Concrete mix design for hot weather

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Abstract

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Concrete Mix Design for Hot Weather

by

Husain Jubran Al-Gahtani

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

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This thesis, written by Husain Jubran Al-Gahtani under the direction of his Thesis Committee, and approved by all its members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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Date Dec 17, 1985

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Member

بسم الله الرحمن الرحيم

فَمَآ أُوتِيتُم مِّن شَيۡءٖ فَمَتَٰعُ ٱلۡحَيَوٰةِ ٱلدُّنۡيَاۖ وَمَا عِندَ ٱللَّهِ
خَيۡرٞ وَأَبۡقَىٰ لِلَّذِينَ ءَامَنُواْ وَعَلَىٰ رَبِّهِمۡ يَتَوَكَّلُونَ

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TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table		Page

LIST OF FIGURES

Figure		Page

" مـــوجـــــــــز "

تعتمد عملية تصميم الخلطة الخرسانية على عوامل ومتغيرات عديدة منها خواص المواد المستخدمه وطرق تحضير الخرسانة ووضعها وتثبيتها ثم معالجتها بالاضافة الى تقديـــر الكميات النسبيه لمكوناتها . وعادة مايكون تقدير تلك الكميات بواسطة تعيين كل من نسبة الماء للاسمنت والركام الكلى للاسمنت والرمل للركام الكلى . وتصبح عملية التصميم أكثر صعوبة فــى الحصول على تصميم أمثل فى جو حــــار .

ولأجل الحصول على طريقة مناسبة لتصميم الخرسانة بحيث تكون مناسبة لظروف المنــاخ الحار فقد تمت دراسة تأثير كل من المتغيرات الآتيـــة :-

١) نسبة الماء للاسمنت ،
٢) نسبة الركام الكلى للاسمنت .
٣) نسبة الرمل للركام الكلى .
٤) درجة حرارة الخلطة عند وضعها بالاضافة الى ظروف معالجتها فى الجو الحار .

ولاختبار تأثير كل من تلك المتغيرات على كل من مقاومة الضغط للخرسانة وقابلية تشكيلها - فقد اتبعت طريقة تصميم المتغير التجريبى .

وقد استخدمت النتائج التجريبية لتطوير معادلات لحساب مقاومة الضغط وقابلية التشكيل بواسطة التحليل التراجعى . وقد تم استخدام تلك المعادلات بواسطة برنامج للحاسب الآلـــى فى عمل جداول لغرض استخدامها فى عملية تصميم الخرسانة .

ABSTRACT

The design of a concrete mix is a complex procedure. It depends on many factors such as properties of materials ,method of preparation , compaction , placement and curing of concrete , as well as the requirements of a construction job such as workability and durability. Once these factors are specified, the remaining task involves proportioning of the quantities of materials. This is usually carried out in terms of determining the water-cement ratio, aggregate-cement ratio or cement content, and sand to total aggregate ratio for particular gradations of aggregates and maximum size of coarse aggregate. This procedure becomes more difficult to achieve for an optimum mix design in hot weather conditions.

In order to develop a suitable method for concrete mix design in hot weather, the effects of the following factors were considered : (i) water-cement ratio, (ii) total aggregate to cement ratio, (iii) sand to total aggregate ratio and (iv) concrete mix temperature at placement in conjunction with field conditions for curing in hot weather.

To examine the effects of the above factors on compressive strength and workability of concrete, the method of factorial experimental design was adopted which enables the evaluation of the combined effects of various factors

and their interactions. The data for workability, in terms of slump, and the compressive strength was subjected to regression analysis to develop equations for predicting compressive strength and workability. The equations were used through a computer program to generate tables for use in concrete mix design.

CHAPTER 1 : PROBLEMS OF HOT WEATHER CONCRETING

1.1 INTRODUCTION

1.1.1 Concrete Performance in the Local Environmental Conditions

Every year a large number of concrete construction projects are executed in hot weather conditions in many countries around the world. The rapid development of the infrastructure facilities in the Gulf region has resulted in huge concrete construction program executed in the last decade. Within the Kingdom of Saudi Arabia these constructions have mostly been carried out in the central and coastal parts which are characterized by hot climatic conditions. It has been observed through a growing number of case histories that within a short span of time various defects ranging from unsightly blemishes to serious failures have occurred in many types of concrete construction works in the Gulf region. Studies(1) have shown that the problem of concrete durability in hot climate countries, such as prevailing in Saudi Arabia and other Gulf and Middle East countries, is due to three main reasons :

(i) aggressive effects of a hot climate.

(ii) low quality of construction materials.

(iii) unskilled labor, lack of proper supervision and inadequate specification and design/construction

practices which do not commensurate with local conditions.

A typical profile of the concrete deterioration problem in the hot weather conditions of the Gulf region is given in a study carried out at UPM(2). For this study, condition surveys accompanied by comprehensive recordings and photographic documentation were carried out on 42 concrete structures located in Al-Khobar, Dhahran and Dammam habitations. The results of investigation indicate an alarming condition of structures constructed 15-20 years ago.

1.1.2 Hot Weather and Its Effects

Hot weather is defined in the ACI Manual(3) as "any combination of high air temperature, low relative humidity, and wind velocity". Most parts of Saudi Arabia are included in the typical environment classified as hot weather. In these regions summer temperatures are frequently in excess of 40 °C. Humidity is at very low values in the central parts and varies from very low to high in the coastal flats within a short span of time. The contrast between night and the maximum day temperatures and humidities is large. The data on relative humidity, maximum, average and minimum temperatures based on 15 years average is presented in

Figures 1.1, 1.2 and 1.3 for Riyadh, Dhahran and Jeddah areas respectively(4) to provide an indication of the ambient hot weather conditions. Direct solar radiation on hardened concrete surfaces may raise the temperature to as high as 70 °C on a typical summer day in these regions.

Hot weather creates many problems in preparation, placing, compaction and curing of concrete. The possible adverse effects of hot weather conditions on concrete quality could be summarized as follows :

(i) Rapid evaporation of mixing water resulting in rapid slump loss of concrete.

(ii) Reduced concrete strength due to :

(a) an increase in the quantity of mixing water as a result of enhanced water demand.

(b) insufficient curing at high temperature.

(c) non-uniform precipitation of the products of hydration between cement grains due to comparatively rapid hydration.

(d) micro-cracking as a result of strain incompatibility due to different expansions of concrete constituents.

(iii) Reduction in setting time of cement which creates difficulty in handling and finishing the concrete.

(iv) Thermal cracking and increased plastic shrinkage cracking.

(v) Reduced durability due to an increase in the mixing water and cracking.

(vi) Formation of cold joints.

(vii) Increased difficulty in controlling entrained air content.

(viii) Increased permeability.

Compressive Strength being the most important property of structural concrete, many investigations have been carried out to evaluate the effects of hot weather conditions on the concrete strength(5,6,7,8).

Price(5) carried out two types of experiments to investigate the effect of temperature at preparation and curing on the strength of concrete. In the first type, concrete was cast and cured at several constant temperatures in the range of 5 °C to 46 °C. The results showed that concrete cast and cured at the highest temperature developed the highest 28-day strength. In the other type of experiment, concrete was cast and kept for two hours at several temperatures in the range of 5 °C to 46 °C and then cured at 21°C for 28 days. Such treatment produced opposite results as the concrete cast at the highest temperature but cured normally produced the lowest 28-day strength.

Klieger(6) found a reduction in concrete strength of the order of about 15% at 41 °C as compared to that produced at 23 °C. In this study, concrete was made of different types of Portland cement and was mixed, placed and cured at several temperatures in the range of -4 °C to 49 °C. The results showed that strength increased with increase in

initial and curing temperatures for the comparatively early ages of 1, 3 and 7 days but decreased at later ages. Similar results have also been reported in a Portland Cement Association publication(7). In those tests the specimens were prepared and cured up to 28 days at constant temperatures in the range of 23°C to 49°C.

The effect of hot-humid climate on compressive strength of mortar was also investigated by Berhane(8). The variables studied were air and mortar temperatures and the type of cement. This investigation showed that the 28 days exposure to hot-humid environment adversely affected the later age strength of mortar. The adverse effect generally increased with temperature in mortars prepared with Type I cement, while mortar specimens prepared with Type V cement showed a higher reduction in strength at 30°C than at 40°C.

Many other tests have been reported in connection with studies to evaluate the effect of high temperatures on the properties of concrete. Researches reported in the ACI Special Publications(9,10,11) showed reductions in strength. However, most of these tests were carried out at very high temperatures which were maintained constant during the curing periods. Such high temperatures do not simulate the hot weather field conditions where the ambient temperatures usually show a daily variation in the range of 25°C to 50°C.

The above mentioned literature review shows that conflicting results were obtained in some of the studies cited above. Moreover, the tests reported in these publications are not directly applicable to the field conditions mainly for the following two reasons :

(i) the range of temperatures and humidities in these studies are either lower or very much higher than those prevailing in most parts of Saudi Arabia, Middle East and other countries having hot weather in summer months.

(ii) the experiments were carried out in controlled laboratory conditions which are significantly different from those on a typical construction site in hot weather.

1.1.3 Hot Weather Concreting

Specifications for concreting in hot weather conditions usually identify a temperature limit at placement. In the ACI Manual(3), a maximum concrete temperature of 90°F (32°C) is recommended as an upper limit for the production of good quality concrete. To achieve this limit, certain precautions (3,12,13,14) are recommended. Some of them are to be adopted in advance while others are taken during the preparation, placement and curing of concrete. Some of the recommended precautions are :

(i) placement of concrete at lower temperatures of the day such as late afternoon, evening or night. If concreting is to be done at higher temperatures the following mea--sures may be adopted :

(a) keep aggregates cool by shading them or spray--ing water over them.

(b) use cold water for mixing and if necessary use ice as part of the mixing water.

(ii) use of water reducing and retarding admixtures.

(iii) mixing time to be kept minimum.

(iv) minimize exposure of mixer surface to the direct effect of sun by painting white the drum of the mixer and spraying cold water on its surface.

(v) mixing and delivery of concrete to be done in minimum period.

(Vi) shortest possible time for placement, compaction and finishing of concrete.

(vii) Proper curing of concrete by keeping it moist for making water available for hydration .

Some of these recommended precautions are difficult to follow and when followed meticulously add to the cost of construction. Therefore, concreting has to be continuously carried out at high ambient temperature pertaining to hot weather conditions. Moreover, even if the temperature of a concrete mix is lowered to 32 C or less, there still

remains the curing problem. Curing has to be carried out in hot weather conditions for at least 7 days or even for longer periods.

The ACI Manual for Concrete Practice(3) and several other publications(7,14,15,16) present some graphs to determine the amount of water which evaporates from a concrete mix at different temperatures , relative humidities and wind velocities. However , the range of temperatures which appear in these presentations are below the values prevailing in typical summer months in many parts of Saudi Arabia and other Middle East countries . An investigation carried out at UPM(17) showed that for exposure of concrete in natural hot weather conditions , the evaporation of water is higher than what is predicted using the available data.

1.1.4 Mix Design For Local Environmental Conditions

The design of a concrete mix is a complex procedure. It depends on many factors such as properties of materials ,method of preparation , compaction , placement and curing of concrete , as well as the requirements of a construction job such as workability and durability. Once these factors are specified, the remaining task involves proportioning of the quantities of materials. This is usually carried out in terms of determining the water-cement ratio, aggregate-

cement ratio or cement content, and sand to total aggregate ratio for particular gradations of aggregates and maximum size of coarse aggregate. This procedure becomes more difficult to achieve for an optimum mix design in hot weather conditions due to the fact that two additional factors influence the mix design in these conditions. These are (i) placement temperature causing evaporation of water from a concrete mix. This increases the water demand for the required workability of the mix and hence decreases the strength of concrete and (ii) curing conditions in hot weather.

The most widely used method of concrete mix design In practice is the one given by the American Concrete Institute(18). This method of proportioning concrete mixtures makes use of the fact that for a given maximum aggregate size, the workability of concrete can be approximately determined by the water content independently of other mix parameters. The mix water quantum is determined from tables to achieve the required workability. The bulk volume of coarse aggregate is then evaluated from tables for a given maximum aggregate size and the fineness modulus of sand. The water-cement ratio is chosen to satisfy the twin requirements of strength and durability. Using the evaluated mix water quantum and the chosen water-cement ratio, the cement content can be calculated. The quantity of

fine aggregate can then be calculated for the required volume of concrete. This method(18) and other mix design methods suggested by various investigators (19,20,21,22,23) are applicable for environmental situations similar to normal laboratory conditions and for materials, specially the aggregates which are significantly different from those available in the countries having hot climate. There are only limited studies pertaining to the mix design of concrete using local construction materials of Saudi Arabia(24,25,26).

An investigation(24) was carried out to optimize concrete strength using local aggregates available in eastern province of Saudi Arabia . The first part of the study focuses on selection of the best aggregate type from the strength view point. To achieve this objective, aggregates from various quarries in the eastern province were surveyed and tested for chemical and mechanical properties . In the second part of the study concrete strength was optimized using the selected aggregate. A water cement ratio of 0.35 was chosen to achieve high concrete strength values in conjunction with a slump of 2 inches. The other variables such as the maximum size of coarse aggregate , cement content and coarse aggregate to total aggregate ratio were varied one by one for obtaining the best results with each variable. Once the optimum value of a particular variable

was found , it was used for considering the effect of other variables. The results of this investigation showed that the optimum values of maximum size of coarse aggregate and the coarse to total aggregate ratio were 3/8" and 0.65 respectively.

In the second investigation(26), the various constituents of a concrete mix were optimized for an improved durability performance of concrete in the eastern province. The results suggested a minimum cement factor of 650 Lb/yd3 and water cement ratio in the range of 0.45 to 0.50 for high durability performance . The optimum coarse to total aggregate ratio was the same for both strength and workability and was found to be 0.775. This value was found to be valid for cement contents in the range from 500lb/yd3 to 650lb/yd3. The value of coarse to total aggregate ratio for a cement content of 800lb/yd3 was found to be 0.625.

The third investigation(26) presented a statistical approach to optimization of concrete mix design. The effects of three most important parameters influencing the strength and workability of a concrete mix viz. water-cement ratio , coarse to total aggregate ratio and aggregate-cement ratio were investigated. A Factorial Experimental Design was used to evaluate the combined effects of various variables and their interactions when used simultaneously. The results of

this investigation showed that there are two different optimum values of coarse to total aggregate ratio; one for maximum slump and the other for maximum strength. The coarse to total aggregate ratio for the maximum slump was found to be 0.65 and that for maximum strength was close to 0.60.

Mix design for hot weather conditions requires further modifications to include the considerations pertaining to the adverse effects of hot weather. The most important of these is the additional mix water required to maintain the desired level of concrete workability. This additional water causes an increase in the water-cement ratio of a mix resulting in reduction of concrete strength(12) Therefore, it is necessary for proper design of a concrete mix to estimate the required quantity of mixing water as accurately as possible in order to obtain the specified compressive strength and workability in hot weather conditions.

1.2 OBJECTIVE AND SCOPE

The main objective of this study is to present a suitable mix design method for concrete mixtures prepared and cured in the natural atmospheric conditions of hot weather in comparison with that for the normal laboratory conditions.

This research has been carried out in accordance with the following experimental program:

1. Determination of optimum value of sand to total aggregate ratio :

Nine mixes were prepared with different water-cement ratios, aggregate-cement ratios and sand-total aggregate ratios. Each mix was cast and cured inside the laboratory. Results of compressive strength and slump were used to identify the optimum value of sand to total aggregate ratio.

2. Determination of effect of hot weather on workability and compressive strength of concrete :

Fifty four different mixes with three different water-cement ratios, six different aggregate-cement ratios and six different concrete mix temperatures, as given in Table 1.1, were prepared to achieve the stated objectives. Workability and compressive strength at 3, 7, 14 and 28 days were determined for all the fifty four mixes.

3. Statistical Analysis of Data :

Data related to the compressive strength and workability were analyzed using statistical methods to evaluate the effects of the variables on mix design.

Regression analysis of workability and compressive strength data were carried out with the objective to develop equations for predicting workability and compressive strength of concrete for various combinations of water-cement ratio, aggregate-cement ratio and concrete mix temperature.

5. Preparation of mix design tables :

In order to utilize the equations developed in 4 above, tables were generated for the design of concrete mixes to give the required compressive strength and workability in hot weather conditions .

Flow chart in Figure 1.4 shows the complete research program.

Table 1.1 : Layout of The Experimental Design

Water--cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Mix No					
		Concrete Temperature at Placement					
		26°C *	26°C **	35°C **	38°C **	41°c **	44°C **
0.45	4.0	A1	A2	A3	A4	A5	A6
	4.5	B1	B2	B3	B4	B5	B6
	5.0	C1	C2	C3	C4	C5	C6
0.50	5.0	D1	D2	D3	D4	D5	D6
	5.5	E1	E2	E3	E4	E5	E6
	6.0	F1	F2	F3	F4	F5	F6
0.55	5.5	G1	G2	G3	G4	G5	G6
	6.0	H1	H2	H3	H4	H5	H6
	6.5	I1	I2	I3	I4	I5	I6

