II, from September 1990 to December 1990 as Engineer-I); Research Assistant, Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, June 1983 to October 1985; Assistant Engineer, U.P. State Bridge Corporation Ltd., India, June 1982 to June 1983; Associate Lecturer, Aligarh Muslim University, Aligarh, U.P., India, December 1982 to May 1982.

Professional Affiliations: Member of American Concrete Institute (ACI); Member of American Society of Civil Engineers (ASCE); Member of National Association of Corrosion Engineers (NACE); Consulting Member of ACI Committee on Polymers in Concrete; Associate Member of ACI Committee on Corrosion of Metals in Concrete.

Honors and Awards: Member of National Honor Society, Phi Kappa Phi; Member of National Engineering Honor Society, Tau Beta Pi; Member of National Civil Engineering Honor Society, Chi Epsilon; recipient of National Association of Corrosion Engineers' student fellowship for two consecutive years: 1991 and 1992; recipient of Oklahoma State University's 1992 Graduate Research Excellence award.

Other Scholarly Activities: Author or co-author of more than 15 technical papers in major refereed international journals.