* Cured in normal laboratory conditions

** Cured in hot weather

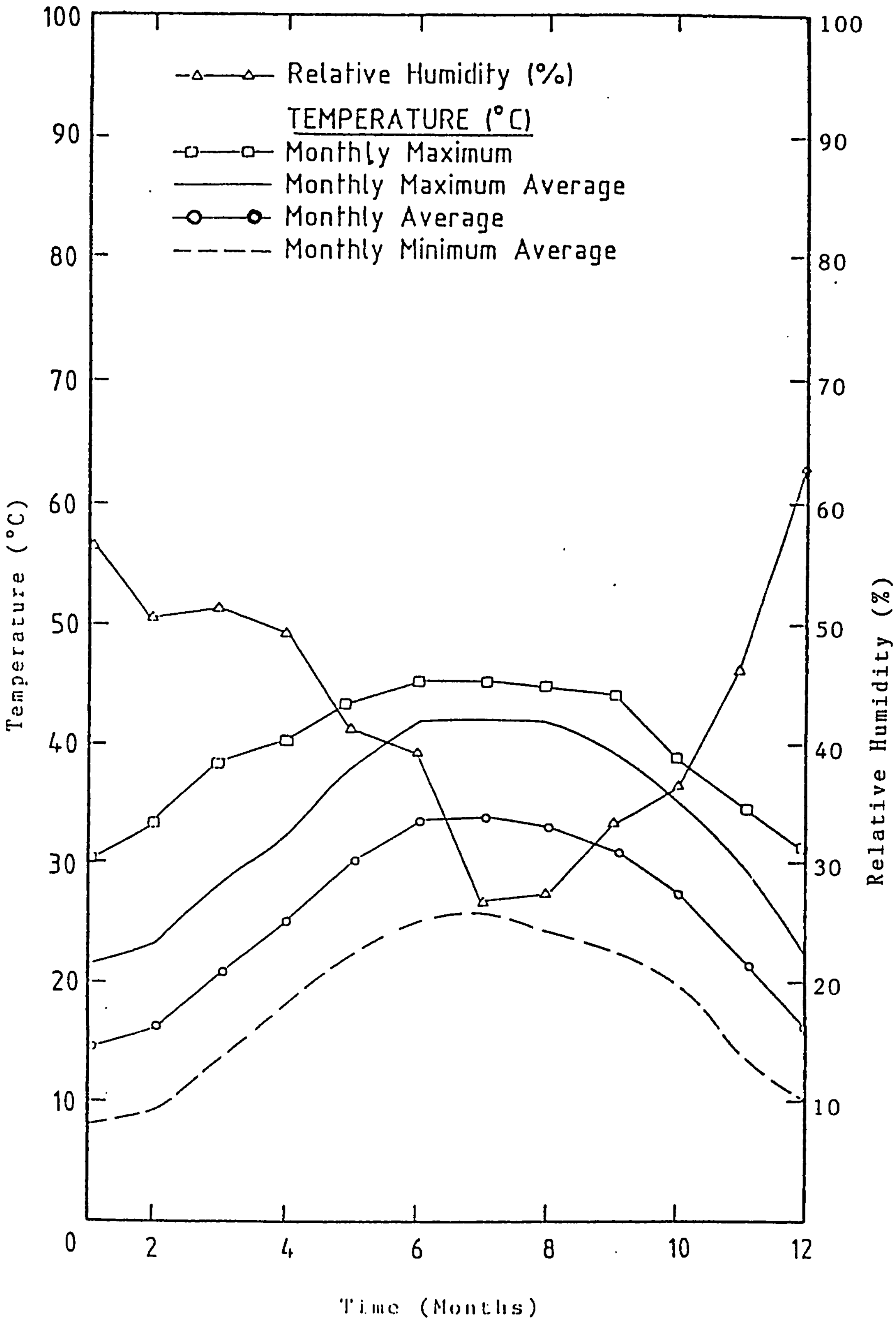

Figure 1.1 : Climate of Riyadh

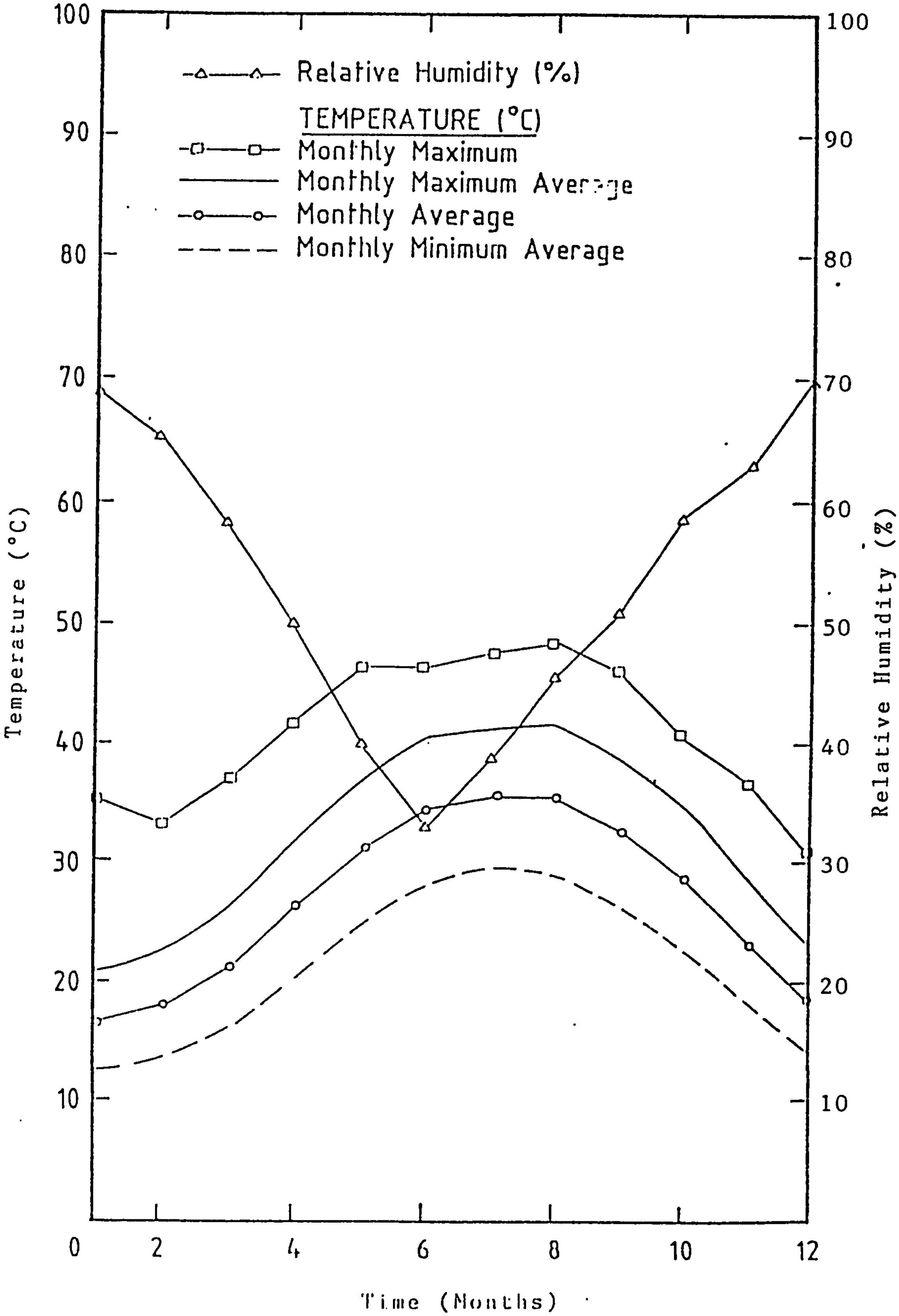

Figure 1.2 : Climate of Dhahran

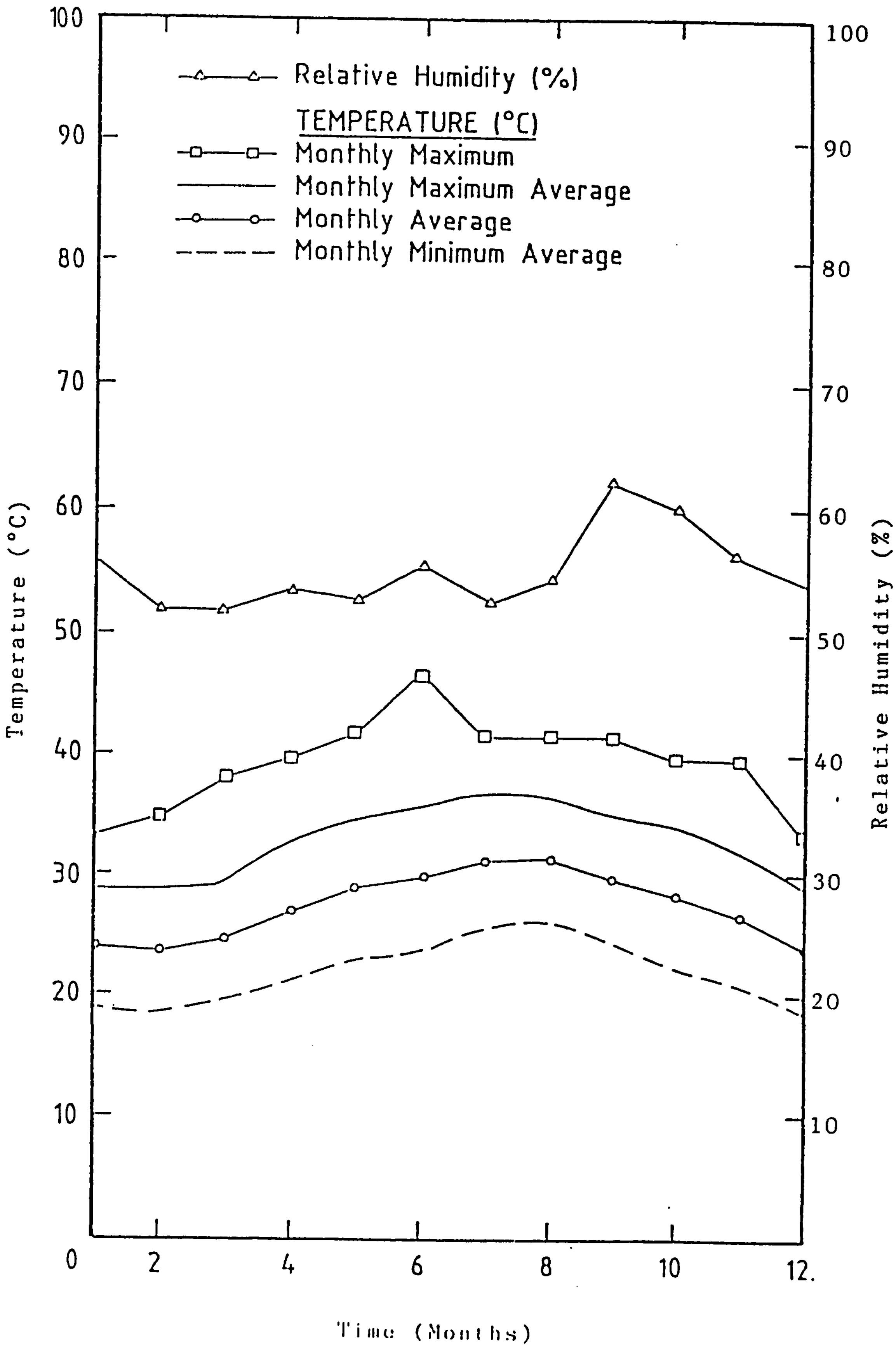

Figure 1.3 : Climate of Jeddah

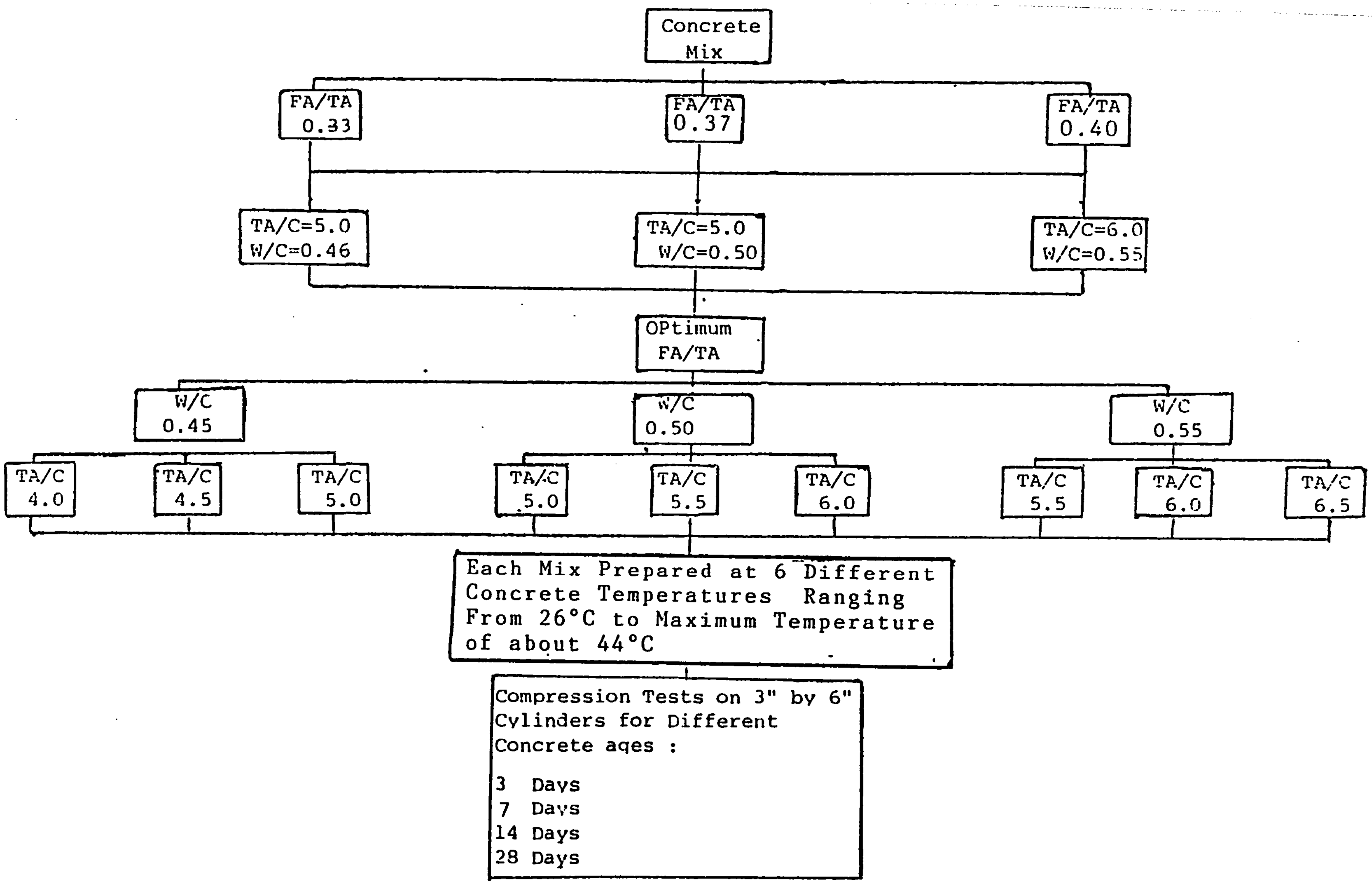

Figure1.4: Flow Chart for the Research Program

CHAPTER 2 : METHODOLOGY OF INVESTIGATION

2.1 DESIGN OF EXPERIMENTS

As stated in Chapter 1, this research has been carried out to develop a mix design method for concrete prepared and cured in natural hot weather conditions in comparison with that for the normal laboratory conditions. This entails that in addition to the usual mix design parameters of water-cement ratio (W/C)*, total aggregate-cement ratio (TA/C)* and fine to total aggregate ratio (FA/TA)*, this study will also have to include the effects of concrete temperatures at placement (Tc)* in conjunction with typical hot weather curing conditions. The simultaneous consideration of all these four variables (W/C, TA/C, FA/TA and Tc) will require preparation of a large number of mixes to achieve reasonably accurate results within the limited period of hot weather in a year. For this reason , one of the variables (FA/TA) was considered separately through an experimental program to determine the optimum value of the binary aggregate parameter (FA/TA) for given aggregate gradations.

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*The following notations are used in the subsequent text:
W/C is the effective water-cement ratio
TA/C is the total aggregate-cement ratio
FA/TA is the fine to total aggregate ratio

Typical mixes using local materials were prepared in the program by varying the above parameters (W/C, TA/C and FA/TA ratios). The details of the mixes along with the results of workability and 28-day compressive strength are given in Table 2.1. These data enabled evaluation of the optimum value of sand-total aggregate ratio for maximum value of compressive strength of concrete as can be seen in figure 2.1. The optimum FA/TA was found to be 0.37. Thereafter, only three variables namely, water-cement ratio (W/C), total aggregate-cement ratio (TA/C) and concrete mix temperature (Tc) were left for simultaneous consideration. To examine the effects of the above factors on compressive strength and workability of concrete, the method of factorial experimental design(26) was adopted.

In the factorial design method the effects of all factors are considered simultaneously. Since lower values of W/C ratio in combination with higher values of TA/C ratio may give too dry mixes and higher values of W/C ratio in combination with lower values of TA/C ratio may give too wet mixes, such combinations are most likely to result in the development of misleading data. For this reason, these combinations (too dry and too wet concrete mixes) were excluded from the experimental program. Three levels of water-cement ratio (0.45 , 0.50 , 0.55) were considered . For each water-cement ratio , three levels of aggregete-

cement ratio in the range of 4.0 to 6.5 were chosen to cover a suitable range of slump values from zero to 6.5 inches. This gave a total of nine different mixes. Each of the nine mixes was prepared at six different concrete temperatures ranging from the normal laboratory temperature of about 26°C to a maximum temperature of 44°C. This required preparation of a total of 54 concrete mixes . The details of all mixes are shown in Table 2.2.

The general approach in designing the mixes in terms of strength and workability has been to develop data in a manner which would enable the mix designer to choose the required effective W/C and TA/C ratios for the required compressive strength and workability for concrete prepared at a given placement temperature and cured in hot weather. The water-cement ratio obtained from the developed mix design data will not include the water allowance for evaporation due to hot weather conditions. Therefore, in order to obtain total water-cement ratio, the extra evaporative water should be added to the effective water-cement ratio chosen from the mix design data. Also, the quantity of water based on this W/C ratio must be adjusted for the absorption of water by the aggregates.

2.2 MATERIALS

2.2.1 Coarse Aggregate

The coarse aggregate used in this investigation was brought from Abu-Hadriah which is a potential source of large aggregate supply in the eastern province. The aggregate was brought from the crusher operated by Al-Ajinah Company. The crushed limestone aggregate consists mainly of calcite as a major mineral(91%) with quartz(4%) and dolomite(4%).

Absorption tests were conducted on the aggregate in accordance with the ASTM standard C128. The absorption capacity of the aggregate is required for determining the total amount of water to be used for each mix. The absorption of the coarse aggregate used in this investigation was found to be 2.21%.

The grading of the coarse aggregate was chosen so that it falls midway between the grading limits of ASTM standard C33 for size No 67 corresponding to 3/4" maximum size of aggregate. The adopted grading and the corresponding ASTM limits are shown in Table 2.3 and Figure 2.2.

The following tests on coarse aggregate were carried out in accordance with ASTM standard C33 (27) :

(a) Specific gravity and absorption of coarse aggregate (ASTM C127).

(b) Clay lumps and friable particles in aggregates (ASTM C142).

(c) Soundness of aggregates using sodium sulphate (ASTM C88).

(d) Chemical analysis of coarse aggregate (ASTM C295).

The results of the above tests are given in Tables 2.4 and 2.5.

2.2.2 Fine Aggregates

Fine aggregate used in this investigation was dune sand brought from Abqaiq road. It consists of quartz, gypsum, calcite and feldspar. It has an absorption of 0.692% and a fineness modulus of 1.503. The grading for the sand is shown in Table 2.6 and Figure 2.3. The figure shows that the gradation of this sand falls outside the ASTM limits on the finer side. The results of chemical analysis of this sand are given in Table 2.7.

2.2.3 Cement

The cement used in preparing the specimens was ASTM Type I, Ordinary Portland Cement. The chemical analysis of the cement is given in Table 2.8.

2.2.4 water

Potable water from the laboratory tap was used for preparing and curing the specimens. Chemical analysis of the water is given in Table 2.9.

2.3 PREPARATION OF SPECIMENS

2.3.1 Preparation of Materials

All the materials were proportioned by weight to give the required ratios of water to cement (W/C), total aggregate to cement (TA/C) and sand to total aggregate (FA/TA). For mixes to be prepared outside the laboratory in hot weather, the ingredients (cement, sand and coarse aggregate) were placed in the sun for different durations prior to mixing so as to raise their temperature to the required levels. The duration of exposure to the sun depended upon the ambient temperature and the required concrete mix temperature. The temperatures of the ingredients were recorded prior to mixing.

2.3.2 Mixing Process

Mixing was carried out using an electrically operated concrete mixer of 6 ft3 capacity. The interior of the mixer was dampened before use. The mixing was done in accordance with ASTM standard C192. Materials were put into the mixer

in the following sequence. First the coarse aggregate was transferred to the mixer. A part of the mixing water was added to the coarse aggregate and mixing started. After a few revolutions cement, sand and some of the mixing water were added and mixing continued for one minute. Thereafter, the remaining water was added and mixing continued for 45 seconds. The concrete was then discharged from the mixer into a tray and remixed for about one minute using hand trowels. Temperature of concrete was measured by placing a thermometer in the mix. Humidity and ambient air temperature were also recorded during the time of concreting.

2.3.3 Additional Mixing Water

For concrete mixes prepared outside the laboratory in hot weather, suitable amounts of extra water were needed to compensate for the loss of water due to evaporation of mixing water in hot weather conditions which causes reduction in workability of concrete. The amount of extra water required for this purpose is, therefore, controlled by the criterion that the the slump of the mix prepared in hot weather conditions should be nearly the same as the slump of the corresponding mix prepared inside the laboratory at normal temperature.

The amount of additional water required to compensate for evaporation can be obtained using the graph given in the ACI

Manual(3). This graph is reproduced as Figure 2.4 here. Table 2.10 gives the amounts of additional water required for various mixes prepared in hot weather at the concrete mix temperature of 35°C and 38°C using these graphs. These quantities were computed for 40% relative humidity, wind velocity of 15 and 20 mph and air temperature of 40°C. The concrete surface area was taken to be 4 sq ft equal to the size of the tray in which concrete was poured from the mixer. The evaporation was assumed to take place for 15 minutes which was approximately the time taken for mixing of concrete and preparation of the specimens.

It has been found that the quantity of additional water required for restoration of slump of concrete in hot weather conditions is generally more than what is predicted using the graph in Figure 2.4. Besides the humidity, wind velocity and the concrete mix temperature, the evaporation is found to be controlled also by the temperature of the ingredients, quantity of aggregate and the time of preparation. Higher evaporation occurs with the higher temperature of the ingredients, the greater quantity of aggregate in the mix and when the mixes are prepared very near to the hottest part of the day. Considering these factors greater quantities were actually added to various mixes as given in Table 2.10. However for the mixes A and B the quantity of extra water added was less than that

predicted by the ACI graph. This was done because the mixes A and B were prepared at 35°C and 38°C in relatively milder hot weather i.e in the month of September.

The comparison of the actually added extra water with that predicted by the ACI graph was not made for other mixes having temperatures of 41°C and 44°C because the ACI graph is not prepared for such high concrete temperatures.

The slump of various concrete mixes with the greater quantities of actually added extra water was nearly the same as that of the corresponding mixes prepared inside the laboratory as can be seen in Tables 4.1 to 4.9 in chapter 4.

2.3.4 Workability

Workability is probably the most important property of fresh concrete. Strength of concrete is seriously affected by the degree of its compaction which in turn is affected by workability. It is, therefore, necessary that the workability of concrete be of such an order that the concrete may be transported, placed, compacted and finished with sufficient ease and efficiency. A concrete that satisfies the above conditions is a workable concrete. Workability has been defined by Newman (24) as the measure of compactibility, mobility and stability. Glanville (25) defines workability as the amount of useful work necessary to produce full compaction. Workability is affected by

several factors. The main factors being water content, maximum size of coarse aggregate, grading, shape and texture of aggregates. Another important factor is concrete temperature. The higher the concrete temperature the more is the evaporation of mixing water and hence lesser the workability of concrete.

Slump being the most widely used method of workability evaluation on construction sites, workability was measured by means of slump test in this investigation. The test was performed in accordance with the ASTM standard C143.

2.3.5 Casting of Specimens

Sixteen 3"x6" cylinders were cast from each concrete mix. The moulds were filled in three approximately equal layers and were vibrated using a small laboratory vibrating table. Four cylinders were vibrated at a time in four sets. After the cylinders were finished, the surfaces were covered with polythene bags to prevent evaporation of water from the surface. The cylinders were left in the moulds at the place of preparation for about 24 hours; thereafter they were demoulded for curing.

2.3.6 Curing of Specimens

The specimens were cured in the following conditions :

I. Specimens prepared and cured inside the laboratory at no--rmal temperature of about 26°C(no effect of hot weather)

II. Specimens prepared inside the laboratory at normal temp-erature but cured outside the laboratory in hot weather The specimens were transferred to the curing site imm-ediately after casting.
This represents the situation in which necessary pre-cautions are taken to reduce the temperature of con-crete mix at preparation.

III. Specimens prepared and cured outside the laboratory in hot weather at different concrete temperatures ranging from 35° to 44°C.

All the specimens were cured after demoulding by keeping them covered with moist burlap to simulate actual field conditions. Water was sprayed over the specimens twice a day.

2.3.7 Testing of Concrete Specimens

Compressive strength tests were carried out at the ages of 3,7,14 and 28 days. The specimens were uncovered and placed in the air inside the laboratory for about two hours and were capped on the uneven top surface. Capping was done using a sulphur compound in accordance with the ASTM Standard C617. Compressive strength tests were carried out using a hydraulically operated compression testing machine of 8-inch ram. A minimum of three cylinders were tested at each age. The compressive strength versus age curves are

plotted in Figures A.1 to A.54 and are given in Appendix A.

Table 2.1 : Slump and 28-day Compressive Strength of Concrete Mixes Prepared to determine Optimum Fine Aggreg- -ate to Total Aggregate Ratio (FA/TA)

Mix No	Type of Mixing	FA/TA	W/C	TA/C	Slump (in)	28-day compressive strength (psi)
1	Mixer	0.33	0.46	5.0	0.0	3991
2	Mixer	0.37	0.46	5.0	1.0	5391
3	Mixer	0.40	0.46	5.0	0.0	4974
4	Mixer	0.33	0.50	5.0	6.5	3645
5	Mixer	0.37	0.50	5.0	2.5	4950
6	Mixer	0.40	0.50	5.0	2.75	4850
7	Hand	0.33	0.55	6.0	5.0	2678
8	Hand	0.37	0.55	6.0	3.0	4761
9	Hand	0.40	0.55	6.0	1.75	3587

Table 2.2 : Details of Mixes

Mix No	Place of Prepara--tion	Place of Curing	Concrete Temp at Placement Tc (C)	Mix* Proportions		Extra Water % of Mix Weight
				W/C	TA/C	
A1	Inside	Inside	26	0.45	4.0	0.0
A2	Inside	Outside	26	0.45	4.0	0.00
A3	Outside	Outside	35	0.45	4.0	0.15
A4	Outside	Outside	38	0.45	4.0	0.20
A5	Outside	Outside	41	0.45	4.0	0.75
A6	Outside	Outside	44	0.45	4.0	0.90
B1	Inside	Inside	26	0.45	4.5	0.00
B2	Inside	Outside	26	0.45	4.5	0.00
B3	Outside	Outside	35	0.45	4.5	0.10
B4	Outside	Outside	38	0.45	4.5	0.25
B5	Outside	Outside	41	0.45	4.5	0.75
B6	Outside	Outside	44	0.45	4.5	1.00
C1	Inside	Inside	26	0.45	5.0	0.00
C2	Inside	Outside	26	0.45	5.0	0.00
C3	Outside	Outside	35	0.45	5.0	0.25
C4	Outside	Outside	38	0.45	5.0	0.50
C5	Outside	Outside	41	0.45	5.0	0.75
C6	Outside	Outside	44	0.45	5.0	1.00

Table 2.2 Cont.

Mix No	Place of Prepara-tion	Place of Curing	Concrete Temp at Placement Tc(C)	Mix * Proportions		Extra Water % of Mix Weight
				W/C	A/C	
D1	Inside	Inside	26	0.50	5.0	0.00
D2	Inside	Outside	26	0.50	5.0	0.00
D3	Outside	Outside	35	0.50	5.0	0.25
D4	Outside	Outside	38	0.50	5.0	0.50
D5	Outside	Outside	41	0.50	5.0	0.75
D6	Outside	Outside	44	0.50	5.0	1.00
E1	Inside	Inside	26	0.50	5.5	0.00
E2	Inside	Outside	26	0.50	5.5	0.00
E3	Outside	Outside	35	0.50	5.5	0.50
E4	Outside	Outside	38	0.50	5.5	0.75
E5	Outside	Outside	41	0.50	5.5	1.00
E6	Outside	Outside	44	0.50	5.5	1.25
F1	Inside	Inside	26	0.50	6.0	0.00
F2	Inside	Outside	26	0.50	6.0	0.00
F3	Outside	Outside	35	0.50	6.0	0.50
F4	Outside	Outside	38	0.50	6.0	0.75
F5	Outside	Outside	41	0.50	6.0	1.00
F6	Outside	Outside	44	0.50	6.0	1.25

Table 2.2 Cont.

Mix No	Place of Prepara-tion	Place of Curing	Concrete Temp at Placement Tc(C)	Mix* Proportions		Extra Water % of Mix Weight
				W/C	A/C	
G1	Inside	Inside	26	0.55	5.5	0.00
G2	Inside	Outside	26	0.55	5.5	0.00
G3	Outside	Outside	35	0.55	5.5	0.50
G4	Outside	Outside	38	0.55	5.5	0.75
G5	Outside	Outside	41	0.55	5.5	1.00
G6	Outside	Outside	44	0.55	5.5	1.25
H1	Inside	Inside	26	0.55	6.0	0.00
H2	Inside	Outside	26	0.55	6.0	0.00
H3	Outside	Outside	35	0.55	6.0	0.40
H4	Outside	Outside	38	0.55	6.0	0.55
H5	Outside	Outside	41	0.55	6.0	0.90
H6	Outside	Outside	44	0.55	6.0	1.10
I1	Inside	Inside	26	0.55	6.5	0.00
I2	Inside	Outside	26	0.45	6.5	0.00
I3	Outside	Outside	35	0.55	6.5	0.40
I4	Outside	Outside	38	0.55	6.5	0.65
I5	Outside	Outside	41	0.55	6.5	0.90
I6	Outside	Outside	44	0.55	6.5	1.10

* FA/TA was 0.37 for all the mixes.

TABLE 2.3 : Grading of Coarse Aggregate Used in the Mixes

Size of Sieve	Percentage Passing	Percentage passing(ASTM)
3/4"	95.0	90 - 100
3/8"	37.5	20 - 55
#4	5.0	0 - 10
#8	0	0 - 5

Table 2.4 : Test Results on Coarse Aggregate*

Test	Result
Bulk Specific Gravity	2.39
Bulk Specific Gravity(SSD)	2.44
Apparent Specific Gravity	2.52
Percent Clay Lumps and Friable Particles	0.42
Soundness	1.16

* Adopted from reference 27.

TABLE 2.5 : Chemical Analysis of Coarse Aggregate*

Chemical Composition	Percent
Silica	4.29
Aluminum Oxide	0.20
Iron Oxide	0.23
Magnesium Oxide	0.99
Calcium Oxide	52.5
Sodium Oxide	0.031
Potassium Oxide	0.087
Titanium Oxide	0.1
Ignition Loss	41.2
Total	99.628

* Adopted from reference 27.

Table 2.6 : Sieve Analysis of Fine Aggregate(ASTM C136)

Sieve #	Percentage passing(ASTM)	Percentage Passing	Cumulative % Retained
8	80-100	100	0.00
16	50-85	99.97	0.03
30	25-60	94.55	5.45
50	10-30	41.00	59.0
100	2-10	14.21	85.79
200		0.42	99.58
Pan		0.04	99.96

FM = (0.03 + 5.45 + 59.0 + 85.79)/100 = 1.503

TABLE 2.7 : Chemical Analysis of Fine Aggregate*

Chemical Composition	Percent
Silica	82.2
Aluminum Oxide	3.78
Iron Oxide	0.79
Magnesium Oxide	0.81
Calcium Oxide	3.72
Sodium Oxide	0.96
Potassium Oxide	1.05
Titanium Oxide	0.29
Ignition Loss	2.77
Total	96.37

* Adopted from reference 27.

Table (2.8) : Chemical Analysis of Cement

Oxide	Percent
Calcium Dioxide	63.26
Silicon Oxide	21.41
Aluminum Oxide	6.40
Ferric Oxide	2.88
Magnesium Oxide	1.46
Sulphur Oxide	2.18
Loss on Ignition	0.53
Insoluble Residue	0.27
Undetermined	1.61
Calculated C_3S	41.41
Calculated C_2S	30.22
Calculated C_3A	12.09
Calculated C_4AF	8.76

Table (2.9) : Chemical Analysis of Water Used for Curing and Preparation of Concrete Specimens*

PH	6.5
Conductivity umps/cm	350
Dissolved Solids	203
Alkalinity, Total as CaCo3 mg/l	55
Hardness, Total as CaCo3 mg/l	80
Hardness, Calcium as CaCo3 mg/l	30
Hardness, Magnesium as CaCo3 mg/l	50
Chloride as Cl mg/l	58
Sulphate as So4 mg/l	43
Organic Matter as TOC mg/l	6.0
Oil and Grease mg/l	1.2

* Adopted from reference 27.

Table 2.10 : Comparison of Additional Water Used in the Experiments with that Obtained by the ACI Graph.

Air Temperature = 40° C , Humidity = 40%

Concrete Temp. °C	Wind Velocity mph	Required Add-itional Water kg/m2/hr	Required Add-itional Water kg (lb)	Quantities of Additional Water as Used for Experiments kg(lb) Mix No A	B	C	D	E	F	G	H	I
35	15	1.80	0.167 (0.38)	0.11 (0.24)	0.07 (0.16)	0.18 (0.39)	0.18 (0.39)	0.35 (0.79)	0.35 (0.79)	0.35 (0.79)	0.27 (0.62)	0.27 (0.62)
35	20	2.3	0.214 (0.48)									
38	15	2.3	0.214 (0.48)	0.14 (0.32)	0.17 (0.39)	0.35 (0.78)	0.35 (0.78)	0.51 (1.15)	0.51 (1.15)	0.51 (1.15)	0.37 (0.84)	0.44 (0.99)
38	20	2.95	0.274 (0.61)									

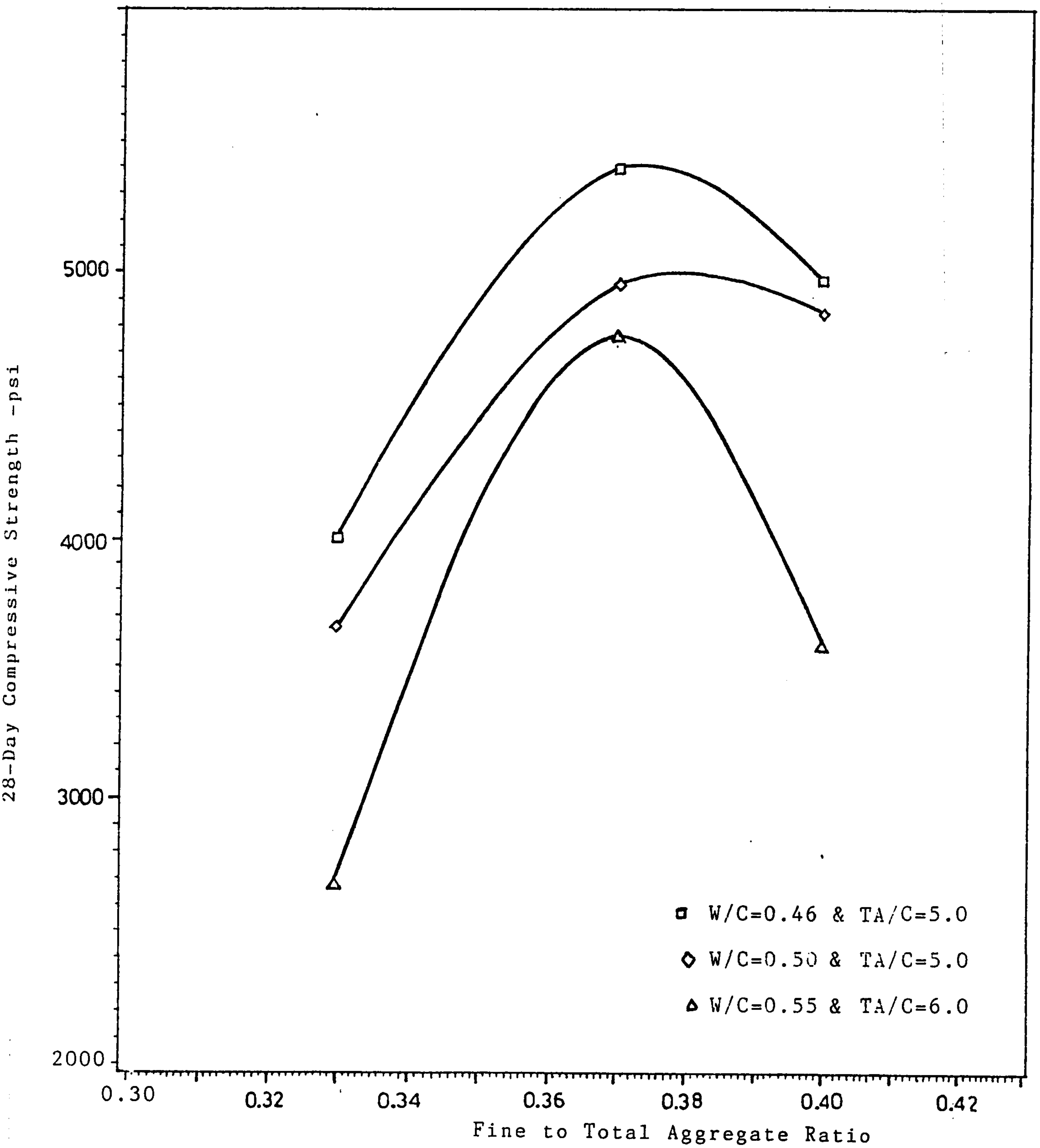

Figure 2.1 : Comparison of Compressive Strength for Various Fine to Total Aggregate Ratio

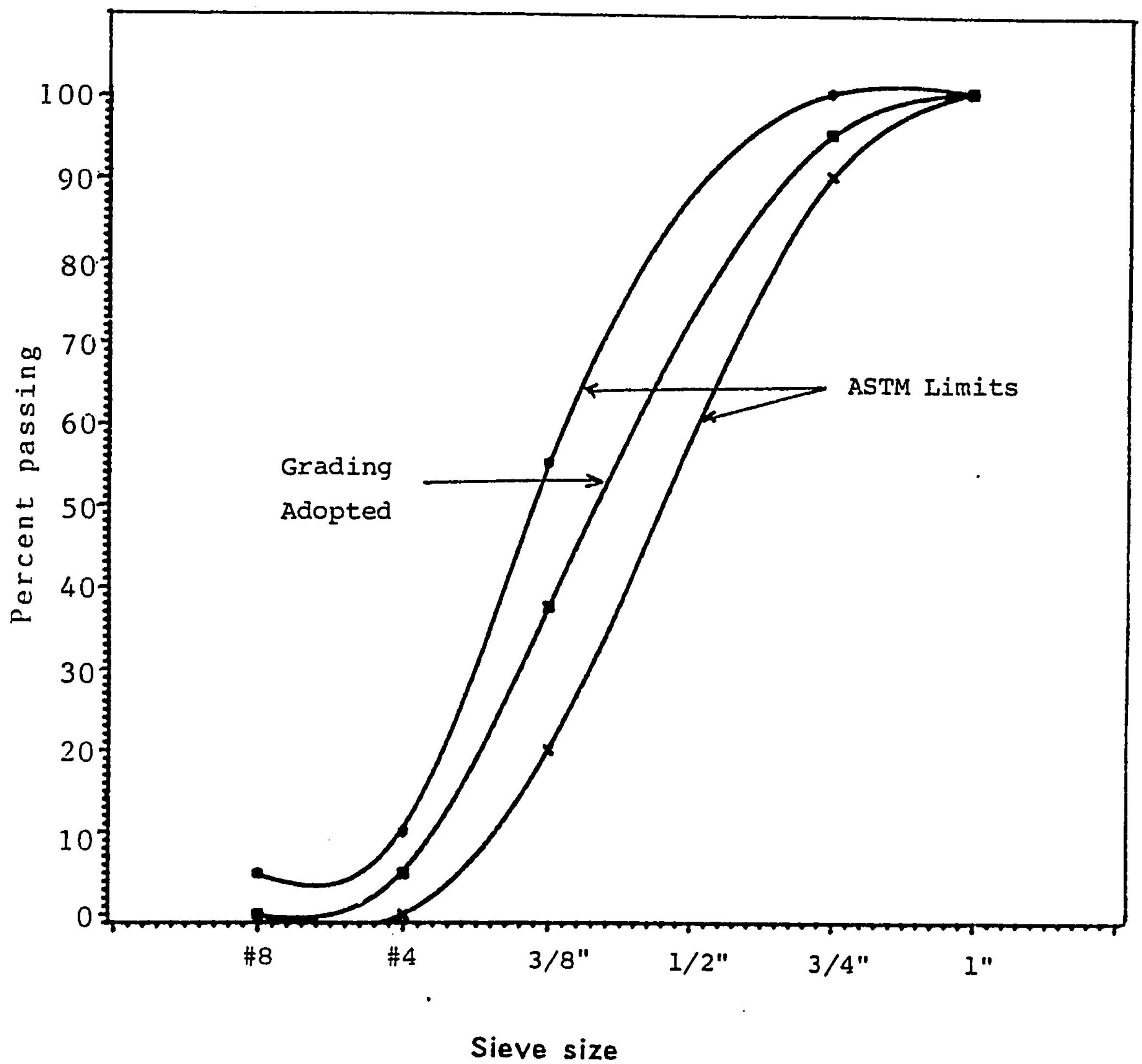

Figure2.2 : Grading of coarse aggregate used in the mixes.

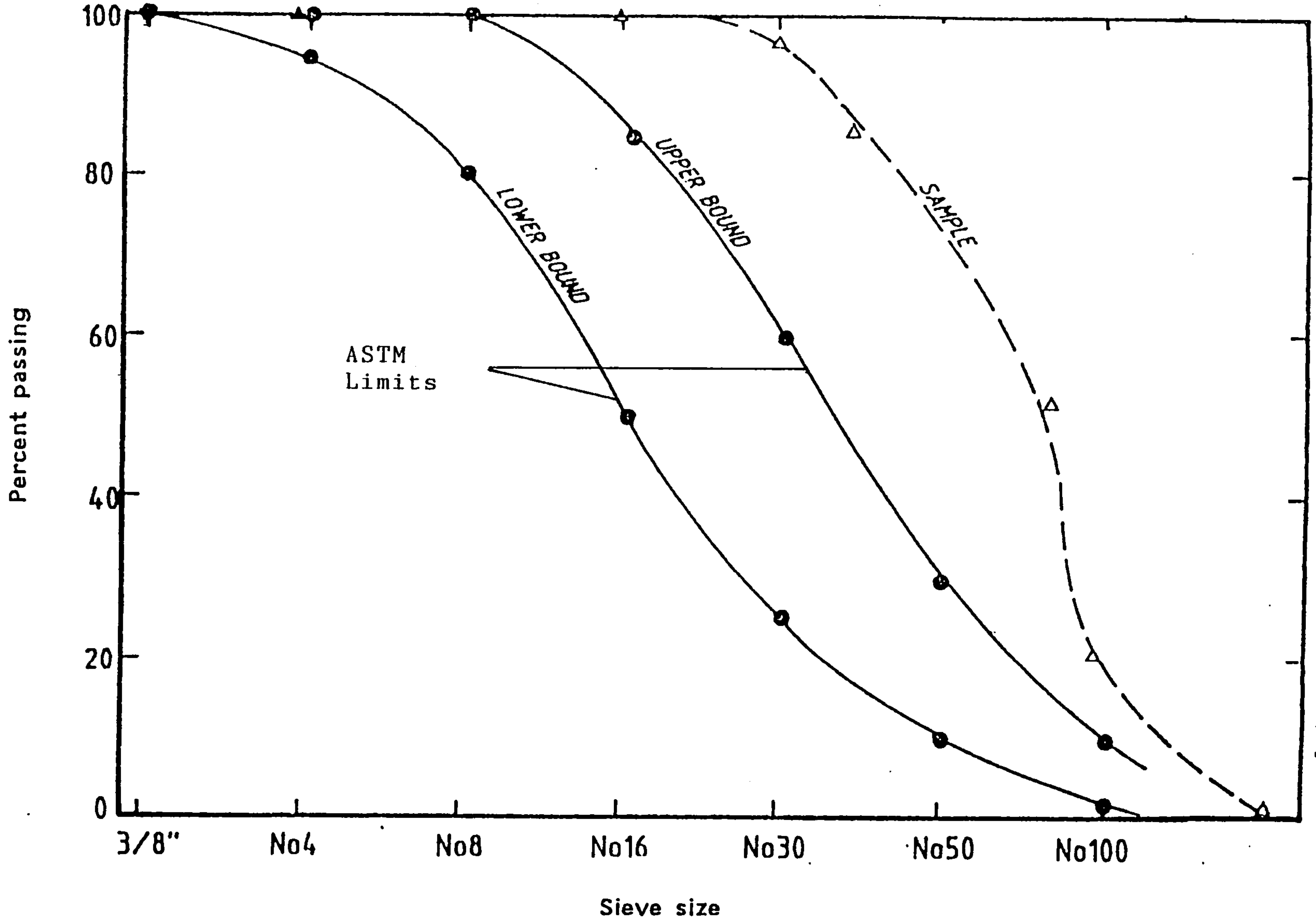

Figure 2.3; Grading of fine aggregate used in the mixes.

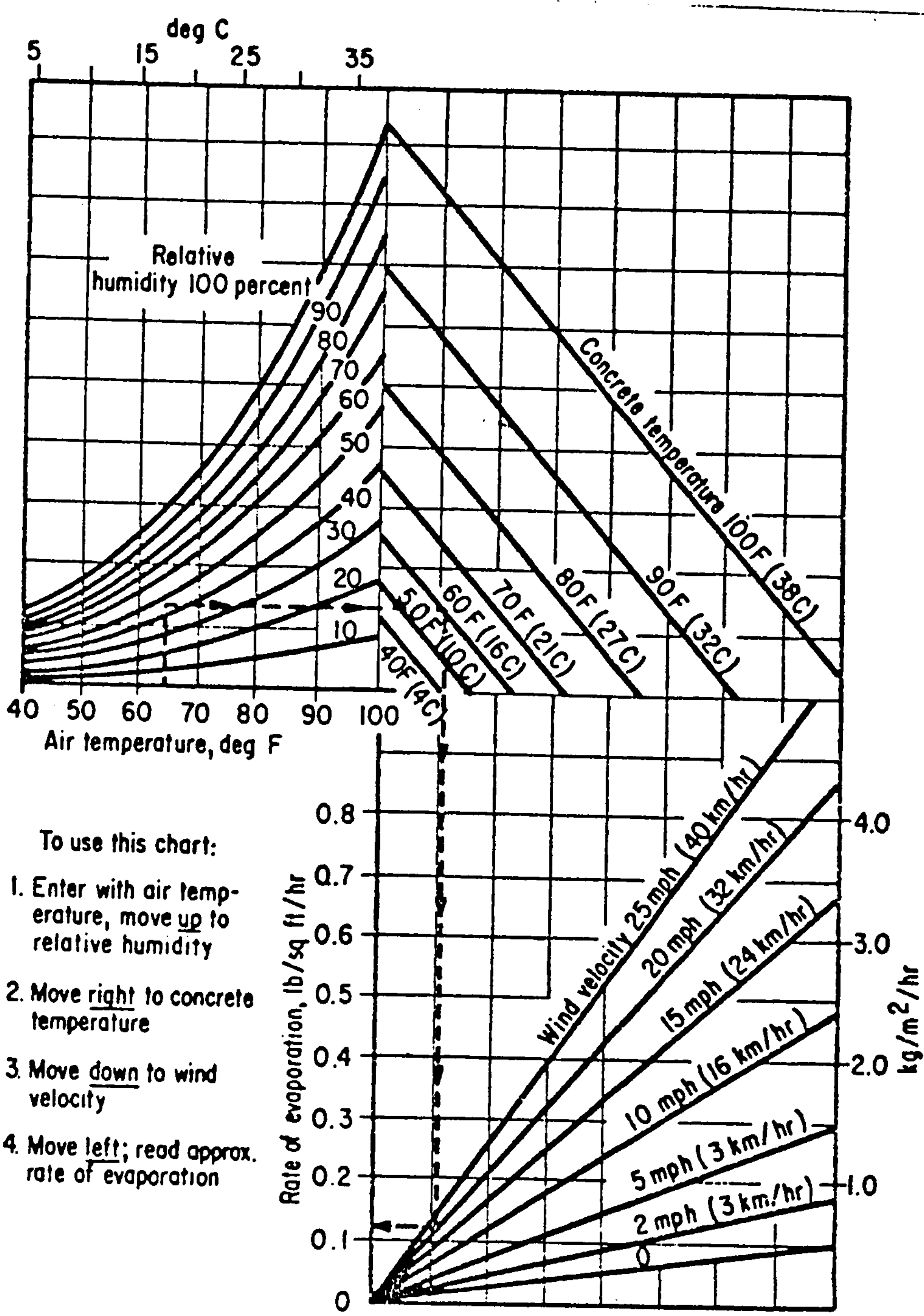

Figure 2.4 : Effect of Concrete and Air Temperature, Relative Humidity and Wind Velocity on the Rate of Evaporation of Surface Moi--sture from Concrete
ACI Graph

CHAPTER 3 : STATISTICAL ANALYSIS

3.1 GENERAL

Statistical analysis helps experimenters in drawing valid and meaningful conclusions from the experimental data. When the problem involves data that are subjected to experimental errors, statistical methodology is the only objective approach to analysis of the data.

The experiments in this investigation were designed primarily to investigate the effects of water-cement ratio(W/C), total aggregate-cement ratio(TA/C) and concrete mix temperature (Tc) and the interactions between these factors on the workability and 28-day compressive strength of concrete.

The statistical analysis for the compressive strength involves three factors W/C ratio(A) at 3 levels, TA/C ratio(B) at 6 levels, and Tc (C) at 6 levels. However, due to the fact that all the levels of TA/C ratio cannot be used in combination with each level of W/C ratio, as explained earlier in section 2.1, a reduced 3×6×6 factorial experimental design was adopted to cover suitable ranges of workability and compressive strength. The layout of the reduced factorial experiment design is shown in Table (3.1). The levels used for each factor are given in Table (3.2).

The analysis of variance of compressive strength data is divided into two parts :

1. Two-factor analysis of variance of strength data for W/C ratio as factor A and concrete mix temperature as factor C :

   To determine the effects of W/C ratio, concrete mix temperature Tc and their interaction on the compressive strength of concrete, this analysis is further subdivided into two groups. The specimens in the first group were prepared inside the laboratory and the analysis of variance has been done for compressive strength of the specimens cured in hot weather as compared to that for the specimens cured inside the laboratory. The objective of this analysis is to determine the effects of W/C ratio and curing conditions in hot weather on the compressive strength of concrete. The second group of specimens was prepared at different temperatures and cured in hot weather. The objective of this analysis is to determine the effect of temperature of concrete mix at placement on the compressive strength of concrete. Each value of the compressive strength used in the data of this analysis is taken as the average of three values of compressive strength obtained from tests on 3"x6" cylinders for three levels of TA/C retio for each W/C ratio.

2. Two-factor analysis of variance of strength data for TA/C ratio as factor B and concrete mix temperature as factor C :

To determine the effects of TA/C ratio, concrete mix temperature Tc and their interaction on the compressive strength of concrete, this analysis is further subdivided into two groups. The specimens in the first group were prepared inside the laboratory and the analysis of variance has been done for compressive strength of the specimens cured in hot weather as compared to that for specimens cured inside the laboratory. The objective of this analysis is to determine the effects of TA/C ratio and curing conditions in hot weather on the compressive strength of concrete. The second group of specimens was prepared at different temperatures and cured in hot weather. The objective of this analysis is to determine the effects of TA/C ratio and temperature of concrete mix at placement on the compressive strength of concrete. The analysis for both groups is carried out for each W/C ratio.

The analysis of variance of strength data for the combination of factors W/C ratio and TA/C ratio could not be performed because of the "missing data" on some of their combinations. The reason for missing data is given in Section 2.1. The mathematical reason for this is explained in the following section. Similarly for the same reason the analysis of variance was not performed for the workability data. However, test results showed definite and significant effects of W/C and TA/C ratios on workability as will be discussed in Chapter 4.

3.2 TWO-FACTOR ANALYSIS OF VARIANCE

This analysis is used when the experiment involves two factors and their treatment combinations. Assume a two factor factorial experiment in which one of the factors is A with "a" levels and the other is B with "b" levels. Assume there are "n" replicates of the experiment and let Y_{ijk} represent the observation taken under the ith level of factor A and the jth level of factor B in the kth replicate. The a×b factorial design with "n" replicates for each combination generate a×b×n observations as shown below.

Factor B

		1	2	. . .	b
Factor A	1	Y_{111} , . . . , Y_{11n}	Y_{121} , . . . , Y_{12n}		Y_{1b1} , . . . , Y_{1bn}
	2	Y_{211} , . . . , Y_{21n}	Y_{221} , . . . , Y_{22n}		Y_{2b1} , . . . , Y_{2bn}
	⋮				
	a	Y_{a11} , . . . , Y_{a1n}	Y_{a21} , . . . , Y_{a2n}		Y_{ab1} , . . . , Y_{abn}

where,

$Y_{ij.}$ = Sum of observations in the (ij)th cell.

$Y_{i..}$ = Sum of observations under the ith level of factor A.

$Y_{.j.}$ = Sum of observations under the jth level of factor B.

$Y_{...}$ = Sum of all the abn observations

$\bar{Y}_{i..}$ = Mean of the observations under the ith level of

factor A = $1/bn \sum_{jk} Y_{ijk}$

$\bar{Y}_{.j.}$ = Mean of the observations under the jth level of factor B = $1/an \sum_{ik} Y_{ijk}$

$\bar{Y}_{...}$ = Mean of all the abn observations = $1/abn \sum Y_{ijk}$

The observations can be described by the linear additive statistical model with two factors and an interaction :

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \qquad \begin{cases} i=1,2,..,a \\ j=1,2,..,b \\ k=1,2,..,n \end{cases} \qquad (3.1)$$

where,

μ is the overall mean effect

α_i is the effect of the ith level of factor A

β_j is the effect of the jth level of factor B

$(\alpha\beta)_{ij}$ is the effect of the interaction between α_i and β_j

ε_{ijk} is the random error component

The above variables are called the model parameters and the least square estimates of these parameters are given by :

$$\hat{\alpha}_i = (\bar{Y}_{i..} - \bar{Y}_{...})$$

$$\hat{\beta}_j = (\bar{Y}_{.j.} - \bar{Y}_{...}) \qquad (3.2)$$

$$(\widehat{\alpha\beta})_{ij} = (\bar{Y}_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...})$$

with the following conditions on the parameters :

$$\sum_i \alpha_i = 0$$

$$\sum_j \beta_j = 0 \qquad (3.3)$$

$$\sum_i \sum_j (\alpha\beta)_{ij} = 0$$

The total corrected sum of squares of the experiment observations may be expressed as :

$$SS(T) = \sum_i \sum_j \sum_k (Yijk - \bar{Y}...)^2$$

Using equations (3.1) and (3.2), the above expression for the total sum of squares can be expanded into

$$SS(T) = \sum\sum\sum[(\bar{Y}_{i..} - \bar{Y}_{...}) + (\bar{Y}_{.j.} - \bar{Y}_{...})$$

$$+ (\bar{Y}_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...}) \qquad (3.4)$$

$$+ (Y_{ijk} - \bar{Y}_{ij.})]^2$$

The six cross products on the right hand side of the above multinomial equation are zero because

$$\sum_i (Y_{i..} - Y_{...}) = 0$$

$$\sum_j (Y_{.j.} - Y_{...}) = 0$$

$$\sum_i \sum_j (Y_{ij.} - Y_{i..} - Y_{.j.} + Y_{...}) = 0$$

Therefore equation (3.3) is reduced to the following equation:

$$SS(T)= bn \sum_i (\bar{Y}_{i..} - \bar{Y}_{...})^2 + an \sum_j (\bar{Y}_{.j.} - \bar{Y}_{...})^2$$

$$+ n \sum_i \sum_j (\bar{Y}_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...})^2 \qquad (3.5)$$

$$+ \sum_i \sum_j \sum_k (Y_{ijk} - \bar{Y}_{ij.})^2$$

Note that the total corrected sum of squares has been partitioned into a sum of squares due to factor A (SSA), a sum of squares due to factor B (SSB), a sum of squares due to the interaction between A and B (SSAB) and a sum of squares due to error (SSE).
We may write equation(3.5) symbolically as :

$$SS(T) = SS(A) + SS(B) + SS(AB) + SS(E)$$

where:

$$SS(A) = bn \sum_i (\bar{Y}_{i..} - \bar{Y}_{...})^2$$

$$SS(B) = an \sum_j (\bar{Y}_{.j.} - \bar{Y}_{...})^2$$

$$SS(AB) = n \sum_i \sum_j (Y_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...})^2 \qquad (3.6)$$

$$SS(E) = \sum_i \sum_j \sum_k (Y_{ijk} - \bar{Y}_{...})^2$$

In order to carry out the analysis of variance for a two factor experiment with n replicates, the following table is constructed.

Source of Va-riation	Degrees of Freedom	Sum of Squares SS	Mean Squares MS	F
A	a-1	SS(A)	MS(A)=SS(A)/(a-1)	MS(A)/MS(E)
B	b-1	SS(B)	MS(B)=SS(B)/(b-1)	MS(B)/MS(E)
AB	(a-1)(b-1)	SS(AB)	MS(AB)=SS(AB)/(a-1)(b-1)	MS(AB)/MS(E)
ERROR	ab(n-1)	SS(E)	MS(E)=SS(E)/ab(n-1)	
TOTAL	abn-1	SS(T)		

The sum of squares in the above table are calculated using equations (3.6) which are valid for complete block design i.e when the data for all combinations of factors are available. However, for incomplete block design, all equations (3.3) which are the basic assumptions for this method cannot be satisfied. To show this consider the data of strength for the factors W/C ratio (A) and TA/C ratio (B). Now let us check equations (3.3) for this data.

Using equation (3.3) and the data of compressive strength in Table 4.1 to 4.9 in Chapter 4 :

(i) <u>Check $\Sigma \alpha_i = 0$.</u> :

$\alpha_1 = (Y_{1..} - Y_{...}) = 5445.7 - 4571.9 = 873.8$

$\alpha_2 = (Y_{2..} - Y_{...}) = 4483.3 - 4571.9 = -88.6$

$\alpha_3 = (Y_{3..} - Y_{...}) = 3786.6 - 4571.9 = -785.2$

$\Sigma \alpha_i = 000.0$ (1st condition of Eq 3.3 is satisfied)

(ii) <u>Check $\Sigma \beta_j = 0.$</u> :

$\beta_1 = (Y_{.1.} - Y_{...}) = 5482.9 - 4571.9 = 911.0$

$\beta_2 = (Y_{.2.} - Y_{...}) = 5539.0 - 4571.9 = 967.1$

$\beta_3 = (Y_{.3.} - Y_{...}) = 4920.8 - 4571.9 = 348.9$

$\beta_4 = (Y_{.4.} - Y_{...}) = 4134.6 - 4571.9 = -437.3$

$\beta_5 = (Y_{.5.} - Y_{...}) = 4124.3 - 4571.9 = -447.6$

$\beta_6 = (Y_{.6.} - Y_{...}) = 3765.4 - 4571.9 = -806.5$

$\Sigma \beta_j = 535.6 \neq 0$

(2nd condition of Eq 3.3 is not satisfied)

(iii <u>Check $\Sigma \Sigma a\beta_{ij} = 0.$</u> :

$\alpha\beta_{ij} = (Y_{ij.} - Y_{i..} - Y_{.j.} + Y_{...})$

$\alpha\beta_{11} = 5482.9 - 5445.6 - 5482.9 + 4571.9 = -873.7$

$\alpha\beta_{12} = 5539.0 - 5445.6 - 5539.0 + 4571.9 = -873.7$

$\alpha\beta_{13}$ = 5315.0 -5445.6 -4920.8 +4571.9 = - 479.5

$\alpha\beta_{23}$ = 4526.6 -5539.0 -4920.8 +4571.9 = -1361.3

$\alpha\beta_{24}$ = 4463.4 -5539.0 -4134.6 +4571.9 = - 683.3

$\alpha\beta_{25}$ = 4459.9 -5539.0 -4124.3 +4571.9 = - 631.5

$\alpha\beta_{34}$ = 3805.9 -4920.8 -4134.6 +4571.9 = - 677.6

$\alpha\beta_{35}$ = 3788.7 -4920.8 -4124.3 +4571.9 = - 684.5

$\alpha\beta_{36}$ = 3765.4 -4920.8 -3765.4 +4571.9 = - 348.5

$$\Sigma\ \Sigma\ \alpha\beta_{ij} = -6613 \neq 0$$

(3rd condition of Eq 3.3 is not satisfied)

Thus equations (3.3) are not satisfied. Therefore, the analysis of variance for the combination of factors A and B cannot be performed using the present method. However, the results of various analyses for other combinations are given in chapter 4.

3.3 REGRESSION ANALYSIS

The data of workability and 28 day compressive strength were subjected to polynomial regression to develop equations for predicting workability and compressive strength of concrete for various values of W/C ratio, TA/C ratio and concrete mix temperature Tc. The regression analysis was carried out using the computer program SAS. The input

data for the program included the dependent variables of compressive strength and workability and the independent variables of W/C ratio, TA/C ratio and concrete mix temperature Tc. Attempts were made to fit various models with experimental data and the one with the least deviation from the experimental data was chosen. The selected model for compressive strength of the specimens prepared and cured in the normal laboratory conditions is :

$$\text{Strength} = \alpha_0 + \alpha_1(TA/C) + \alpha_2(1/W/C) \tag{3.7}$$

The selected model for compressive strength of the specimens prepared and cured in hot weather is :

$$\begin{aligned}\text{Strength} = {} & \beta_0 + \beta_1(W/C) + \beta_2(TA/C) + \beta_3(Tc) \\ & + \beta_4(W/C)(TA/C) + \beta_5(W/C)(Tc) + \beta_6(TA/C)^2 \\ & + \beta_7(Tc)^2 + \beta_8(W/C)(Tc)^2\end{aligned} \tag{3.8}$$

The selected model for workability is :

$$\begin{aligned}\text{Workability} = {} & \gamma_0 + \gamma_1(W/C) + \gamma_2(TA/C) \\ & + \gamma_3(W/C)(TA/C) + \gamma_4(W/C)^2 \\ & + \gamma_5(TA/C)(W/C)^2\end{aligned} \tag{3.9}$$

The coefficients in the above models were obtained from regression analysis. The coefficients in the strength equation (3.7) are given in Table 3.3. The analysis of variance for the model is given in Table 3.4. Similarly the coefficients for the equations (3.8) and (3.9) and the corresponding analyses of variance are given in Tables 3.5-3.8. The accuracy of the models is discussed in the following section.

3.4 COMPARISON OF EXPERIMENTAL AND PREDICTED VALUES

The values of compressive strength computed by the equations (3.7) and (3.8) are compared with the experimentally determined values in Table 3.9. Similarly the experimental values of workability are compared with those computed by the equation (3.9) in Table 3.10. These comparisons are also illustrated in Figures 3.1 and 3.2. In both cases the comparison showed a close agreement between the experimental and computed values as shown by 95% confidence limits around computed values. This is also confirmed by the R-square values for the three models given in Tables 3.4, 3.6 and 3.8. R-square is called the coefficient of multiple determination which can be used to judge the adequacy of the fitness of a regression model. R-square is often referred to as the amount of variability in the data accounted for by the regression model. As an example, the value of R-square for the strength model represented by the equation is 0.9895. This means that 98.95 percent of the variability in the strength data is accounted for by the model and as such the model can be used for prediction purposes with good accuracy. The F and R-square values of the three models are reproduced in Table 3.11 which shows an overall picture for adequacy of these models.

Table (3.1) : Layout Plan of Factorial Experimental Design

Levels of A (W/C)	Levels of B (TA/C)	Levels of C (Tc)					
		c_1	c_2	c_3	c_4	c_5	c_6
a_1	b_1	$a_1 b_1 c_1$	$a_1 b_1 c_2$	$a_1 b_1 c_3$	$a_1 b_1 c_4$	$a_1 b_1 c_5$	$a_1 b_1 c_6$
	b_2	$a_1 b_2 c_1$	$a_1 b_2 c_2$	$a_1 b_2 c_3$	$a_1 b_2 c_4$	$a_1 b_2 c_5$	$a_1 b_2 c_6$
	b_3	$a_1 b_3 c_1$	$a_1 b_3 c_2$	$a_1 b_3 c_3$	$a_1 b_3 c_4$	$a_1 b_3 c_5$	$a_1 b_3 c_6$
a_2	b_3	$a_2 b_3 c_1$	$a_2 b_3 c_2$	$a_2 b_3 c_3$	$a_2 b_3 c_4$	$a_2 b_3 c_5$	$a_2 b_3 c_6$
	b_4	$a_2 b_4 c_1$	$a_2 b_4 c_2$	$a_2 b_4 c_3$	$a_2 b_4 c_4$	$a_2 b_4 c_5$	$a_2 b_4 c_6$
	b_5	$a_2 b_5 c_1$	$a_2 b_5 c_2$	$a_2 b_5 c_3$	$a_2 b_5 c_4$	$a_2 b_5 c_5$	$a_2 b_5 c_6$
a_3	b_4	$a_3 b_4 c_1$	$a_3 b_4 c_2$	$a_3 b_4 c_3$	$a_3 b_4 c_4$	$a_3 b_4 c_5$	$a_3 b_4 c_6$
	b_5	$a_3 b_5 c_1$	$a_3 b_5 c_2$	$a_3 b_5 c_3$	$a_3 b_5 c_4$	$a_3 b_5 c_5$	$a_3 b_5 c_6$
	b_6	$a_3 b_6 c_1$	$a_3 b_6 c_2$	$a_3 b_6 c_3$	$a_3 b_6 c_4$	$a_3 b_6 c_5$	$a_3 b_6 c_6$

Table (3.2) : Codes for Factors and Levels

Factor	Factor code	Levels of code					
		1	2	3	4	5	6
W/C	A	a_1=0.45	a_2=0.50	a_3=0.55			
TA/C	B	b_1=4.0	b_2=4.5	b_3=5.0	b_4=5.5	b_5=6.0	b_6=6.5
Tc(C)	C	c_1=26*	c_2=26**	c_3=35**	c_4=38**	c_5=41**	c_6=44**

* Cured inside the laboratory

** Cured in hot weather

Table (3.3): Regression Constants of Strength Equation(3.7)

Coefficient	Value
α_0	925.91
α_1	-277.05
α_2	2748.34

Table(3.4): Analysis of Variance for Strength Equation(3.7)

Source	DF	Sum of Squares	Mean Squares	F Value	R-Square
Model	2	3639357	1819679	682.866	0.9956
Error	6	15988.597	2664.766		
Total	8	3655346			

Table (3.5): Regression Constants of Strength Equation(3.8)

Coefficient	Value
β_0	69340.902
β_1	-125404
β_2	-953.656
β_3	-1905.587
β_4	4013.699
β_5	3459.704
β_6	-103.180
β_7	17.083
β_8	-31.481

Table(3.6): Analysis of Variance for Strength Equation(3.8)

Source	DF	Sum of Squares	Mean Squares	F Value	R-Square
Model	8	19676301	2459538	316.571	0.9895
Error	27	209771	7769.31		
Total	35	19886073			

Table (3.7): Regression Constants of Workability Eq.(3.9)

Coefficient	Value
γ_0	1238.13
γ_1	-5138.75
γ_2	-212.00
γ_3	870.00
γ_4	5375.00
γ_5	-900.00

Table (3.8) : Analysis of Variance for Workability Eq.(3.9)

Source	DF	Sum of Squares	Mean Squares	F Value	R-Square
Model	5	27.687500	5.537500	17.720	0.9672
Error	3	0.937500	0.312500		
Total	8	28.625000			

Table (3.9) : Comparison of Experimental with Computed Values of Compressive Strength.

Mix No	W/C	TA/C	Temp Tc °C	Experimental Comp. Strength (psi)	Computed Comp. Strength (psi)	95% Confidence Limits
A1	0.45	4.0	26	5938	5925	± 103.24
B1	0.45	4.5	26	5726	5787	
C1	0.45	5.0	26	5587	5648	
D1	0.50	5.0	26	5095	5037	
E1	0.50	5.5	26	4855	4899	
F1	0.50	6.0	26	4789	4760	
G1	0.55	5.5	26	4331	4399	
H1	0.55	6.0	26	4267	4261	
I1	0.55	6.5	26	4223	4122	
A3	0.45	4.0	35	5955	6036	±176.28
B3	0.45	4.5	35	6146	6024	
C3	0.45	5.0	35	6106	5960	
A4	0.45	4.0	38	5700	5629	
B4	0.45	4.5	38	5668	5616	
C4	0.45	5.0	38	5449	5552	
A5	0.45	4.0	41	5333	5274	
B5	0.45	4.5	41	5331	5261	
C5	0.45	5.0	41	5044	5197	

Table (3.9) Cont.

Mix No	W/C	TA/C	Temp Tc °C	Experimental Comp. Strength (psi)	Computed Comp. Strength (psi)	95% Confidence Limits
A6	0.45	4.0	44	4879	4971	± 176.28
B6	0.45	4.5	44	4943	4959	
C6	0.45	5.0	44	4943	4895	
D3	0.50	5.0	35	4788	4819	
E3	0.50	5.5	35	4745	4804	
F3	0.50	6.0	35	4657	4737	
D4	0.50	5.0	38	4622	4586	
E4	0.50	5.5	38	4571	4571	
F4	0.50	6.0	38	4468	4504	
D5	0.50	5.0	41	4388	4377	
E5	0.50	5.5	41	4394	4362	
F5	0.50	6.0	41	4309	4295	
D6	0.50	5.0	44	4191	4192	
E6	0.50	5.5	44	4076	4177	
F6	0.50	6.0	44	4250	4110	
G3	0.55	5.5	35	3891	3764	
H3	0.55	6.0	35	3817	3798	
I3	0.55	6.5	35	3748	3780	

Table (3.9) Cont.

Mix No	W/C	TA/C	Temp Tc °C	Experimental Comp. Strength (psi)	Computed Comp. Strength (psi)	95% Confidence Limits
G4	0.55	5.5	38	3688	3705	±176.28
H4	0.55	6.0	38	3750	3739	
I4	0.55	6.5	38	3710	3721	
G5	0.55	5.5	41	3563	3642	
H5	0.55	6.0	41	3685	3676	
I5	0.55	6.5	41	3660	3658	
G6	0.55	5.5	44	3530	3575	
H6	0.55	6.0	44	3547	3608	
I6	0.55	6.5	44	3608	3590	

Table (3.10) : Comparison of Experimental and Computed Values of Concrete Slump.

Mix No	W/C	TA/C	Experimental Slump (In)	Computed Slump (In)	95% Confidence Limits
A1	0.45	4.0	3.000	3.125	± 0.56
B1	0.45	4.5	2.000	1.750	
C1	0.45	5.0	0.250	0.375	
D1	0.50	5.0	2.500	2.500	
E1	0.50	5.5	1.500	1.500	
F1	0.50	6.0	0.500	0.500	
G1	0.55	5.5	6.500	6.125	
H1	0.55	6.0	2.500	3.250	
I1	0.55	6.5	0.750	0.375	

Table 3.11 : F and R-square values of the three models

Model	F-value	R-square
Strength(3.7)	682.866	0.9956
Strength(3.8)	316.571	0.9895
Workability(3.9)	17.72	0.9672

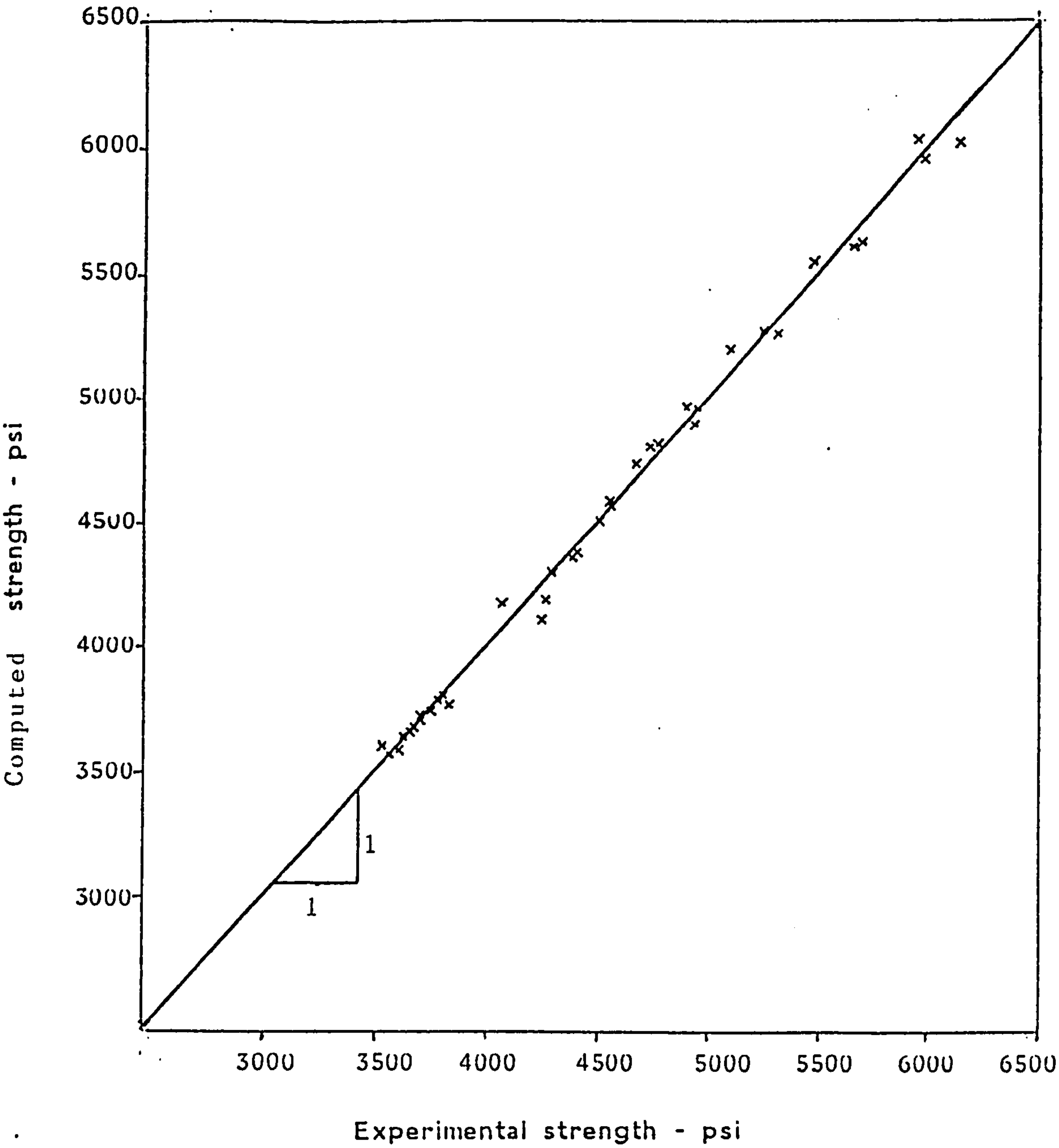

Figure 3.1: Comparison of Computed Strength with Experimental Strength

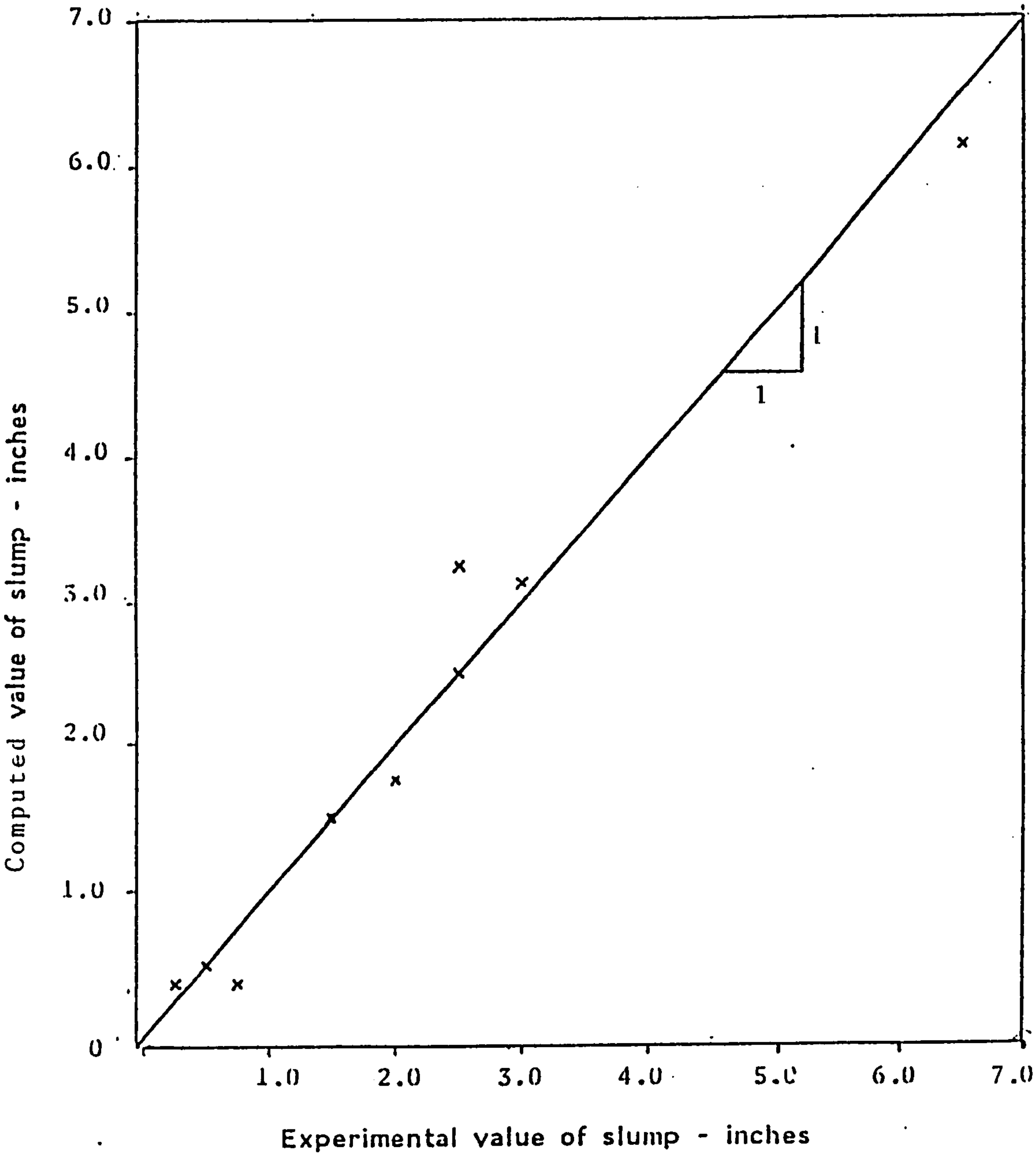

Figure 3.2: Comparison of Computed Slump with Experimental Slump

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 TEST RESULTS

Workability (slump) and compressive strength data for various mixes are given in Tables 4.1 to 4.9. Slump value was measured only once for each mix to evaluate workability. Compressive strength was determined by tests on 3 specimens at the ages of 3, 7 and 14 days and on four specimens at the age of 28 days. The compressive strength is plotted against the age in Figures A.1 to A.54 which are given in Appendix A.

4.2 RESULTS OF ANALYSIS OF VARIANCE

The results of compressive strength given in Tables 4.1 to 4.9 were used as data base for the analysis of variance which consists of two components:

(i) Analysis of variance for W/C ratio and concrete temperature Tc.

(ii) Analysis of variance for TA/C ratio and concrete temperature Tc.

Each of the above components of variance analysis is further subdivided into two groups:

(a) For Specimens prepared and cured in normal laboratory conditions compared to those prepared at normal laboratory conditions but cured in hot weather.

The results of these analyses are given in Tables 4.10 and 4.12 to 4.14 for components (i) and (ii) respectively.

(b) For Specimens prepared and cured in hot weather. The results of these analyses are given in Tables 4.11 and 4.15 to 4.17 for components (i) and (ii) respectively.

4.3 EFFECT OF HOT WEATHER ON COMPRESSIVE STRENGTH OF CONCRETE

4.3.1 Effect of Temperature of Concrete at Placement

The results of the present study show that the 28-day compressive strength of concrete is reduced if concrete is prepared at temperature higher than 26°C under hot weather conditions. This temperature effect on strength is clearly shown in Tables 4.18 through 4.21. These tables show the temperature effect in terms of the ratio of compressive strength(f'c) of the specimens prepared at the experimental concrete temperature(Tc) and cured in hot weather to the compressive strength of the specimens prepared and cured at normal laboratory temperature.

The normal temperature is the usual laboratory temperature taken as 26°C. The hot weather temperature to normal temperature strength ratios are plotted against

concrete temperature in figures 4.1 through 4.9 for various values of W/C and TA/C ratios. These figures clearly show that the strength ratio decreases with increase in concrete temperature. Figure 4.10 shows the same ratios for all the values of W/C and TA/C ratios plotted against Tc. It is clear from this figure that the reduction in compressive strength can be expressed by the following equation

$$R = (1.30\ Tc - 42.1)\% , \quad \text{for } 35°C \leq Tc \leq 44°C$$

The above equation has been obtained from the best fitting line for the data using the computer program SAS. Figure 4.10 shows that the reduction in compressive strength ranges from 4% at 35 °C to 16% at 44 °C.

The above effect of Tc is also confirmed by the results of analysis of variance given in Table 4.11 for the factors W/C and Tc and in Tables 4.15 to 4.17 for the factors TA/C and Tc. These Tables show the highly significant effect of temperature of the mix, Tc, on the compressive strength.

4.3.2 Effect of Additional Mixing Water

The second effect of hot weather is due to extra water required for producing concrete of required workability . Obviously this causes an increase in the initial water cement-ratio and thereby decreases compressive strength. As an example, the extent of this effect can be evaluated by

considering mix A6 which has a net W/C of 0.45 and was prepared at 44 °C. The 28-day compressive strength of this concrete was 4879 psi. The mix A1 having the same proportions which was prepared and cured at 26 °C had 28-day compressive strength of 5937 psi. Therefore, the reduction in strength at 44 °C for mix A6 is 1058 psi.

The amount of extra water added for mix A6 was 0.615 kg. The quantity of cement used in that mix was 12.75 kg. The added amount of water corresponds to an increase in the W/C ratio of 0.049 and accordingly a decrease in compressive strength of about 564 psi at an approximate rate of 115 psi reduction for increase in W/C of 0.01. This means that the reduction in compressive strength due to the extra water required for restoring the workability of mix A6 is about 53% of the total reduction due to hot weather effect.

Similar calculations for another mix E6 show that this mix has a reduction in compressive strength due to extra added water of 710 psi whereas the total reduction in compressive strength due to the effect of hot weather is 779 psi.

It is clear from the above calculations that the additional water required for restoring workability does cause some reduction in strength due to higher water-cement

ratio but this reduction is not consistent for all the mixes. Therefore, it is not necessarily true that the additional water demand is responsible for all the reduction in compressive strength in hot weather conditions.

4.3.3 Effect of Curing Conditions

When curing of concrete is carried out in hot weather conditions, the strength of concrete is adversely affected in two ways. Curing at higher temperature increases the rate of hydration rapidly at early ages, producing protective coating on the hydrating cement grains, and therefore retarding later age rate of hydration(8). This causes reduction in strength. Secondly the amount of water available for hydration is reduced due to rapid evaporation of water from the burlap coverings resulting in insufficient hydration of cement and hence reduction in strength of concrete.

It is generally agreed that within the temperature limits of 0 to 100 °C the chemical and physical characteristics of the products of hydration are not different. This is clearly shown in Figure 4.11 which is reproduced from reference(30). Since no changes in chemical composition or physical structure appear to be responsible for decrease in strength, the decrease in strength is attributed to some factors other than the structure of the gel. Verbeck and Helmuth(30)

attribute the reduction in strength to the heterogeneity of the gel or to its non-uniform distribution in the mass of hardened cement. At lower temperatures hydration is slow and allows the hydration products to diffuse and precipitate relatively uniformly through out the interstitial space between the cement grains. At higher temperatures higher rate of hydration does not allow time for such effective diffusion and there is a tendency for hydration products to precipitate non-uniformly through the space between the cement grains. This results in a highly concentrated and hence weaker gel in the spaces between the grains.

In some investigations(31,32) the reduction in strength due to higher curing temperature is attributed to microcracking caused by the differential expansions of the various constituents of the concrete due to their different coefficients of thermal expansions as given in Table 4.22.

The effect of curing can be clearly seen in Table 4.23 which gives comparison of the compressive strength of the specimens prepared at normal laboratory temperature but cured in hot weather with that of the specimens prepared and cured at normal laboratory temperature. The compressive strength data for the specimens cured in hot weather conditions is expressed as its ratio to the compressive strength of concrete prepared and cured at normal

laboratory temperature. The reduction in compressive strength as given in Table 4.23 ranges from 12% to 16%. This effect is also confirmed by the analysis of variance made in Tables 4.10 and 4.12 to 4.14. It can be seen in these tables that there is a highly significant effect of curing conditions on the strength of concrete.

This effect of curing conditions on the strength of concrete clearly shows that lowering the placement temperature alone does not help in obliterating all the reduction in compressive strength. It is logical to conclude that complying with the commonly recommended practice of lowering the concrete temperature at placement would not completely and adequately eliminate the effect of hot weather on compressive strength. It is necessary to practice good curing characterized by the continuous presence of moisture in the concrete in conjunction with its placement at lower temperature.

4.4 EFFECT OF MIX PROPORTIONS

4.4.1 Effect of Water-cement Ratio (W/C)

4.4.1.1 Effect of W/C Ratio on Compressive Strength

Water-cement ratio is universally recognized as the most important factor in concrete mix design. Its definitive effect on the compressive strength of concrete is well known. When concrete is fully compacted and properly cured

its compressive strength is inversely proportional to the water-cement ratio. This relationship is clearly shown in Table 4.24 for the compressive strength data developed on various concrete mixes tested in this investigation. This effect is further confirmed by the analysis of variance made in Tables 4.10 and 4.11. These data show that water-cement ratio has a highly significant effect on strength of concrete for the mixes prepared at normal laboratory conditions but cured in hot weather as well as for mixes prepared and cured in hot weather. Therefore, the well known W/C ratio law is also valid when concrete is prepared and/or cured in hot weather conditions.

4.4.1.2 Effect of W/C Ratio on Workability

The effect of water-cement ratio on the workability of concrete is shown in Table 4.25 and Figure 4.12. These table and figure show that for any value of TA/C , the slump of a concrete mix increases when its water-cement ratio is increased. The analysis of variance of workability data for W/C and TA/C ratio was not performed because of the missing data on some of the combinations of W/C ratio and TA/C ratio as explained in Section 3.1.

4.4.2 Effect of Total Aggregate-cement Ratio (TA/C)

4.4.2.1 Effect of TA/C Ratio on Compressive Strength

In this investigation, total aggregate-cement ratio (TA/C) showed only a small influence on the compressive strength of concrete. The effect of TA/C on compressive strength is illustrated in Figures 4.13 to 4.16 for specimens prepared and cured in different conditions. In Figure 4.13 a little increase in compressive strength was obtained by lowering the value of TA/C for mixes prepared and cured inside the laboratory in the normal conditions. However for the mixes prepared and cured in hot weather conditions, lowering of TA/C ratio had only a negligible effect on compressive strength. This is clearly shown in Figures 4.14 to 4.16. This is confirmed by the analysis of variance made in Tables 4.15 to 4.17 which show that TA/C ratio has insignificant effect on compressive strength.

The reason for a small increase in strength by lowering TA/C ratio for the specimens prepared and cured inside the laboratory at normal temperature and the absence of this effect for the specimens prepared and cured in hot weather is due to the effect of curing conditions. In the case of the specimens cured inside the laboratory, the hydration of cement is slower. Water is available for hydration and therefore more gel is formed. However, for the specimens

cured in hot weather, the rate of hydration is rapid at early ages, producing protective coating on the hydrating cement grains. As a result some of the cement is still unhydrated and therefore less gel is formed.

The above argument is valid for the specimens cured by covering them in wet burlap and spraying water over the burlap twice a day. The rapid evaporation of water from the specimens in hot weather leaves very little water for hydration as compared to that for the specimens cured at normal laboratory conditions. However, if the specimens are cured at normal laboratory temperature, as in a curing tank, sufficient water is available for hydration of cement and thus the compressive strength of concrete is increased by reducing the TA/C ratio as has been reported in reference(26).

4.4.2.2 Effect of TA/C Ratio on Workability

The effect of TA/C ratio on the workability can be seen in Figure 4.12. For any value of W/C , the slump is increased when TA/C is decreased. The pattern of the curves drawn in this figure shows that the effect of TA/C ratio is more significant for higher levels of W/C ratios.

4.4.3 Effect of Interactions

One of the main advantages of factorial experiments is that the effect of interactions between the factors can be obtained. Interactions are complex relationships among the effects of different factors so that factors are not independent in their effects on the response being measured.

The effect of interaction of the factors W/C ratio and concrete temperature Tc on compressive strength is given by the analysis of variance made in Table 4.11. This analysis shows that the interaction of these factors has a highly significant effect on compressive strength of concrete.

The effect of interaction of the factors TA/C and concrete temperature Tc is given by the analysis of variance made in Tables 4.15 through 4.17. This analysis shows that the interaction of the factors TA/C and Tc has insignificant effect on compressive strength of concrete. This effect is also illustrated in Figures 4.14 through 4.16. In these figures compressive strength versus TA/C was plotted for different concrete temperatures Tc. The parallelism of the curves in these figures shows that the interaction of TA/C and Tc has no significant effect on compressive strength of concrete.

4.5 THE PROPOSED METHOD FOR MIX DESIGN

4.5.1 General

As stated before, the main objective of this study is to develop a suitable method for mix design of concrete prepared and cured in hot weather conditions. In the proposed method based on factorial experimental design, data for workability and compressive strength were obtained by preparing 54 different mixes. The data were used to develop equations (3.8) and (3.9) for predicting compressive strength and workability respectively as given in Section 3.3. The strength equation is in terms of water-cement ratio (W/C), total aggregate-cement ratio (TA/C) and concrete temperature at placement (Tc). The workability equation (3.8) is in terms of W/C ratio and TA/C ratio only. The concrete temperature factor was not included in the workability equation because the required amount of additional mixing water was added to get the same workability of the mixes having the same mix proportions but different temperatures at placement.

For any required values of compressive strength, workability (slump) and expected concrete temperature at placement, the two equations (Eq. 3.8 and 3.9) can be used to determine the required mix proportions i.e effective water-cement ratio (W/C) and total aggregate-cement ratio

(TA/C). For the known optimum value of sand to total aggregate ratio FA/TA (0.37 for this investigation), the coarse to total aggregate ratio (CA/TA) can be calculated. To complete the mix design, the predicted amount of water required to compensate for evaporation of water in hot weather and that for absorption of aggregates should be added to the effective amount of mixing water. In order to determine these mix proportions a computer program was prepared and used as explained in Section 4.5.2.

4.5.2 Computer Program

A computer program has been developed to calculate the proportions of a concrete mix (W/C and TA/C) for the given compressive strength, workability and concrete mix temperature. This program is valid for compressive strength values in the range of 3500 to 6000 psi and for slump in the range of 0 to 6 inches. The program computes the required W/C and TA/C ratios by means of an iterative procedure as shown in the flow chart in Appendix B. The listing of the program is also given in Appendix B.

The input data for the computer program consist of the required compressive strength in psi, the required slump in inches and the expected concrete mix temperature in degrees centigrade. The output of the program consists of the mix proportions in terms of W/C ratio and TA/C ratio and the

calculated compressive strength and slump for these values of mix proportions.

4.5.3 Mix Design Tables

Equations 3.8 and 3.9 for compressive strength and workability developed in Section 3.3 were used to generate Tables for use in concrete mix design for hot weather (Tables 4.26). These tables were prepared using the above mentioned computer program. They can be used to determine the proportions of a concrete mix in terms of water-cement ratio and total aggregate-cement ratio for the desired slump, the compressive strength and the prevailing concrete mix temperature at placement. The tables are suitable for a compressive strength ranging from 3500 to 6000 psi, concrete slump from 0 to 6 inches and concrete mix temperature from 34 °C to 44 °C. An example is given in Appendix C to illustrate the use of these tables.

Table 4.1 : Results of workability and compressive strength for mixes A1-A6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
A1	3.0	3711	3358	3570	4968	4585	4777	5384	5668	5894	6100	5745	5982	5923	5938
A2	3.0	4245	4160	4329	4894	4663	4432	4837	4738	5232	5349	4840	5145	5044	5095
A3	2.75	4571	4995	4524	4759	4759	5000	6018	5560	5674	5955	6014	5716	6133	5955
A4	3.5	4395	4138	4309	4834	4416	4741	5651	5112	5435	5643	5927	5414	5814	5700
A5	2.5	4404	4065	4235	4235	4458	4636	4824	4729	4920	5569	5254	5306	5201	5333
A6	2.5	3713	3538	3362	4275	4188	4624	4509	4927	4463	4904	4707	4756	5149	4879

Table 4.2 : Results of workability and compressive strength for mixes B1-B6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
B1	0.75	4350	4350	4569	5115	4725	4823	5740	5405	5628	5536	5944	5886	5536	5726
B2	0.75	4371	3992	4287	4748	4295	4567	5133	4738	4936	5203	5422	5531	5531	5422
B3	0.50	3992	4203	4371	4760	4665	4854	5603	5338	5074	6330	6023	6207	6023	6145
B4	0.50	3838	3760	4152	4355	4759	4310	4886	4886	5133	6008	5441	5668	5554	5668
B5	0.75	4112	3799	3877	4657	4386	4567	4968	4538	4872	5477	5158	5424	5264	5331
B6	1.0	3678	3327	3538	4305	3974	4140	4386	4617	4801	4943	4992	4745	5091	4943

Table 4.3 : Results of workability and compressive strength for mixes C1-C6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
C1	2.5	3505	3436	3575	4860	4630	4101	5055	4952	5468	5517	5684	5350	5795	5587
C2	2.5	3335	3645	3301	3940	3940	4139	4680	4324	4413	4934	4745	4792	4555	4757
C3	3.0	4264	4015	4181	5298	4840	5196	5750	5203	5531	6585	5747	5807	6286	6106
C4	2.25	4172	3851	4012	4265	4490	4669	5017	4918	5117	5312	5586	5531	5367	5449
C5	3.0	4050	3859	3668	4524	4432	4894	4694	5130	4646	4840	5044	5145	5145	5044
C6	3.0	3309	3309	3476	4413	4076	4160	4788	4509	4695	5133	4738	4985	4936	4948

Table 4.4: Results of workability and compressive strength for mixes D1-D6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
D1	6.5	3046	2782	2987	4012	3629	3859	4636	4279	4458	5349	4840	5145	5044	5095
D2	6.5	2601	2738	2847	3312	3247	3378	4050	3859	3668	4076	4116	3912	4198	4076
D3	7.0	3088	3025	3341	3984	4354	3943	4413	4413	4636	4729	4872	4633	4920	4788
D4	6.5	3343	3088	3152	3771	3552	3698	3973	3629	3897	4827	4554	4599	4508	4622
D5	7.0	3543	3206	3408	3973	3668	3821	3932	4140	4305	4410	4233	4277	4630	4388
D6	6.5	2734	2679	2788	3543	3376	3209	3588	3515	3881	4053	4352	4309	4053	4191

Table 4.5 : Results of workability and compressive strength for mixes E1-E6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
E1	0.5	3242	3543	3209	3940	3940	4139	4881	4509	4602	4658	4854	4953	4953	4855
E2	0.5	2788	2625	2734	3643	3327	3573	4012	3629	3859	4264	4057	4181	4057	4140
E3	0.5	3476	3209	3343	3387	3566	3708	3859	3782	3935	5029	4555	4745	4650	4745
E4	0.75	3408	3248	3087	3432	3362	3713	3860	4218	3820	4696	4423	4651	4514	4571
E5	0.5	2553	2553	2682	3444	3181	3247	4001	3768	3923	4394	4437	4218	4525	4394
E6	0.75	2383	2177	2337	2874	2601	2765	3940	3637	3789	4026	4148	3904	4229	4076

Table 4.6 : Results of workability and compressive strength for mixes F1-F6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
F1	1.5	2994	3152	3278	3956	3877	4034	4590	4374	4157	4968	4777	4824	4585	4789
F2	1.25	2652	2598	2869	3459	3779	3423	3940	3940	4139	4623	4034	4076	4413	4287
F3	2.0	3343	3088	3152	3935	3706	3859	4371	3992	4287	4540	4774	4727	4587	4657
F4	2.0	3176	2873	3055	3576	3301	3439	3872	4076	4239	4287	4467	4558	4558	4468
F5	2.0	3055	2994	3115	3543	3376	3209	3807	3729	4118	4470	4127	4341	4299	4309
F6	2.5	2965	3240	2934	3278	3278	3444	3944	3644	3719	4463	4038	4293	4208	4250

Table 4.7 : Results of workability and compressive strength for mixes G1-G6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
G1	2.5	2360	2223	2314	3145	2873	3085	3678	3327	3538	4331	4374	4157	4460	4331
G2	2.75	2682	2475	2579	2601	2738	2847	3505	3436	3575	3719	3832	3644	3869	3766
G3	2.50	2531	2411	2292	2527	2475	2733	2965	3240	2934	4064	3834	3872	3795	3891
G4	3.0	2111	2111	2218	2874	2655	2710	2984	2811	2926	3707	3558	3595	3892	3688
G5	3.5	2351	2147	2306	3042	2753	2926	3311	3056	3184	3445	3699	3663	3445	3563
G6	3.0	2419	2547	2648	2894	2837	2951	3510	3345	3179	3387	3530	3601	3601	3530

Table 4.8 : Results of workability and compressive strength for mixes H1-H6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Average
H1	0.25	2184	2139	2362	2780	3037	2751	3530	3530	3708	4395	4181	4309	4181	4267
H2	0.25	2674	2470	2525	2951	2780	2894	3476	3175	3409	3888	3521	3668	3594	3668
H3	0.25	2005	1814	1929	2648	2445	2547	2722	2866	2980	3922	3693	3884	3769	3817
H4	0.0	2765	2710	2820	3645	3473	3301	3494	3423	3779	3750	3787	3599	3862	3750
H5	0.25	2378	2599	2353	3143	3143	3301	3601	3327	3395	3639	3749	3528	3823	3685
H6	0.75	2196	2069	2154	3046	2782	2987	3444	3115	3312	3679	3538	3573	3396	3547

Table 4.9 : Results of workability and compressive strength for mixes I1-I6

Mix No	Slump (in)	Compressive Strength - psi													
		3-Day			7-Day			14-Day			28-Day				
		1	2	3	1	2	3	1	2	3	1	2	3	4	Aver--age
I1	2.0	2318	2139	2229	3115	3280	3411	3601	3530	3672	4554	3974	4015	4347	4223
I2	2.0	2362	2251	2139	2527	2475	2733	3181	3476	3148	3552	3735	3698	3588	3643
I3	1.75	2269	2269	2383	3176	2934	2994	3509	3304	3441	3596	3748	3823	3823	3748
I4	1.75	2152	1966	2111	2741	2480	2637	3311	3056	3184	3849	3552	3738	3701	3710
I5	1.5	1814	1910	1986	2411	2364	2459	3037	2894	2751	3844	3477	3697	3624	3660
I6	2.25	2028	1987	2194	2470	2699	2445	2994	2994	3145	3609	3645	3464	3717	3608

Table (4.10): Two Factor Data and Analysis of Variance of Compressive Strength for factors A(W/C) and C(Curing Conditions).

Data

Factor A (W/C)	Factor C (Curing Conditions)	
	c_1	c_2
a_1	22998*	20363
a_2	19648	16668
a_3	17091	14768

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif- -icance (5% level)
A	2	8408064	4204032	536.47	Highly Signif.
C	1	2625536	2625536	335.04	Highly Signif.
A*C	2	26624	13312	1.70	Insignificant
ERROR	18	141056	7836		
TOTAL	23	11201280			

*Each number is sum of 4 values of strength. Each value of strength is an average of 3 observations for 3 TA/C ratios for the same W/C.

Table (4.11): Two Factor Data and Analysis of Variance of Compressive Strength for factors A(W/C) and C(Tc)

Data

Factor A (W/C)	Factor C (Concrete Mix Temperature Tc)			
	c_1	c_2	c_3	c_4
a_1	24275*	22420	20941	19691
a_2	18919	18212	17451	16690
a_3	15272	14862	14542	14246

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif--icance (5% level)
A	2	5356540	12678270	1836.13	Highly Sig.
C	3	2842624	947541	137.23	Highly Sig.
A*C	6	918016	153002	22.15	Significant
ERROR	36	248576	6904		
TOTAL	47	9365760			

*Each number is sum of 4 values of strength. Each value of strength is an average of 3 observations for 3 TA/C ratios for the same W/C.

Table (4.12): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Curing Conditions) for W/C=0.45

Data

Factor B (TA/C)	Factor C (Curing Conditions)	
	c_1	c_2
b_1	23750	20378
b_2	22902	21687
b_3	22346	19026

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif- -incance (5% level)
B	2	756480	378240	11.3	Significant
C	1	2605056	2605056	77.8	Highly Sig.
B*C	2	378368	189184	5.7	Significant
ERROR	18	602624	33479		
TOTAL	23	4342528			

Table (4.13): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Curing Conditions) for W/C=0.50

Data

Factor B (TA/C)	Factor C (Curing Conditions)	
	c_1	c_2
b_3	20378	16302
b_4	19418	16559
b_5	19154	17146

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif- -icance (5%level)
B	2	30976	15488	0.5	Insignif.
C	1	3332352	3332352	103.8	Highly Sig.
B*C	2	269824	134912	4.2	Insignif.
ERROR	18	578048	32113		
TOTAL	23	4211200			

Table (4.14): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Curing Conditions) for W/C=0.55

Data

Factor B (TA/C)	Factor C (Curing Conditions)	
	c_1	c_2
b_4	17322	15064
b_5	17066	14671
b_6	16890	14573

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif-icance (5% level)
B	2	56320	28160	1.1	Insignif.
C	1	2024448	2024448	82.4	Highly Sig.
B*C	2	512	256	0.01	Insignif.
ERROR	18	442112	24562		
TOTAL	23	2523392			

Table (4.15): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Tc) for W/C=0.45

Data

Factor B (TA/C)	Factor C (Concrete Mix Temperature Tc)			
	c_1	c_2	c_3	c_4
b_1	23818	22798	21330	19516
b_2	24583	22671	21323	19771
b_3	24425	21796	20174	19792

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif--icance (5% level)
B	2	147968	73984	1.79	Insignif.
C	3	8763392	2921130	70.76	Highly Sig.
B*C	6	314880	52480	1.27	Insignif.
ERROR	36	1486080	41280		
TOTAL	47	20712320			

Table (4.16): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Tc) for W/C=0.50

Data

Factor B (TA/C)	Factor C (Concrete Mix Temperature Tc)			
	c_1	c_2	c_3	c_4
b_3	19154	18488	17550	16767
b_4	18979	18284	17574	16307
b_5	18628	18870	17237	17002

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif-icance (5% level)
B	2	48640	24320	1.09	Insignif.
c	3	2079232	693077	30.92	Highly Sig.
B*C	6	115968	19328	0.86	Insignif.
ERROR	36	806912	22414		
TOTAL	47	3050752			

Table (4.17): Two Factor Data and Analysis of Variance of Compressive Strength for factors B(TA/C) and C(Tc) for W/C=0.55

Data

Factor B (TA/C)	Factor C (Concrete Mix Temperature Tc)			
	c_1	c_2	c_3	c_4
b_4	15565	14752	14254	14119
b_5	15268	14998	14739	14186
b_6	14990	14840	14642	14435

Analysis of Variance Table for The Above Data

Source of Variation	Degrees of Freedom	Sum of Squares SS	Mean Square MS	Computed F	Signif- -icance (5% level)
B	2	7936	3968	0.26	Insignif.
C	3	436736	145578	9.71	Highly Sig.
B*C	6	87040	14507	0.97	Insignif.
ERROR	36	539648	14990		
TOTAL	47	1071360			

Table(4.18): Comparison of Compressive Strength of The Specimens Prepared at 35°C and Cured in Hot Weather with That of The Specimens Prepared and Cured at Normal Temp.

Mix No	Water-Cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Average Compressive strength		
			at 35°C $f'c(35°C)$ psi	at normal Temp. $f'c(NT)$ psi	$\frac{f'c(35°C)}{f'c(NT)}$
A3	0.45	4.0	5955	5938	1.01
B3	0.45	4.5	6145	5726	1.05
C3	0.45	5.0	6106	5587	1.07
D3	0.50	5.0	4788	5095	0.94
E3	0.50	5.5	4745	4855	0.97
F3	0.50	6.0	4657	4789	0.97
G3	0.55	5.5	3891	4331	0.89
H3	0.55	6.0	3817	4267	0.89
I3	0.55	6.5	3748	4223	0.89

Table(4.19): Comparison of Compressive Strength of The Specimens Prepared at 38°C and Cured in Hot Weather with That of The Specimens Prepared and Cured at Normal Temp.

Mix No	Water-Cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Average Compressive strength		
			at 38 °C f'c(38°C) psi	at normal Temp. f'c(NT) psi	f'c (38°C) / f'c(NT)
A4	0.45	4.0	5700	5938	0.96
B4	0.45	4.5	5668	5726	0.98
C4	0.45	5.0	5449	5587	0.98
D4	0.50	5.0	4622	5095	0.90
E4	0.50	5.5	4571	4855	0.94
F4	0.50	6.0	4468	4789	0.93
G4	0.55	5.5	3688	4331	0.85
H4	0.55	6.0	3750	4267	0.88
I4	0.55	6.5	3710	4223	0.88

Table(4.20): Comparison of Compressive Strength of The Specimens Prepared at 41C and Cured in Hot Weather with That of The Specimens Prepared and Cured at Normal Temp.

Mix No	Water-Cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Average Compressive strength		
			at 41°C $f'C(41°C)$ psi	at normal Temp. $f'c(NT)$ psi	$\frac{f'c(41°C)}{f'c(NT)}$
A5	0.45	4.0	5333	5938	0.90
B5	0.45	4.5	5331	5726	0.93
C5	0.45	5.0	5044	5587	0.90
D5	0.50	5.0	4388	5095	0.86
E5	0.50	5.5	4394	4855	0.90
F5	0.50	6.0	4309	4789	0.90
G5	0.55	5.5	3563	4331	0.82
H5	0.55	6.0	3685	4267	0.86
I5	0.55	6.5	3660	4223	0.87

Table(4.21): Comparison of Compressive Strength of The Specimens Prepared at 44°C and Cured in Hot Weather with That of The Specimens Prepared and Cured at Normal Temp.

Mix No	Water-Cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Average Compressive strength		
			at 44°C f'c(44°C) psi	at normal temp. f'c(NT) psi	$\frac{f'c(44°C)}{f'c(NT)}$
A6	0.45	4.0	4879	5938	0.82
B6	0.45	4.5	4943	5726	0.86
C6	0.45	5.0	4948	5587	0.88
D6	0.50	5.0	4191	5095	0.82
E6	0.50	5.5	4076	4855	0.83
F6	0.50	6.0	4250	4789	0.88
G6	0.55	5.5	3530	4331	0.82
H6	0.55	6.0	3547	4267	0.83
I6	0.55	6.5	3608	4223	0.85

Table 4.22 : Coefficients of Thermal Expansions of Constituents of Concrete*

Constituent	Coefficient 10^{-6} per deg C
Cement Paste	10.8 - 19.8
Aggregates	3.0 - 7.0

* Adopted from reference (33).

Table 4.23 : Comparison of Compressive Strength of The Specimens Prepared at Normal Temperature and Cured in Hot Weather with That of The Specimens Prepared and Cured at Normal Temperature

Mix No	Water-Cement Ratio (W/C)	Total Agg. to Cement Ratio (TA/C)	Average Compressive Strength		
			Cured in Hot Weather f'c(HW)	Cured at Normal Temperature f'c(NT)	$\frac{f'c(HW)}{f'c(NT)}$
A2	0.45	4.0	5095	5938	0.86
B2	0.45	4.5	5422	5726	0.94
C2	0.45	5.0	4757	5587	0.85
D2	0.50	5.0	4076	5095	0.80
E2	0.50	5.5	4140	4855	0.84
F2	0.50	6.0	4287	4789	0.90
G2	0.55	5.5	3766	4331	0.87
H2	0.55	6.0	3668	4267	0.86
I2	0.55	6.5	3643	4223	0.86

Table 4.24 : Comparison of Compressive Strength Versus W/C Ratio for Different TA/C Ratios and Different Conditions of Preparation and Curing.

TA/C=5.0		TA/C=5.5		TA/C=6.0		Mix Temp C	Place of Prep.	Place of Curing
W/C= 0.45	W/C= 0.50	W/C= 0.50	W/C= 0.55	W/C= 0.50	W/C= 0.55			
Compressive Strength psi								
5673	5095	4904	4331	4777	4267	26	Inside	Inside
4757	4176	4140	3766	4203	3668	26	Inside	Outside
6106	4788	4745	3891	4657	3817	35	Outside	Outside
5449	4622	4571	3688	4468	3750	38	Outside	Outside
5044	4388	4394	3563	4309	3685	41	Outside	Outside
4948	4191	4076	3530	4077	3547	44	Outside	Outside

Table 4.25 : Comparison of Slump of Concrete for Various Values of W/C and TA/C Ratios.

W/C	TA/C					
	4.0	4.5	5.0	5.5	6.0	6.5
	Slump (in)					
0.45	3.0	2.0	0.25			
0.50			2.5	1.5	0.75	
0.55				6.5	2.5	0.50

Table 4.26 : Mix Design Tables

Compressive Strength = 3500 psi and Temperature = 34°C

Calc. Slump(in)	1.1		2.0		3.1		4.1		5.1		6.0	
Calc. Strength	3529.1		3527.9		3522.8		3515.2		3502.5		3587.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.565	6.38	0.565	6.26	0.565	6.12	0.565	6.00	0.565	5.86	0.560	5.68

Compressive Strength = 3500 psi and Temperature = 36°C

Calc. Slump(in)	1.1		2.0		3.1		4.1		5.1		6.0	
Calc. Strength	3529.0		3527.8		3522.6		3515.0		3502.3		3574.4	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.565	6.38	0.565	6.26	0.565	6.12	0.565	6.00	0.565	5.86	0.560	5.68

Compressive Strength = 3500 psi and Temperature = 38°C

Calc. Slump(in)	1.1		2.0		3.1		4.1		5.1		6.0	
Calc. Strength	3523.2		3522.0		3516.8		3509.1		3572.3		3557.4	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.565	6.38	0.565	6.26	0.565	6.12	0.565	6.00	0.560	5.82	0.560	5.68

Table 4.26 Cont.

Compressive Strength = 3500 psi and Temperature = 40°C

Calc. Slump(in)	1.1	2.0	3.1	4.1	5.1	6.0
Calc. Strength	3511.7	3510.5	3505.3	3561.8	3550.8	3535.8
Mix	W/C. TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C
Proportions	0.565 6.38	0.565 6.26	0.565 6.12	0.560 5.96	0.560 5.82	0.560 5.68

Compressive Strength = 3500 psi and Temperature = 42°C

Calc. Slump(in)	1.1	2.1	3.1	4.1	5.1	6.0
Calc. Strength	3544.6	3545.7	3542.8	3535.8	3524.8	3509.9
Mix	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C
Proportions	0.560 6.38	0.560 6.24	0.560 6.1	0.560 5.96	0.560 5.82	0.560 5.68

Compressive Strength = 3500 psi and Temperature = 44°C

Calc. Slump(in)	1.1	2.1	3.1	4.1	5.0	6.1
Calc. Strength	3514.3	3515.5	3512.5	3505.5	3543.7	3527.4
Mix	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C	W/C TA/C
Proportions	0.560 6.38	0.560 6.24	0.560 6.10	0.560 5.96	0.555 5.76	0.555 5.60

Table 4.26 Cont.

Compressive Strength = 4000 psi and Temperature = 34°C

Calc. Slump(in)	1.0		2.1		3.1		4.0		5.0		6.0	
Calc. Strength	4090.8		4011.8		4018.6		4016.1		4003.7		4079.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.535	6.34	0.540	6.14	0.540	5.92	0.540	5.72	0.540	5.50	0.535	5.14

Compressive Strength = 4000 psi and Temperature = 36C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4015.1		4036.7		4046.3		4044.1		4030.0		4004.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.535	6.34	0.535	6.10	0.535	5.86	0.535	5.62	0.535	5.38	0.535	5.14

Compressive Strength = 4000 psi and Temperature = 38C

Calc. Slump(in)	1.1		2.0		3.1		4.0		5.1		6.0	
Calc. Strength	4016.4		4042.4		4054.7		4051.6		4032.7		4000.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.530	6.30	0.530	6.04	0.530	5.76	0.530	5.50	0.530	5.22	0.530	4.96

Table 4.26 Cont.

Compressive Strength = 4000 psi and Temperature = 40°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.1	
Calc. Strength	4000.9		4033.1		4046.7		4041.8		4018.3		4021.2	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.525	6.26	0.525	5.96	0.525	5.66	0.525	5.36	0.525	5.06	0.520	4.50

Compressive Strength = 4000 psi and Temperature = 42°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.1		6.0	
Calc. Strength	4041.5		4012.8		4026.7		4016.7		4030.4		4104.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.515	6.12	0.520	5.86	0.520	5.52	0.520	5.18	0.515	4.60	0.475	2.18

Compressive Strength = 4000 psi and Temperature = 44°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4007.2		4051.6		4059.[illegible]		4031.0		4001.6		4091.8	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.510	6.02	0.510	5.60	0.510	5.18	0.510	4.76	0.500	3.74	0.470	2.22

Table 4.26 Cont.

Compressive Strength = 4500 psi and Temperature = 34°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4502.9		4544.9		4557.0		4539.3		4575.9		4514.9	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.515	6.12	0.515	5.74	0.515	5.36	0.515	4.98	0.510	4.34	0.505	3.58

Compressive Strength = 4500 psi and Temperature = 36°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4587.7		4522.9		4530.8		4502.4		4548.1		4536.8	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.505	5.88	0.510	5.60	0.510	5.18	0.510	4.76	0.500	3.74	0.480	2.22

Compressive Strength = 4500 psi and Temperature = 38°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4545.5		4585.4		4573.7		4510.4		4518.2		4643.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.500	5.74	0.500	5.24	0.500	4.74	0.500	4.24	0.485	2.94	0.470	2.22

Table 4.26 Cont.

Compressive Strength = 4500 psi and Temperature = 40°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4593.4		4530.7		4504.4		4530.0		4520.8		4637.0	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.490	5.40	0.495	5.04	0.495	4.50	0.485	3.50	0.475	2.72	0.465	2.34

Compressive Strength = 4500 psi and Temperature = 42°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4532.7		4546.9		4567.3		4532.5		4626.8		4645.9	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.485	5.22	0.485	4.64	0.480	3.92	0.475	3.28	0.465	2.82	0.460	2.52

Compressive Strength = 4500 psi and Temperature = 44°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	4549.4		4553.0		4581.3		4593.2		4609.0		4651.6	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.475	4.92	0.475	4.38	0.470	3.78	0.465	3.32	0.460	2.96	0.455	2.72

Table 4.26 Cont.

Compressive Strength = 5000 psi and Temperature = 34°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5119.4		5022.8		5103.4		5089.9		5006.5		5103.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.490	5.40	0.495	5.04	0.490	4.28	0.485	3.50	0.480	2.78	0.470	2.22

Compressive Strength = 5000 psi and Temperature = 36°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5049.2		5063.3		5011.1		5109.1		5083.2		5081.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.485	5.22	0.485	4.64	0.485	4.08	0.475	3.28	0.470	2.74	0.465	2.34

Compressive Strength = 5000 psi and Temperature = 38°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5075.1		5078.7		5018.9		5025.8		5031.8		5069.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.475	4.92	0.475	4.38	0.475	3.82	0.470	3.26	0.465	2.82	0.460	2.52

Table 4.26 Cont.

Compressive Strength = 5000 psi and Temperature = 40°C

Calc. Slump (in	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5071.5		5082.6		5044.6		5095.4		5158.1		5050.2	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.465	4.78	0.465	4.28	0.465	3.80	0.460	3.40	0.455	3.12	0.455	2.72

Compressive Strength = 5000 psi and Temperature = 42°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.1		6.0	
Calc. Strength	5047.6		5073.4		5066.0		5025.7		5097.5		5022.4	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.455	4.74	0.455	4.34	0.455	3.94	0.455	3.54	0.450	3.30	0.450	2.94

Compressive Strength = 5000 psi and Temperature = 44°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5001.3		5041.3		5060.6		5057.0		5032.3		5120.4	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Prop.	0.445	4.80	0.445	4.48	0.445	4.14	0.445	3.82	0.445	3.50	0.440	3.38

Table 4.26 Cont.

Compressive Strength = 5500 psi and Temperature = 34°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5510.5		5514.2		5592.6		5654.7		5515.1		5576.8	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.475	4.92	0.475	4.38	0.470	3.78	0.465	3.32	0.465	2.82	0.460	2.52

Compressive Strength = 5500 psi and Temperature = 36°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	5515.6		5526.7		5626.9		5560.8		5644.9		5536.9	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.465	4.78	0.465	4.28	0.460	3.86	0.460	3.40	0.455	3.12	0.455	2.72

Compressive Strength = 5500 psi and Temperature = 38°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.1		6.1	
Calc. Strength	5589.6		5516.0		5508.7		5609.3		5559.1		5666.6	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.450	4.76	0.455	4.34	0.455	3.94	0.450	3.68	0.450	3.30	0.445	3.16

Table 4.26 Cont.

Compressive Strength = 5500 psi and Temperature = 40°C

Calc. Slump(in)	1.0		2.1		3.0		4.1		5.0		6.0	
Calc. Strength	5515.8		5562.4		5589.2		5599.9		5593.1		5567.9	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.440	4.84	0.440	4.54	0.440	4.26	0.440	3.96	0.440	3.68	0.440	3.38

Compressive Strength = 5500 psi and Temperature = 42°C

Calc. Slump(in)	1.1		2.0		3.1		4.0		5.1		6.0	
Calc. Strength	5551.8		5536.5		5512.3		5539.9		5558.6		5565.3	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.420	5.02	0.425	4.78	0.430	4.46	0.430	4.24	0.430	4.00	0.430	3.78

Compressive Strength = 5500 psi and Temperature = 44°C

Calc. Slump(in)	1.0		2.1		3.0		4.1		5.1		6.0	
Calc. Strength	5517.9		5520.5		5515.3		5507.9		5541.9		5503.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.400	5.20	0.405	5.02	0.410	4.82	0.415	4.56	0.415	4.40	0.420	4.10

Table 4.26 Cont.

Compressive Strength = 6000 psi and Temperature = 34°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.1		6.0	
Calc. Strength	6021.3		6047.0		6039.7		6164.2		6113.9		6038.8	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.455	4.74	0.455	4.34	0.455	3.94	0.450	3.68	0.450	3.30	0.450	2.94

Compressive Strength = 6000 psi and Temperature = 36°C

Calc. Slump(in)	1.0		2.0		3.0		4.0		5.0		6.0	
Calc. Strength	6066.6		6001.9		6021.3		6017.7		6143.9		6118.8	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.440	4.84	0.445	4.48	0.445	4.14	0.445	3.82	0.440	3.68	0.440	3.38

Compressive Strength = 6000 psi and Temperature = 38°C

Calc. Slump(in)	1.0		2.0		3.1		4.0		5.1		6.0	
Calc. Strength	6041.2		6007.6		6049.1		6076.7		6095.4		6102.1	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.425	4.98	0.430	4.70	0.430	4.46	0.430	4.24	0.430	4.00	0.430	3.78

Table 4.26 Cont.

Compressive Strength = 6000 psi and Temperature = 40°C

Calc. Slump(in)	1.0		2.1		3.0		4.1		5.1		6.0	
Calc. Strength	6029.1		6016.3		6060.6		6036.9		6070.9		6015.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.405	5.16	0.410	4.96	0.410	4.82	0.415	4.56	0.415	4.40	0.420	4.10

Compressive Strength = 6000 psi and Temperature = 42°C

Calc. Slump(in)	1.1		2.1		3.1		4.2		5.0		6.1	
Calc. Strength	6022.4		6010.3		6057.4		6049.5		6029.9		6016.3	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.380	5.32	0.385	5.20	0.385	5.10	0.390	4.94	0.395	4.78	0.400	4.56

Compressive Strength = 6000 psi and Temperature = 44°C

Calc. Slump(in)	1.1		2.1		3.3		4.2		5.1		6.1	
Calc. Strength	6011.9		6002.7		6000.8		6036.4		6026.0		6019.7	
Mix	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C	W/C	TA/C
Proportions	0.350	5.46	0.355	5.38	0.360	5.28	0.360	5.22	0.365	5.12	0.370	5.00

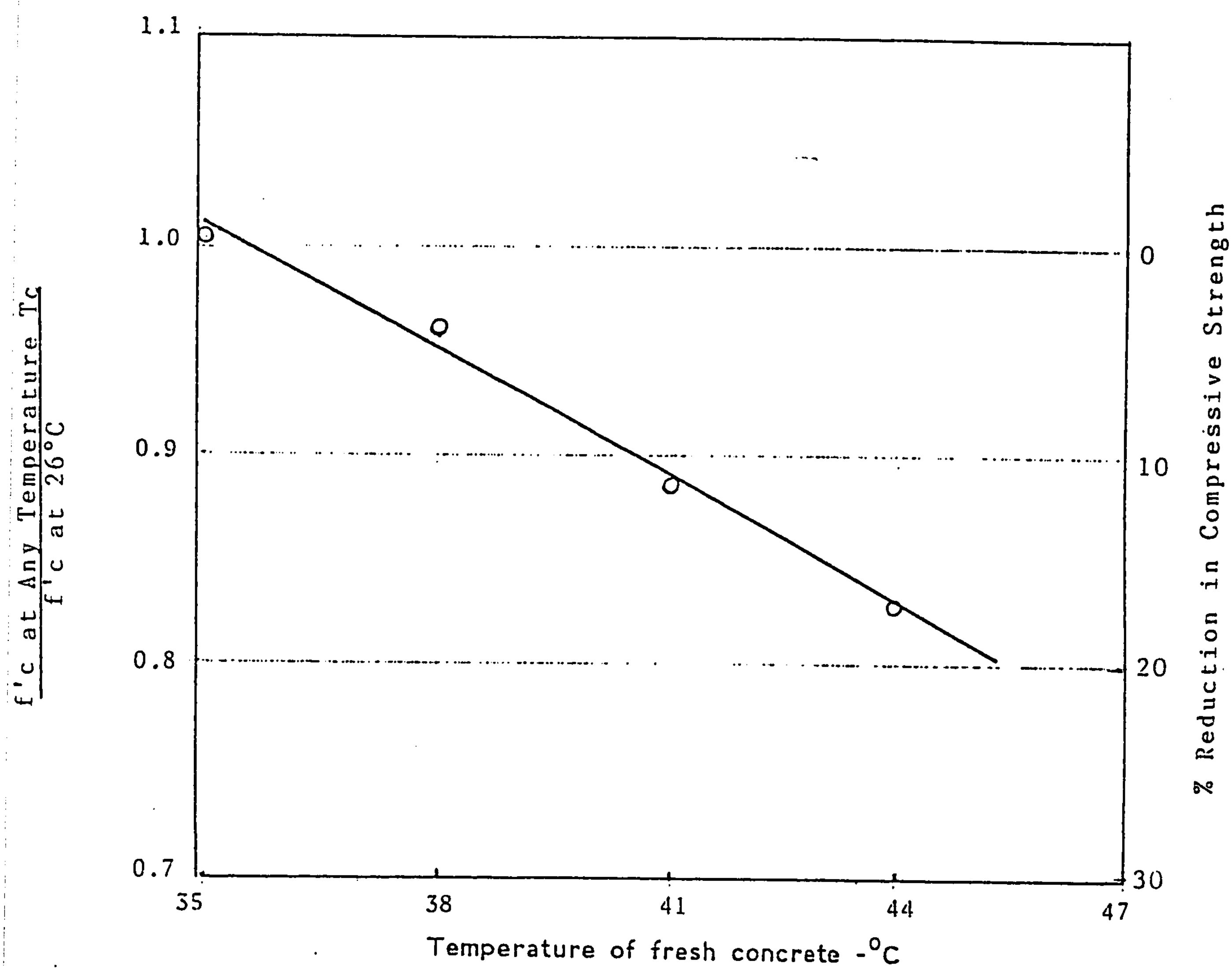

Figure 4.1: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.45 & TA/C=4.0

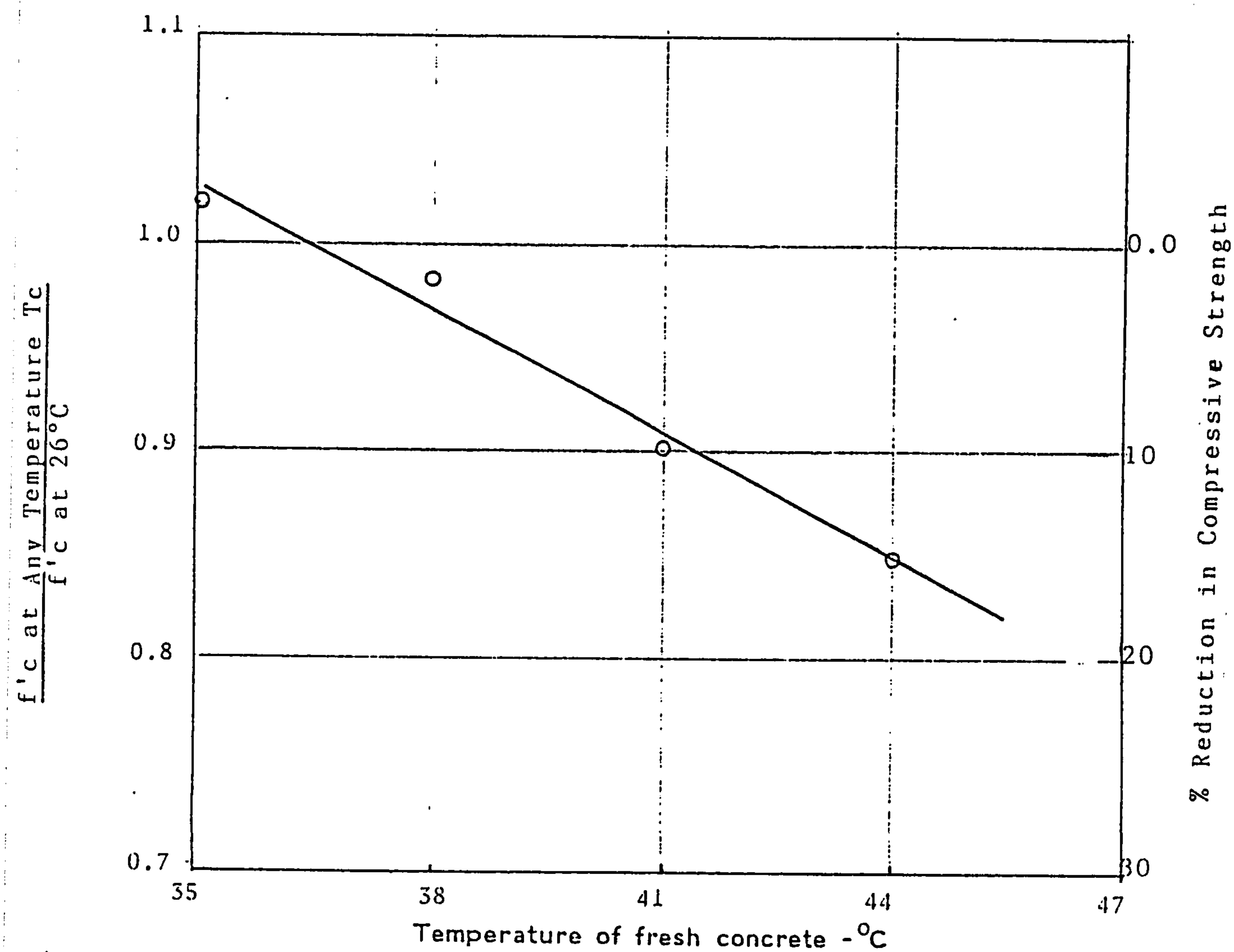

Figure 4.2: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.45 & TA/C=4.5

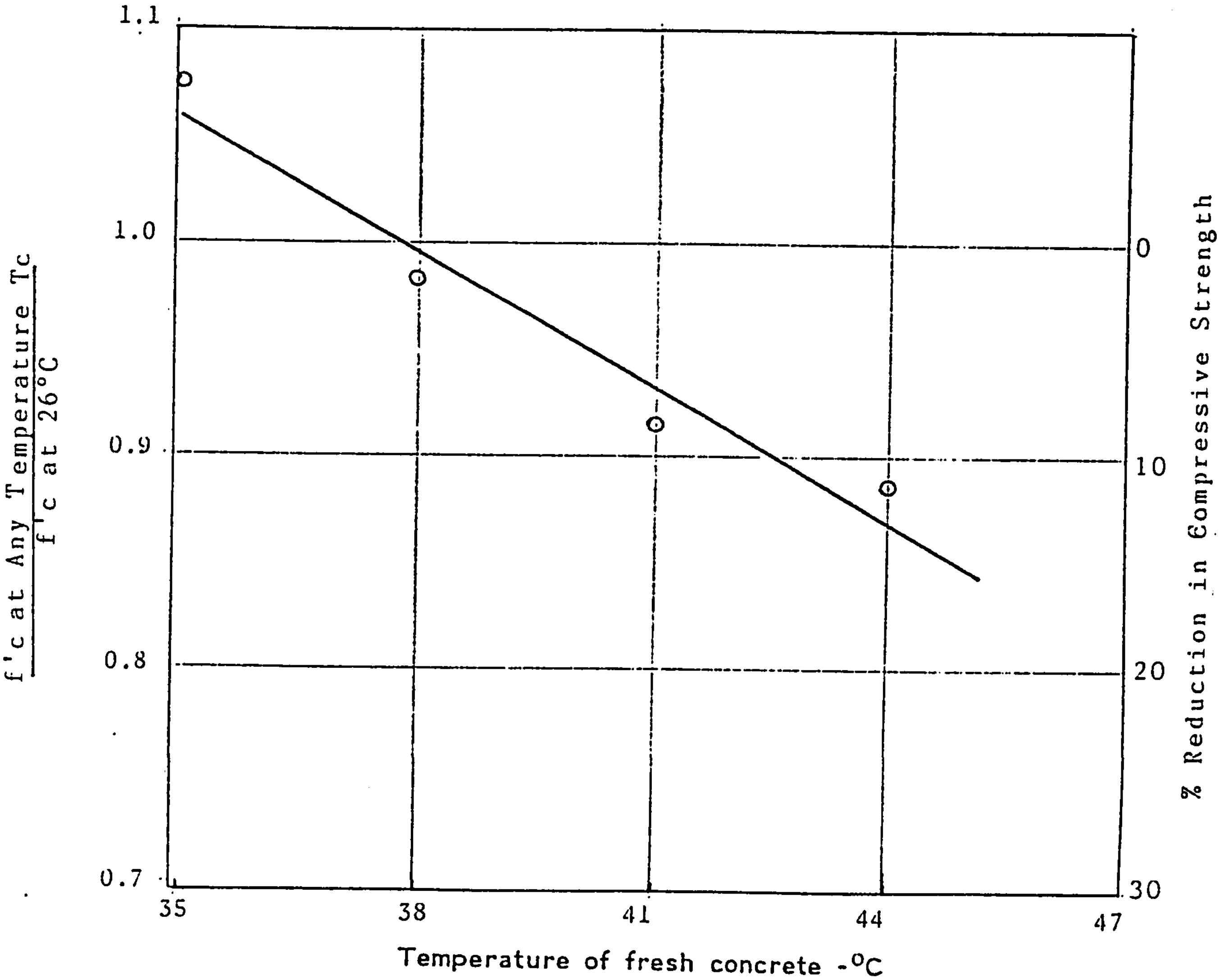

Figure 4.3: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.45 & TA/C=5.0

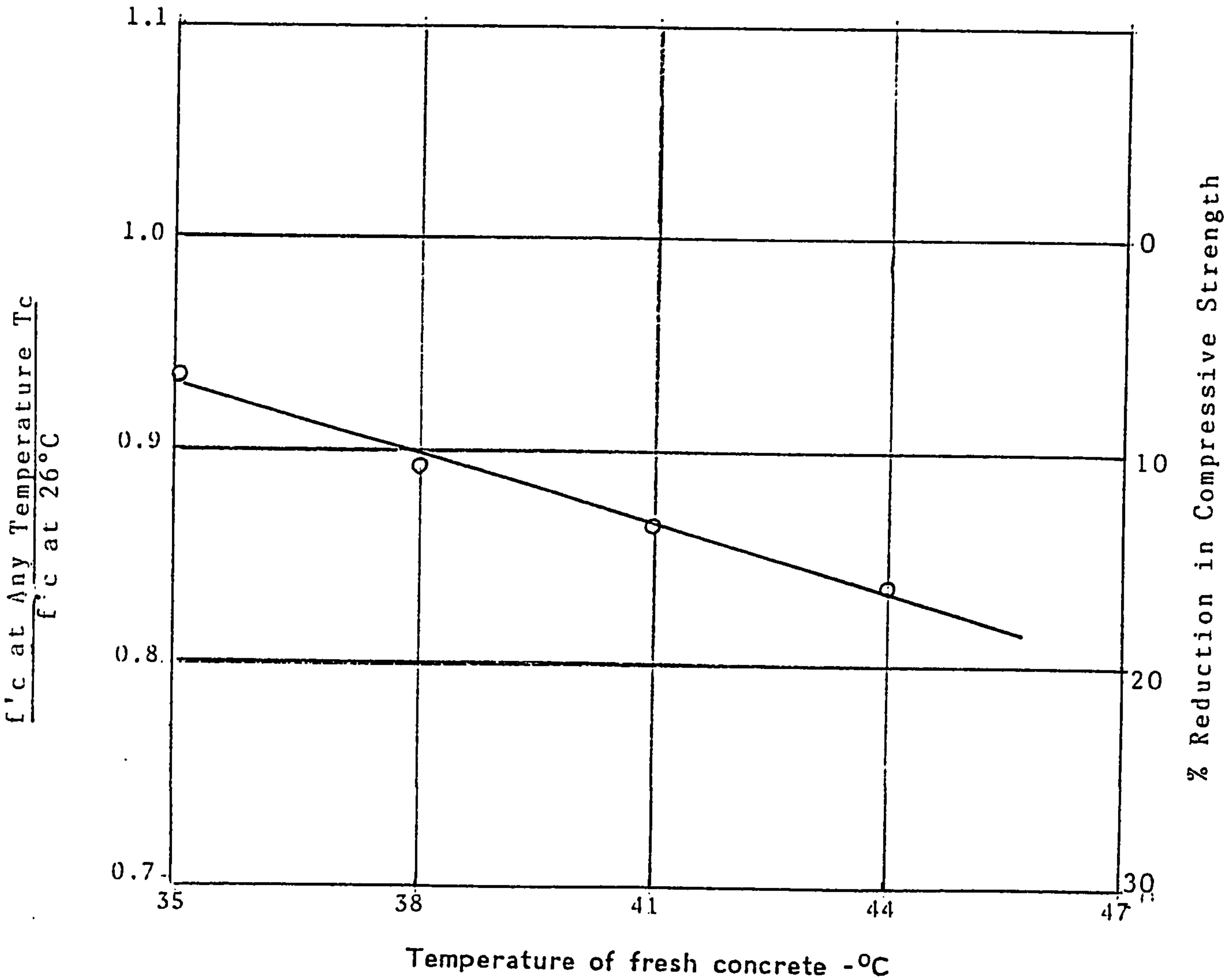

Figure 4.4: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.50 & TA/C=5.0

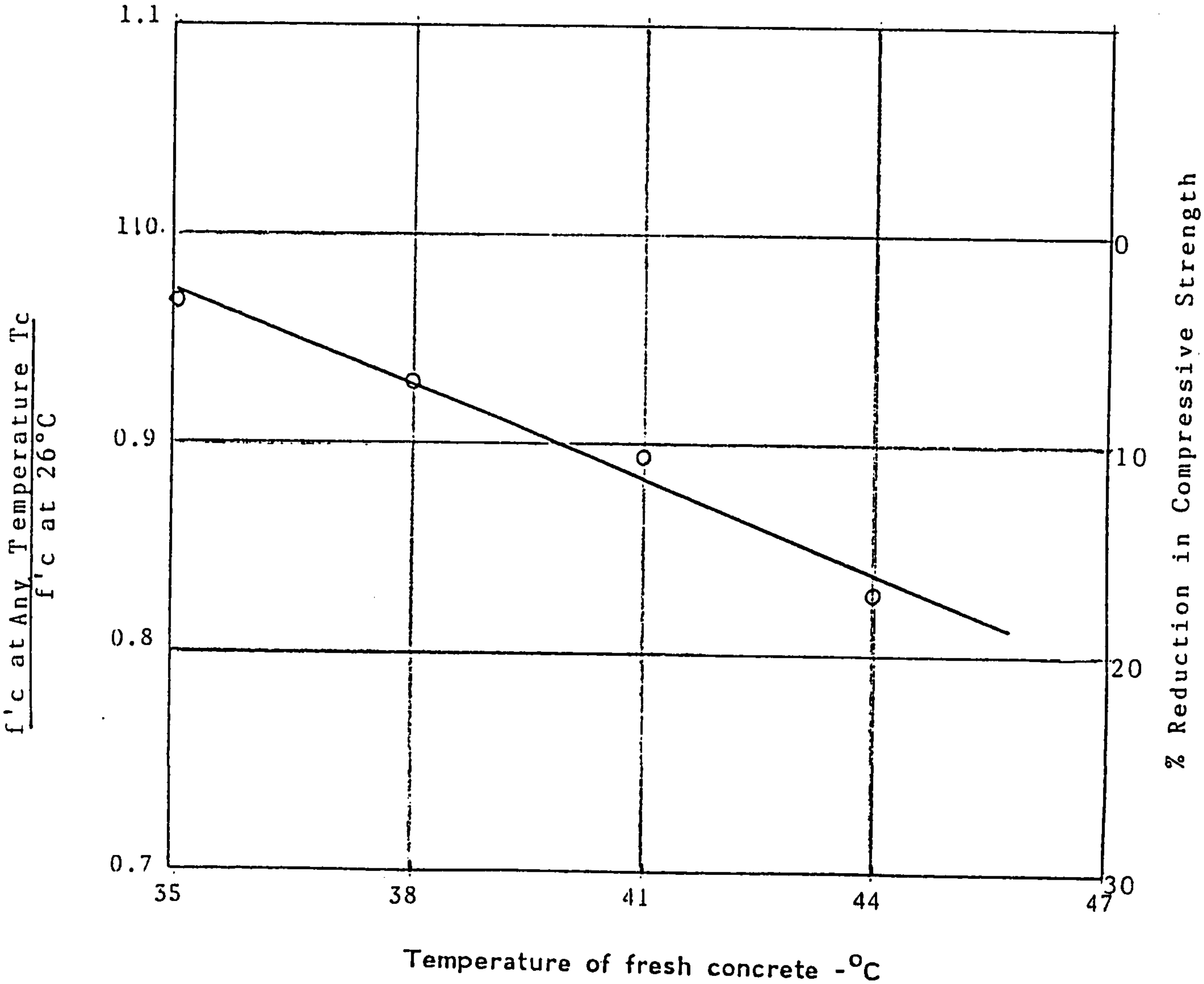

Figure 4.5: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.50 & TA/C=5.5

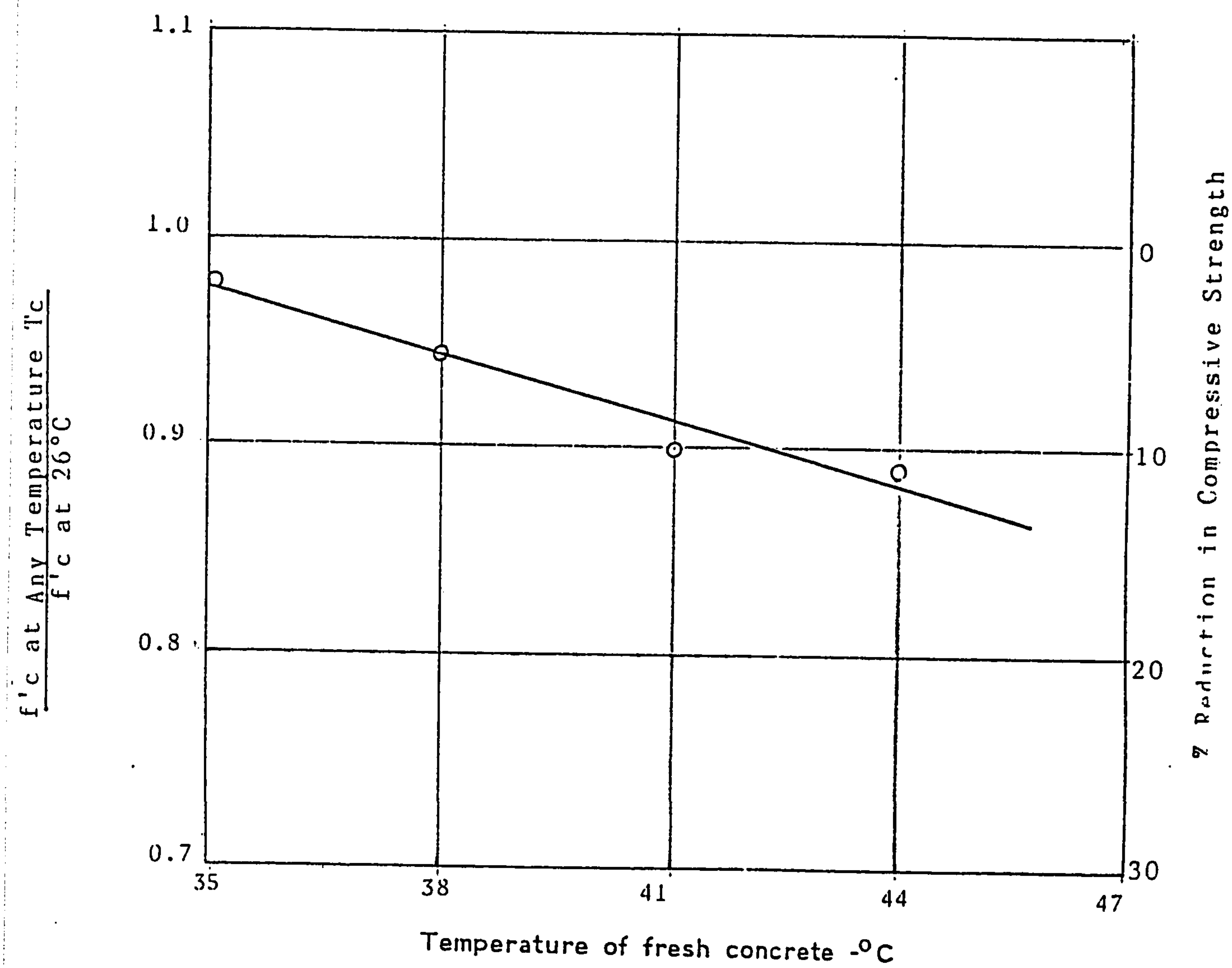

Figure 4.6: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.50 & TA/C=6.0

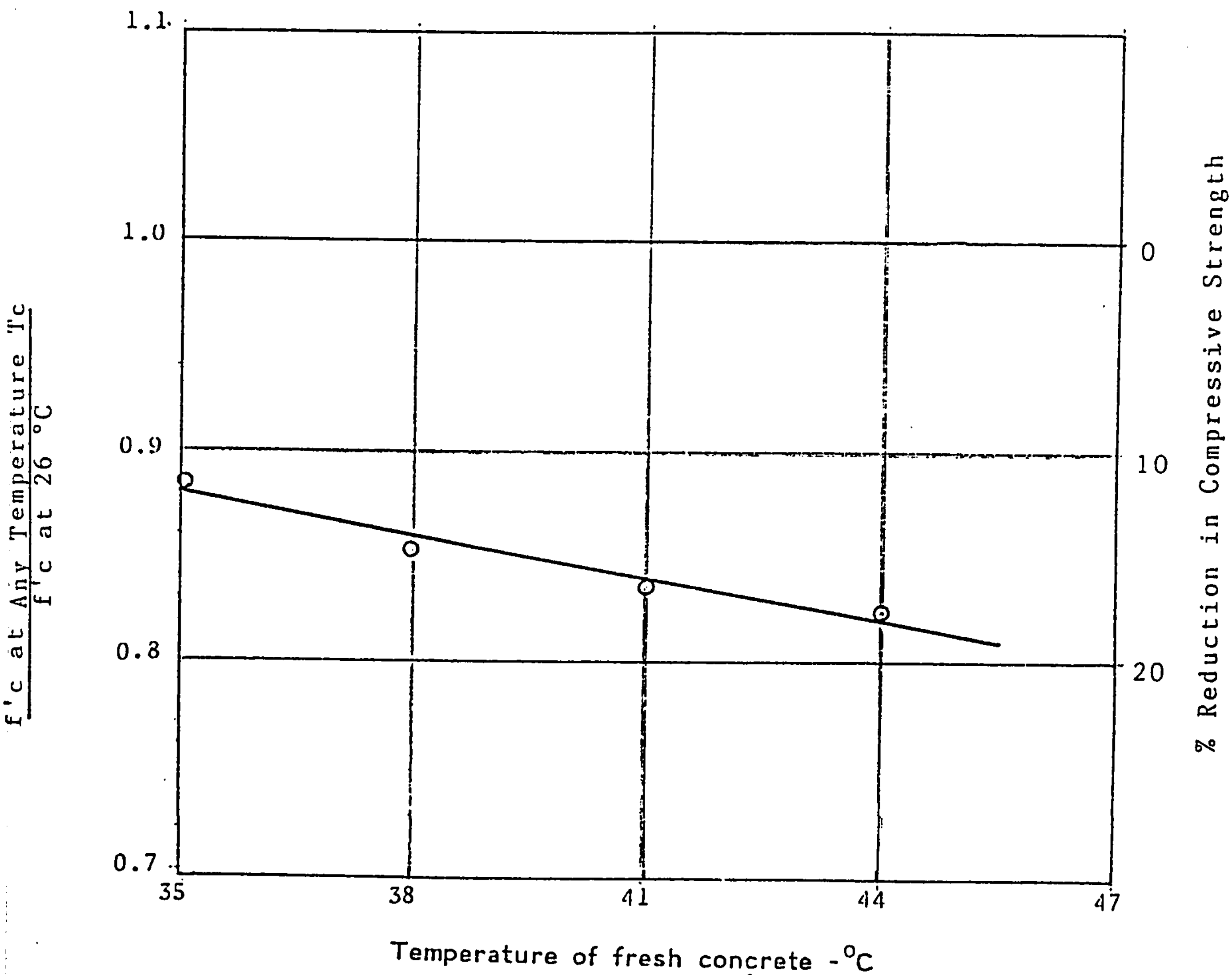

Figure 4.7: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.55 & TA/C=5.5

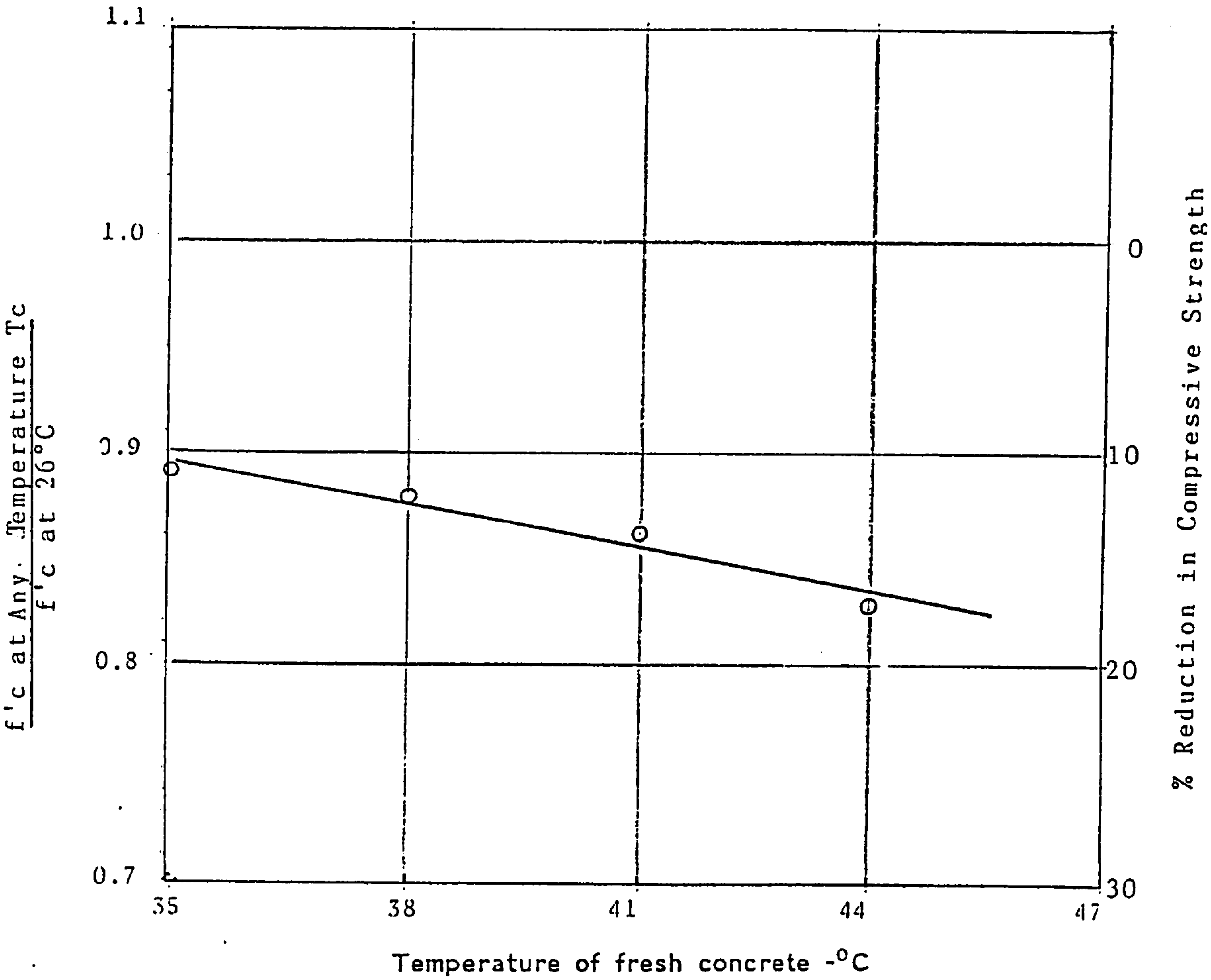

Figure 4.8: Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.55 & TA/C=6.0

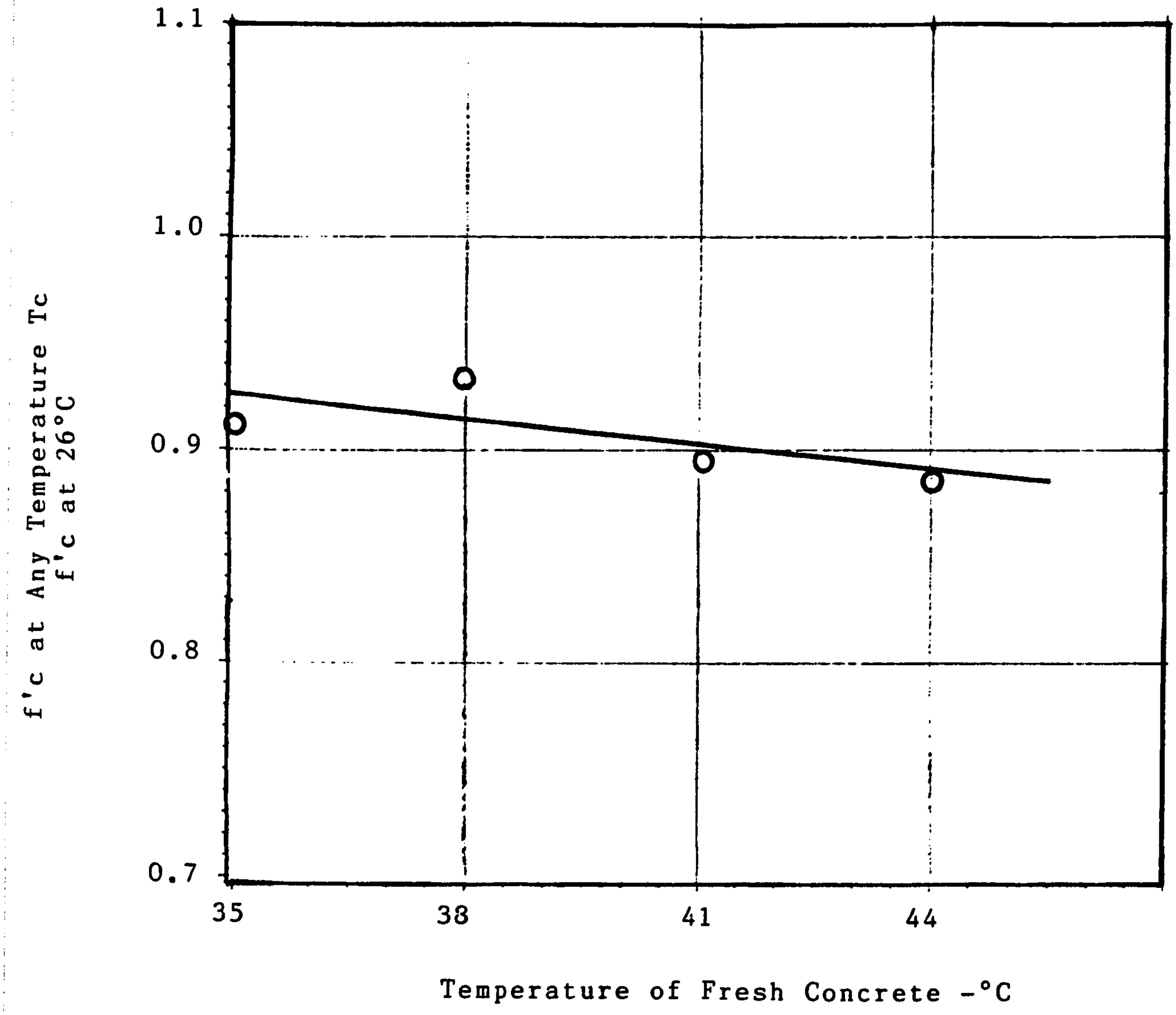

Figure 4.9 : Relationship between Compressive Strength and Concrete Mix Temperature at Placement for W/C=0.55 & TA/C=6.5

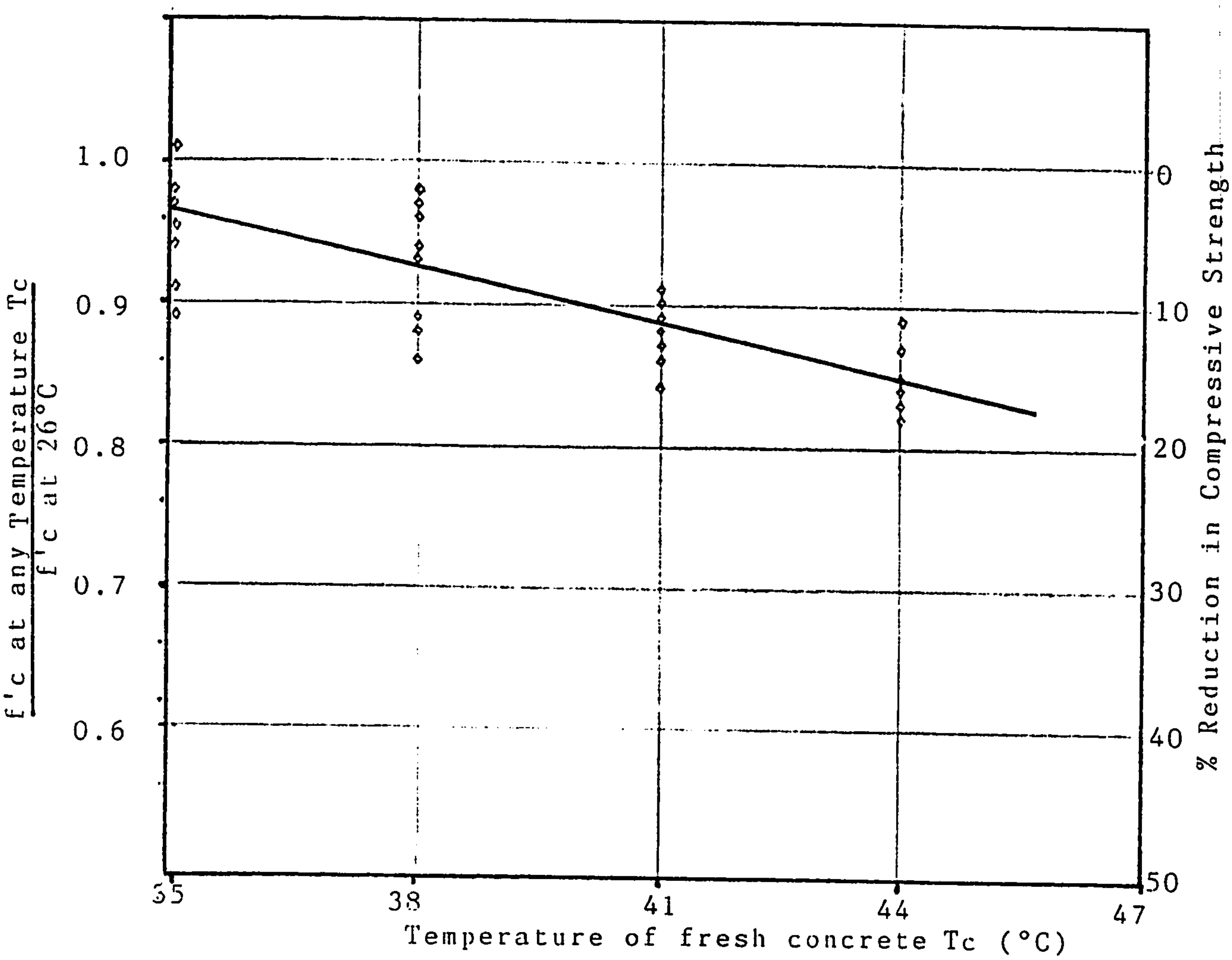

Figure 4.10 : Comparison of Compressive Strength Versus Temperature for All Mixes

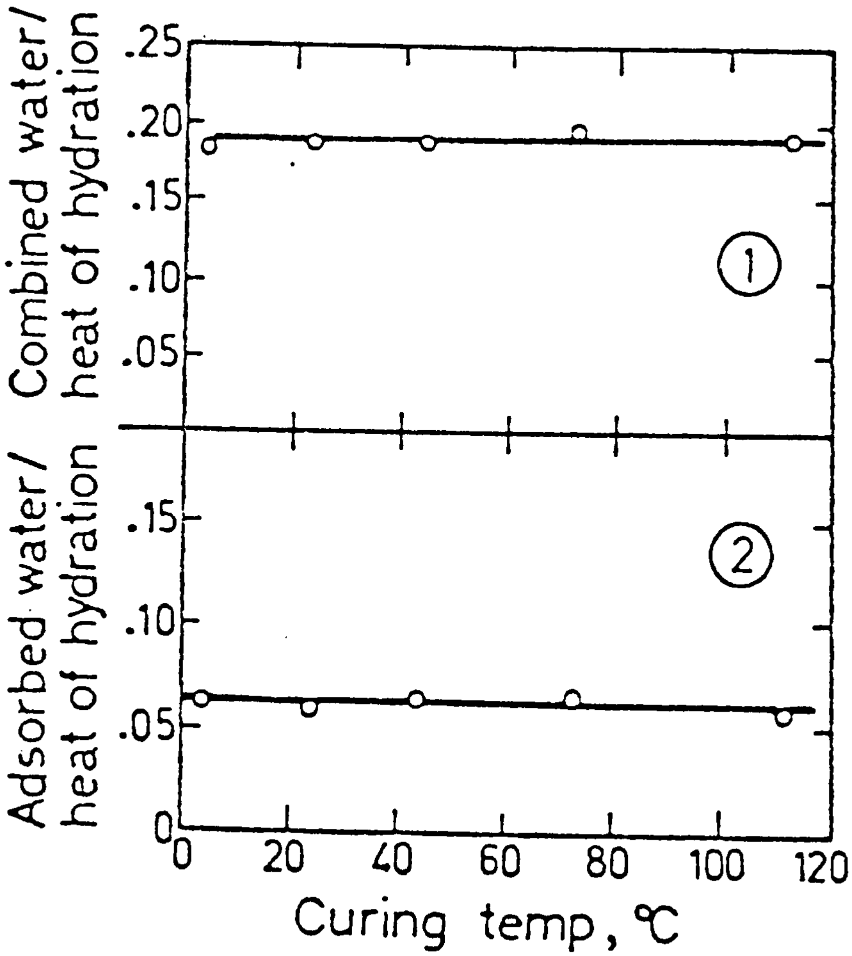

Figure 4.11: Effect of Curing Temperature on Ratio of (1) Combined Water to Heat of Hydration and (2) Adsorbed Water to Heat of Hydration

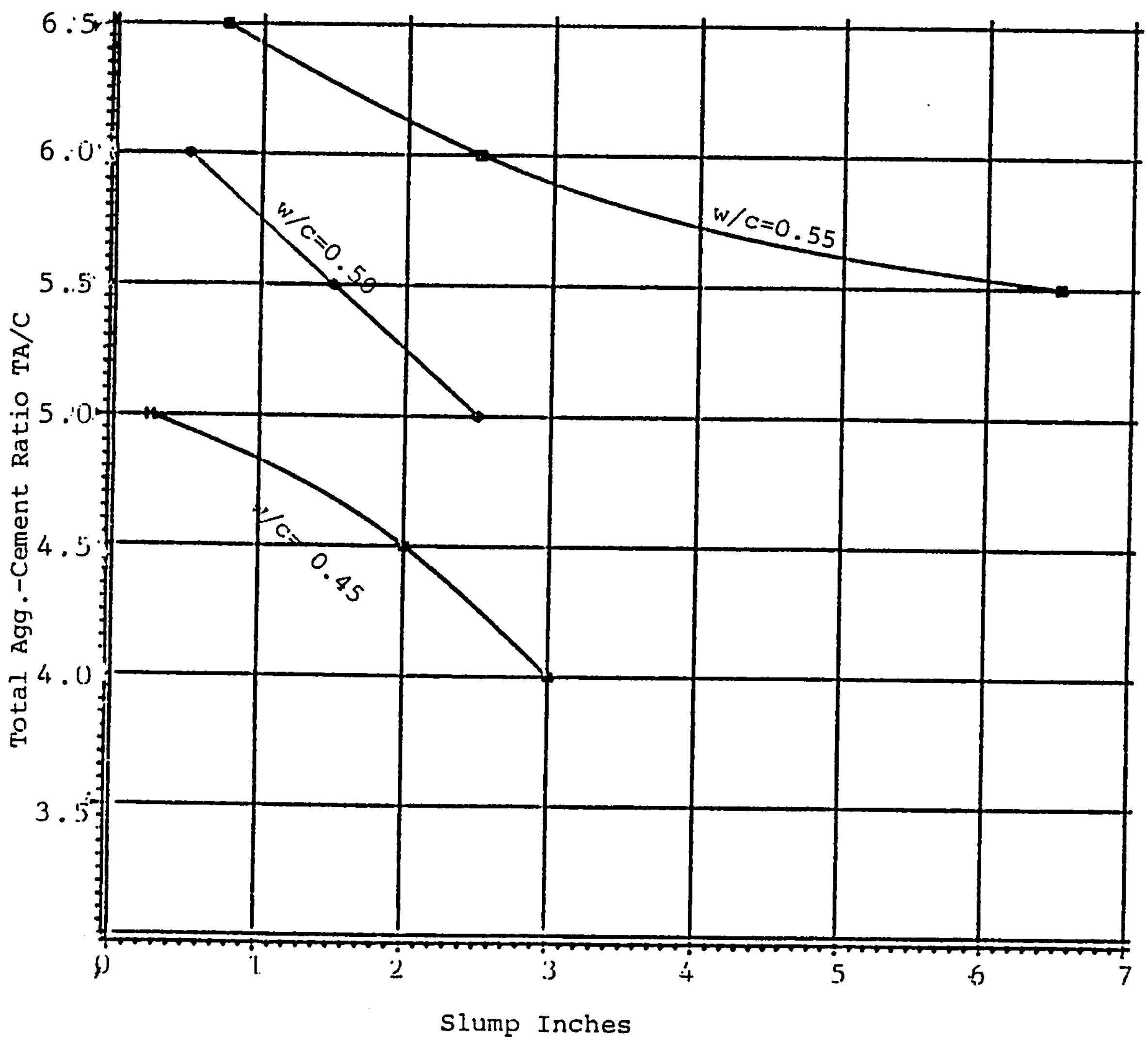

Figure 4.12:Variation of Concrete Slump with Total Agg.-Cement Ratio for Different Values of Water-Cement Ratio.

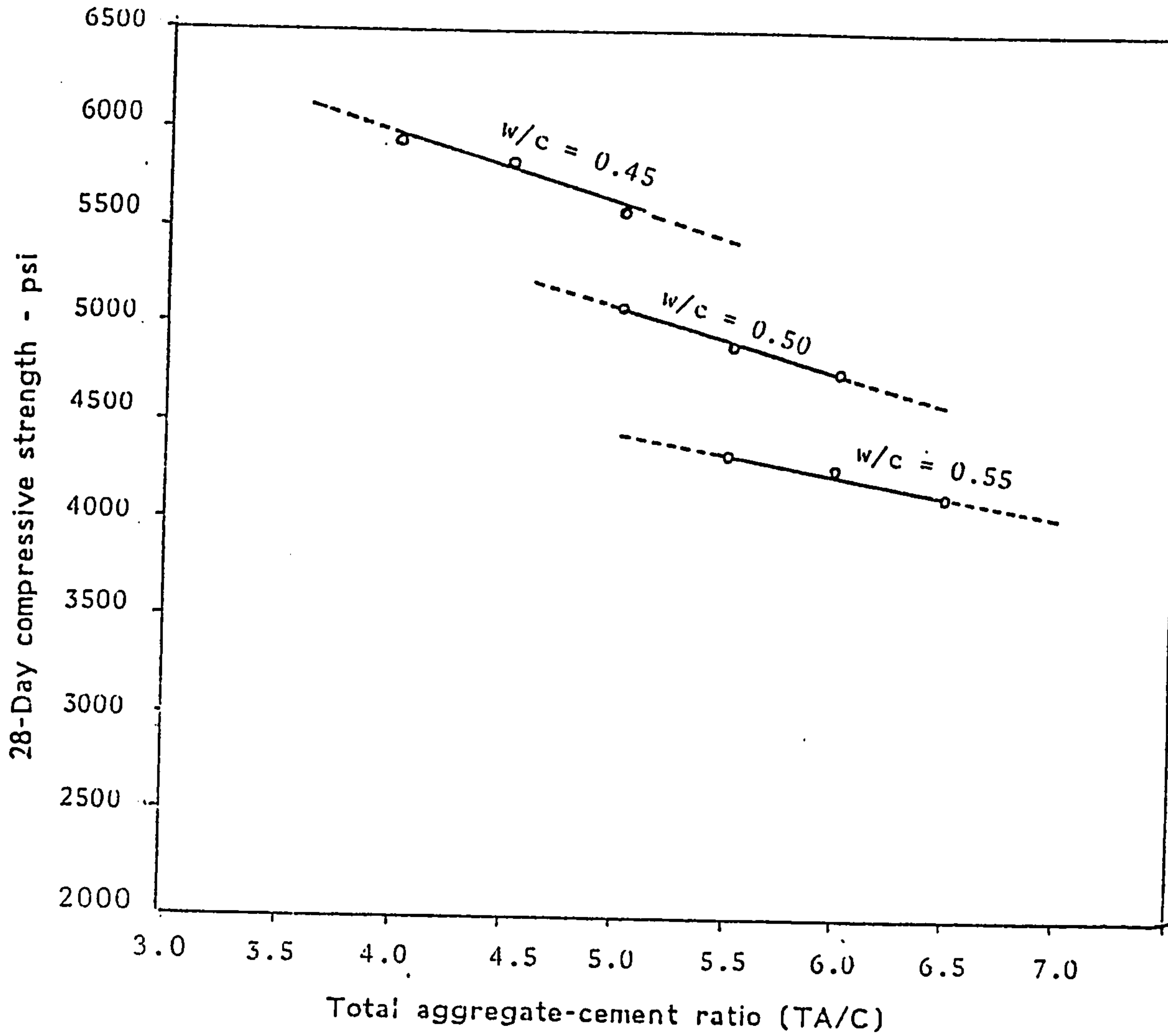

Figure 4.13 : Relationship between Compressive Strength and Total Aggregate-cement Ratio for Mixes Prepared and Cured at Normal Conditions

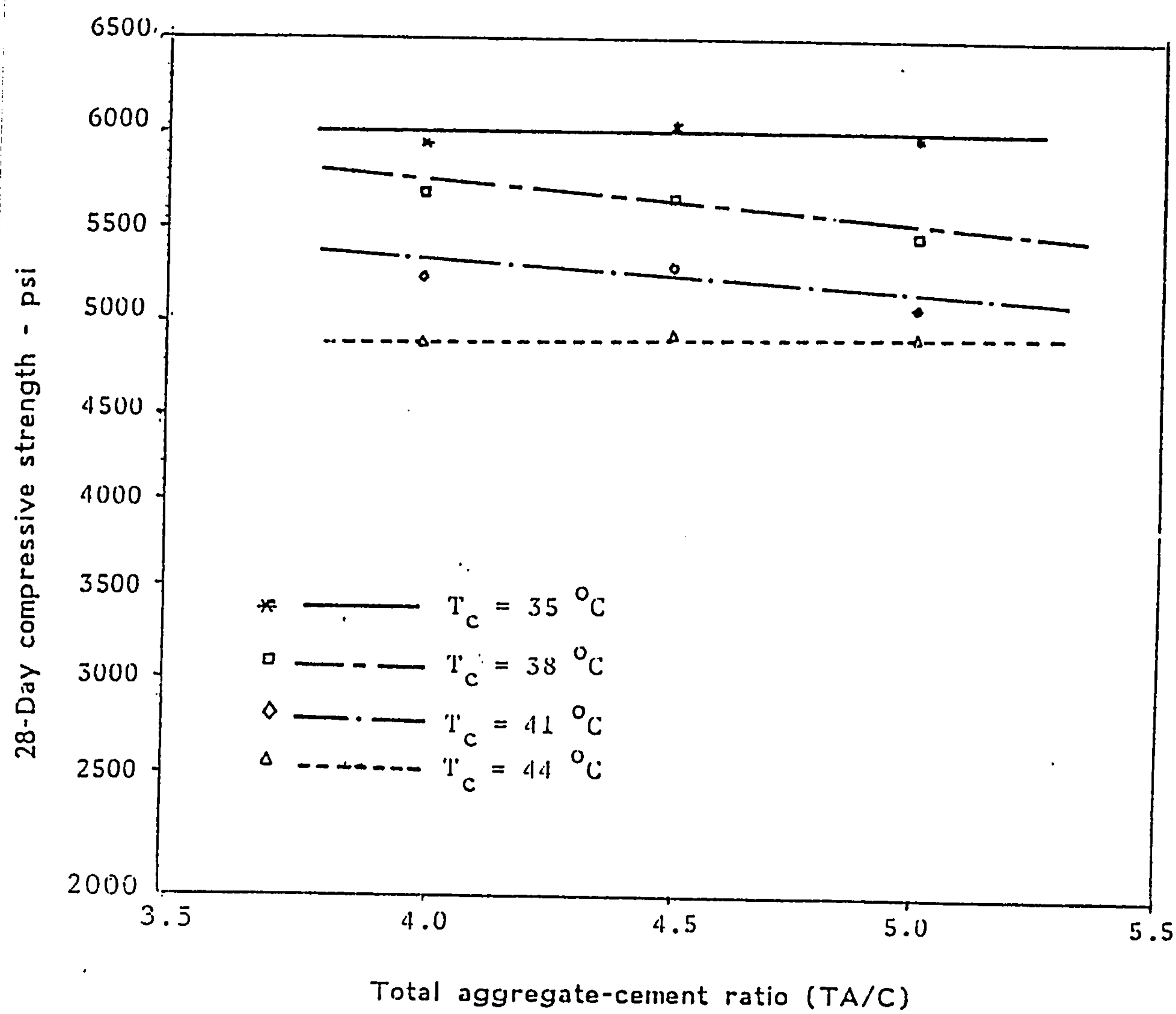

Figure 4.14 : Relationship between Compressive Strength and Total Aggregate-cement Ratio for Mixes Prepared and Cured in Hot Weather Conditions (W/C=0.45)

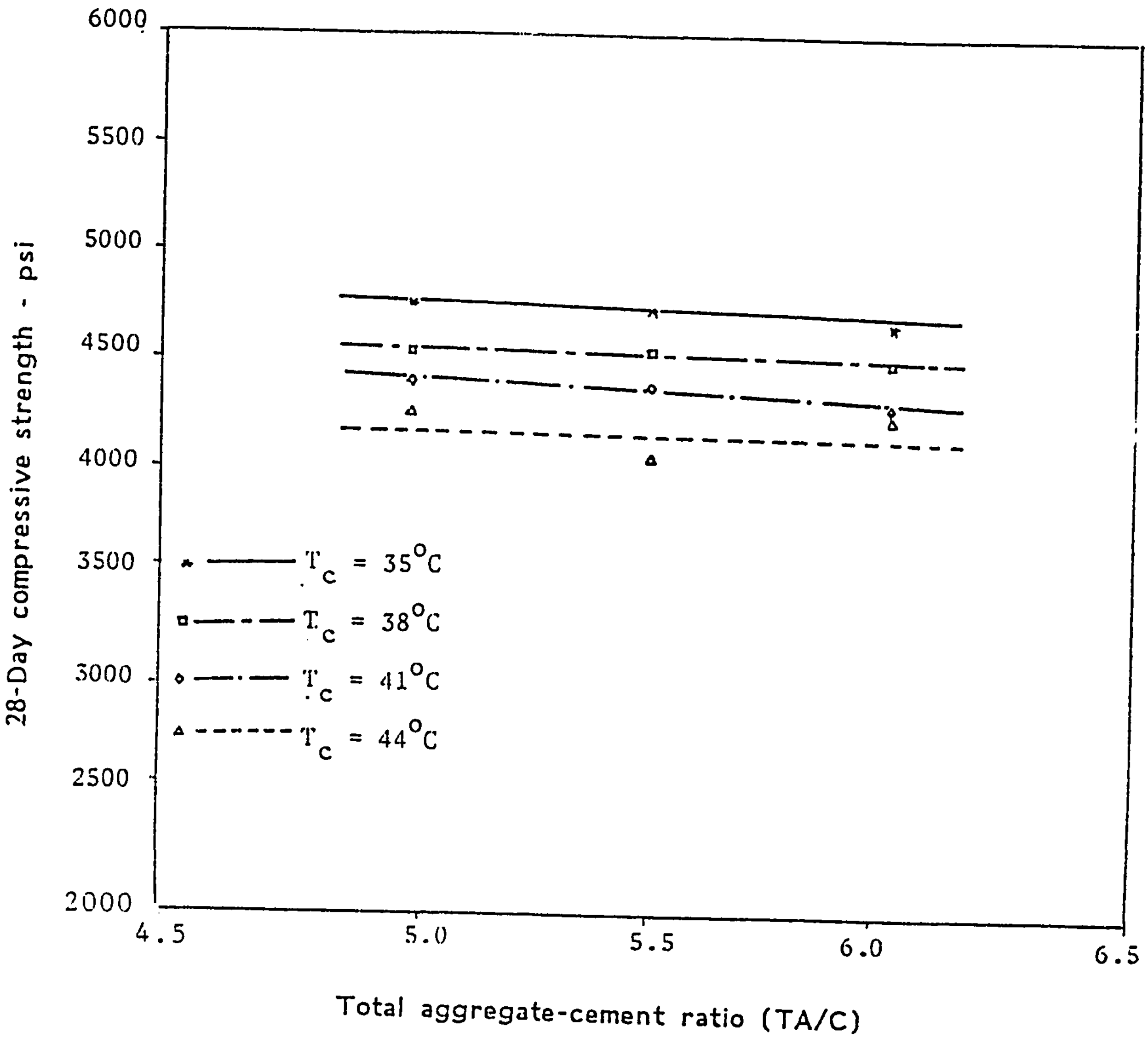

Figure 4.15 : Relationship between Compressive Strength and Total Aggregate-cement Ratio for Mixes Prepared and Cured in Hot Weather Conditions (W/C=0.50)

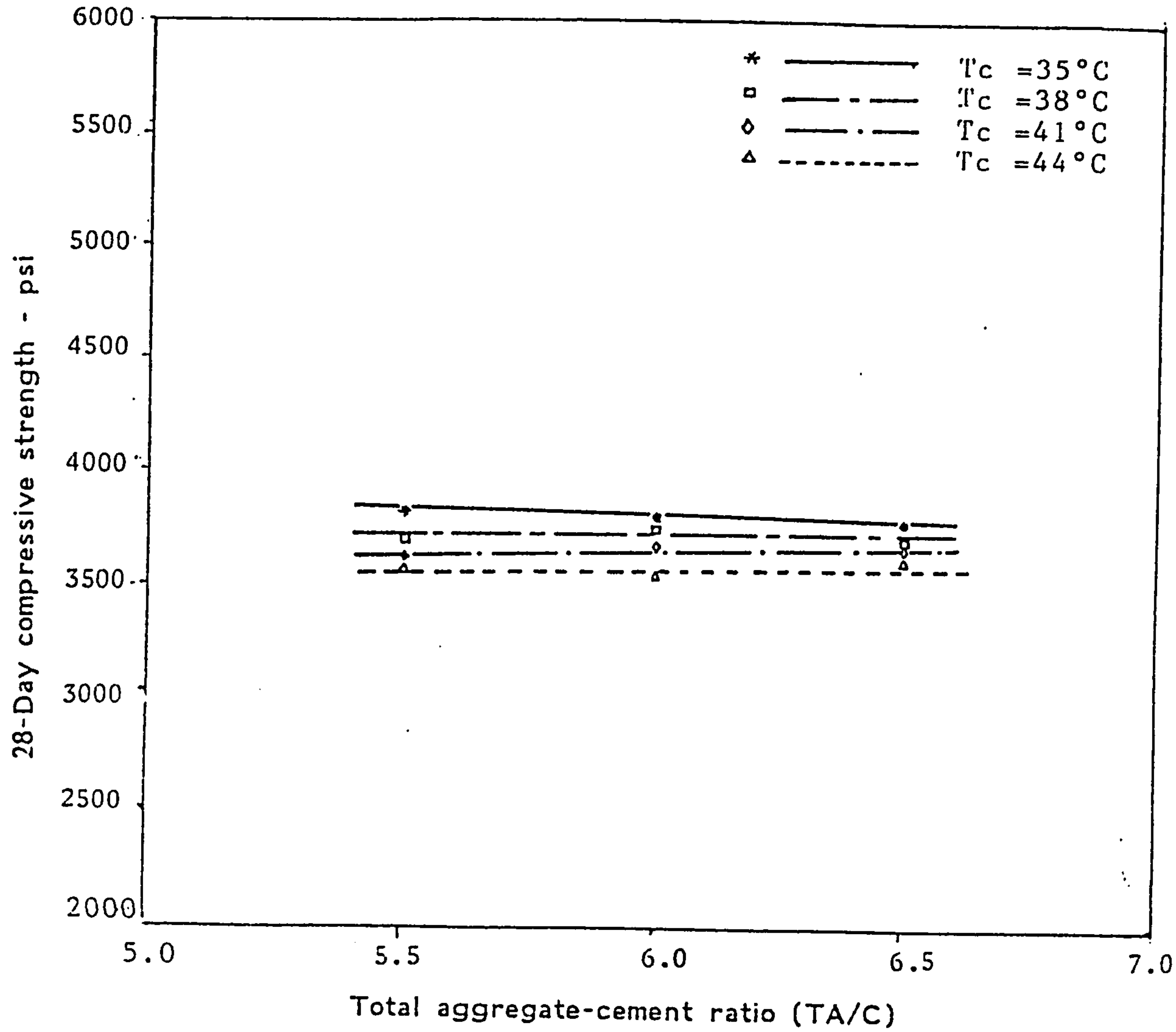

Figure 4.16 : Relationship between Compressive Strength and Total Aggregate-cement Ratio for Mixes Prepared and Cured in Hot Weather Conditions (W/C=0.55)

CHAPTER 5 : CONCLUSIONS

1. In the proposed method for concrete mix design based on factorial experimental design, equations for workability and compressive strength have been obtained by regression analysis using the experimental results. The equations enable computation of slump and compressive strength for different values of water-cement ratio, total aggregate to cement ratio and concrete mix temperature at placement. The analysis of variance for the developed models shows their adequacy for representing the test data.

2. The strength of concrete prepared and cured in hot weather is reduced as compared to that of concrete prepared and cured in the normal laboratory conditions. The reduction increases with increase in concrete mix temperature and can be estimated by the following equation :

$$R = (1.30\ Tc - 42.1)\% \quad \text{for } 35^{\circ}C \leq Tc \leq 44^{\circ}C$$

3. The reduction in strength of concrete can be attributed to the following causes :

   (i) The extra water added for restoring workability increases the initial water-cement ratio which causes corresponding reduction in the strength of concrete.

   (ii) The non-uniform distribution of calcium silicate

hydrate gel due to the rapid rate of hydration at the early age of concrete leaves unhydrated cement particles in the concrete which do not contribute to the strength development.

(iii) Micro-cracks formed by the different expansions of various constituents of concrete due to their different coefficients of thermal expansions are responsible for reduction in the strength of concrete.

(iv) Rapid evaporation of water from the burlap cov--ering leaves insufficient amount of water for proper hydration of cement resulting in lower strength of concrete.

4. Concrete prepared at normal laboratory temperature but cured in hot weather had a reduction in compressive strength as high as 16%. Therefore, lowering the concrete temperature at placement alone does not eliminate the adverse effect of hot weather on compressive strength. It is very necessary to carry out proper curing of concrete in hot weather.

5. For a given water-cement ratio, total aggregate to cement ratio has a negligible effect on compressive strength of concrete prepared and cured in hot weather.

6. The reduction in workability and compressive strength of concrete for hot weather conditions can be compensated by properly designing a concrete mix with (i) sufficient additional mixing water to compensate for the evaporation of

water which causes reduction in slump, (ii) appropriate reduction in W/C ratio to compensate for reduction in strength and (iii) increase in TA/C ratio to compensate for reduction in slump caused by decrease in W/C ratio.

7. A computer program has been developed to predict the proportions of a concrete mix for the required compressive strength, workability and concrete mix temperature at placement with curing in hot weather conditions. This computer program uses the equations obtained by regression analysis stated in para 1 above.

8. The developed equations for compressive strength and workability have been used to generate Tables for use in concrete mix design for hot weather conditions.

9. The proposed method can be used for the design of concrete made with aggregate from different sources. This would involve the study of aggregate properties followed by a limited experimental program similar to the present investigation. The same models for strength and workability can be used in regression analysis to determine the values of constants in the equations for strength and workability. These equations can then be used to generate Mix Design Tables.

Limitations

1. The present investigation does not consider durability

aspect for concrete mix design. The durability problem can be handled by putting limitations on selection of water-cement ratio and cement content.

2. The Mix Design Tables are only applicable for concrete cured in hot weather and in the manner similar to that followed in this investigation.

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APPENDICES

APPENDIX A

Figures Showing the Variation in
Compressive Strength with Age

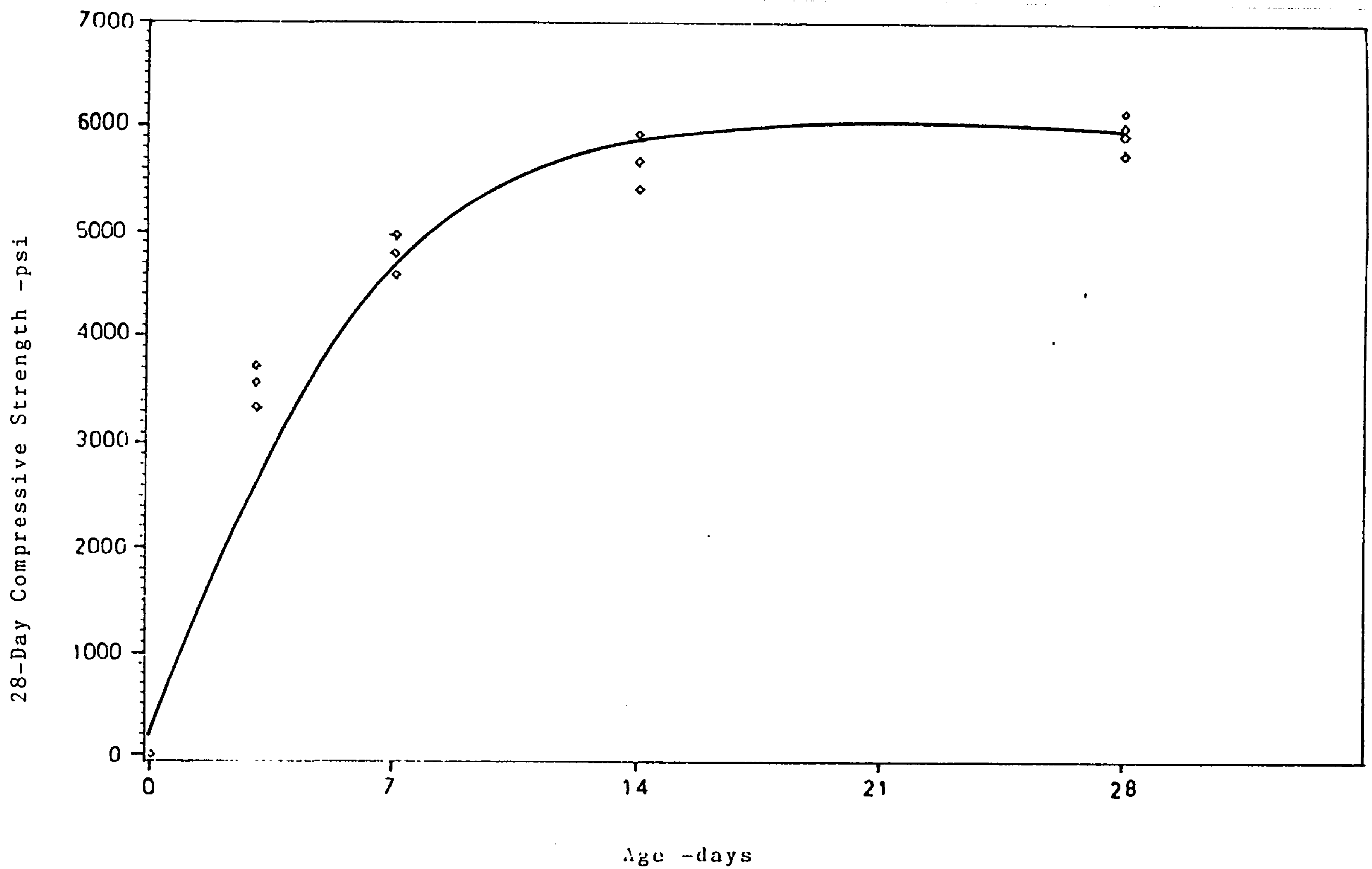


Figure A.1 : Variation of Compressive Strength with Age for Mix A1

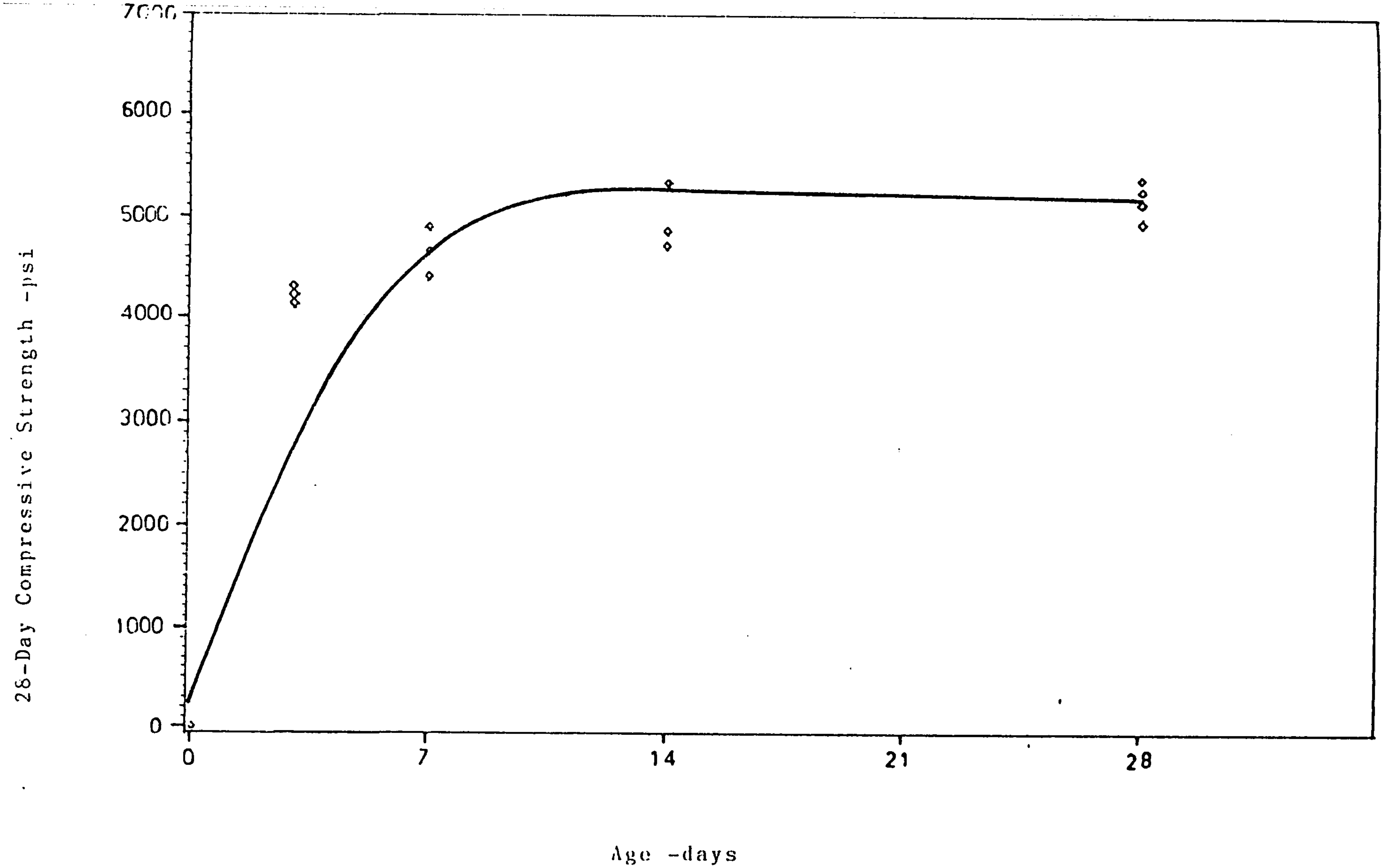


Figure A.2 : Variation of Compressive Strength with Age for Mix A2

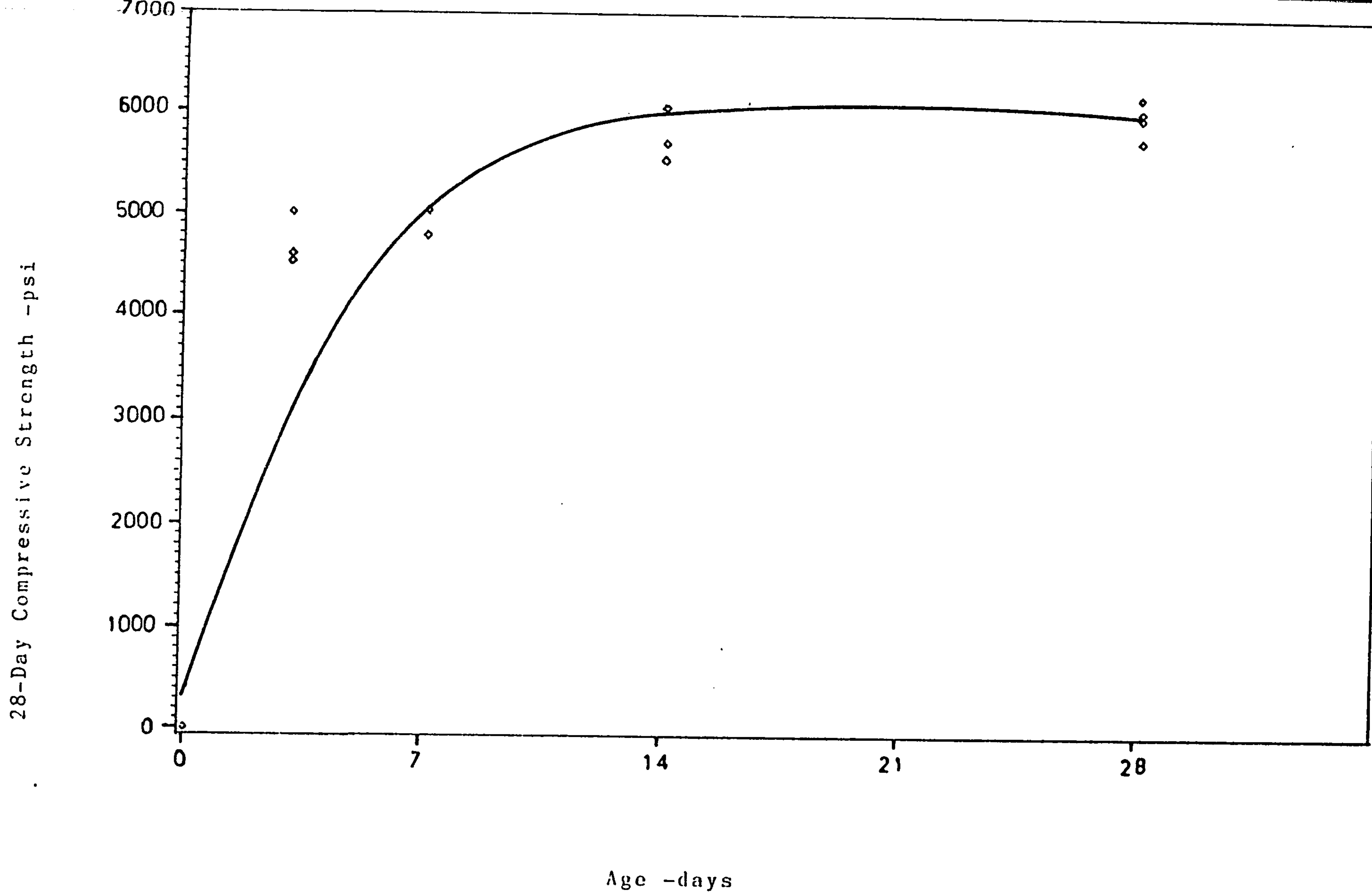


Figure A.3 : Variation of Compressive Strength with Age for Mix A3

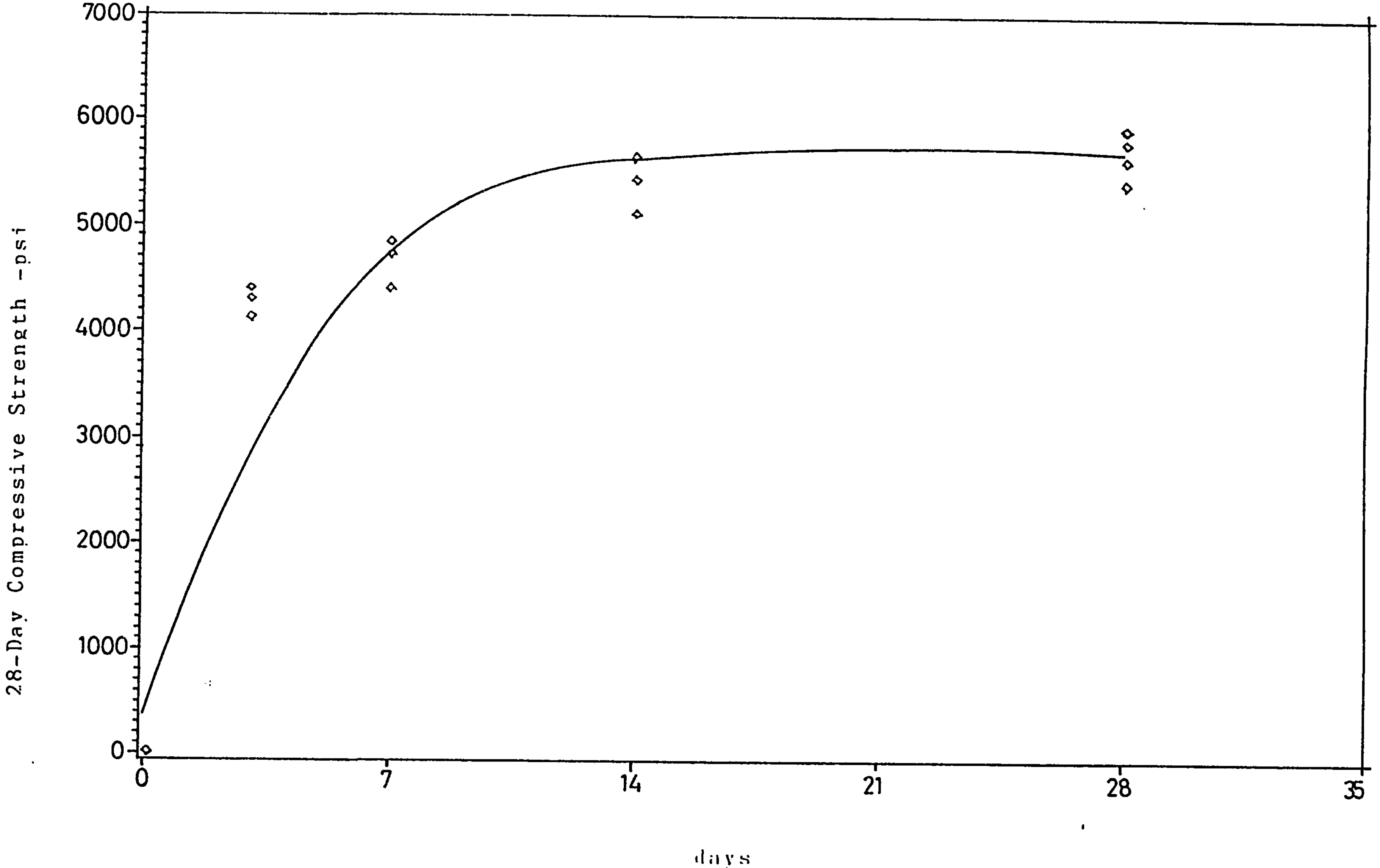


Figure A.4 : Variation of Compressive Strength with Age for Mix A4

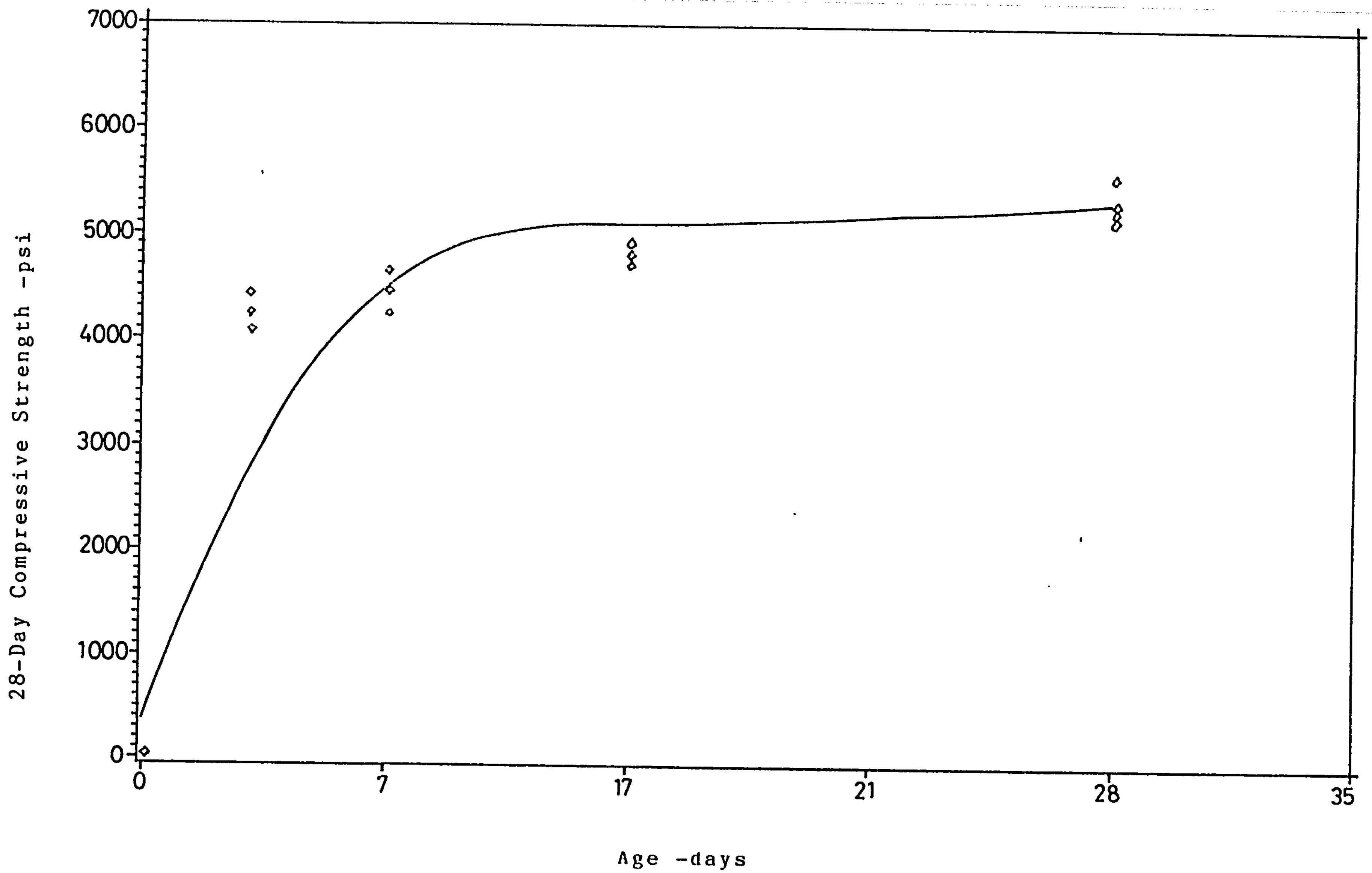


Figure A.5 : Variation of Compressive Strength with Age for Mix A5

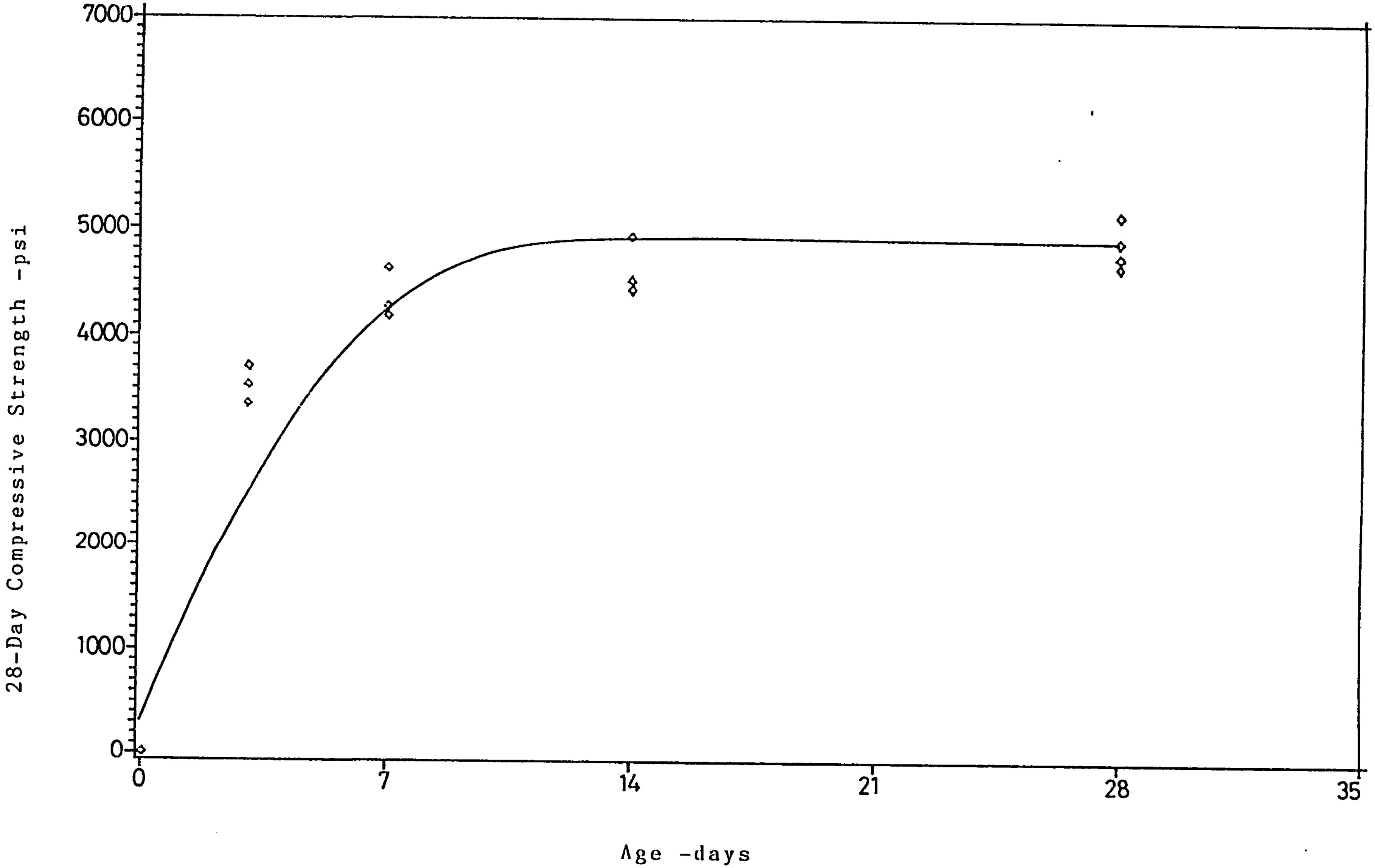


Figure A.6 : Variation of Compressive Strength with Age for Mix A6

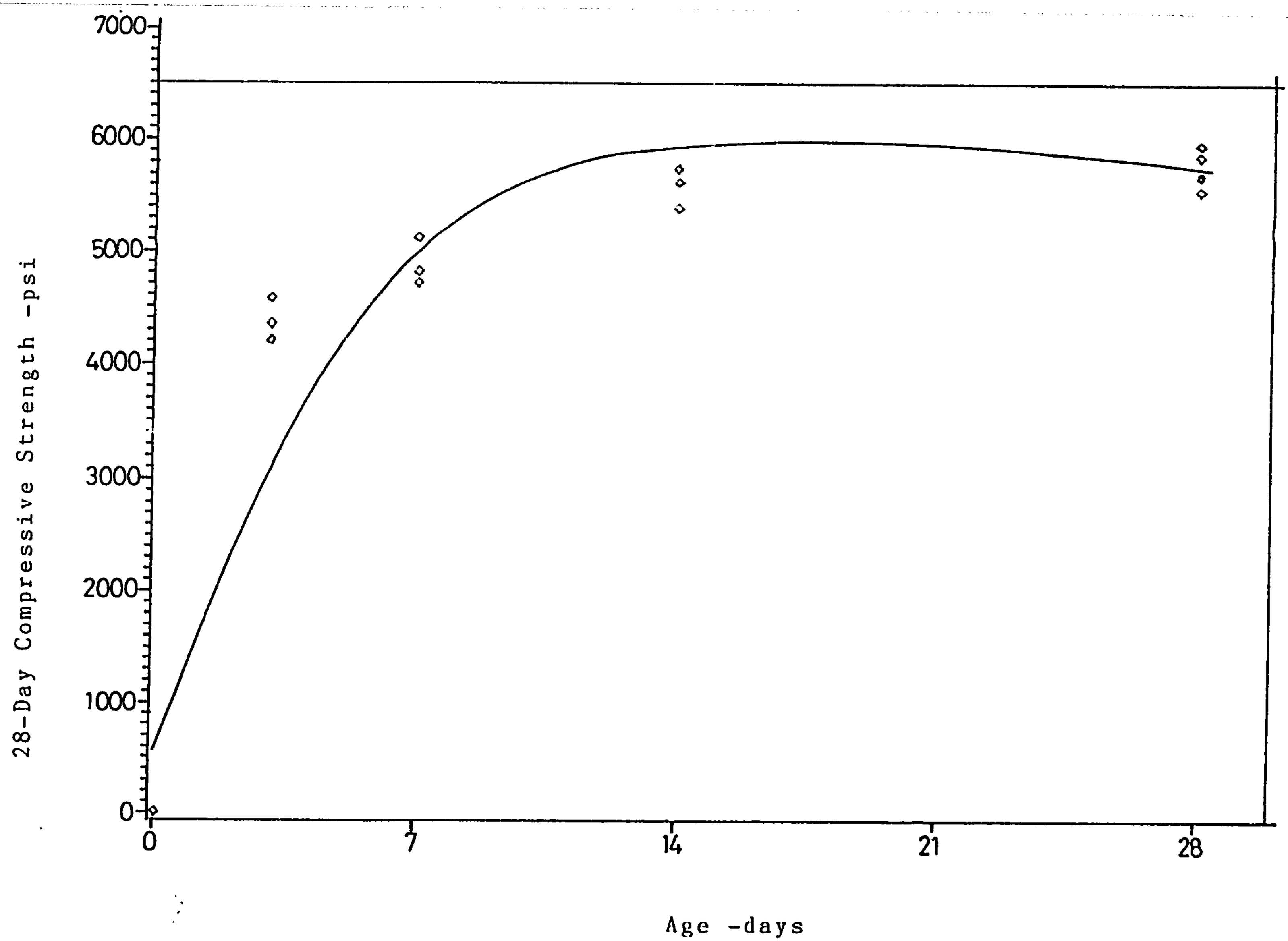


Figure A.7 : Variation of Compressive Strength with Age for Mix B1

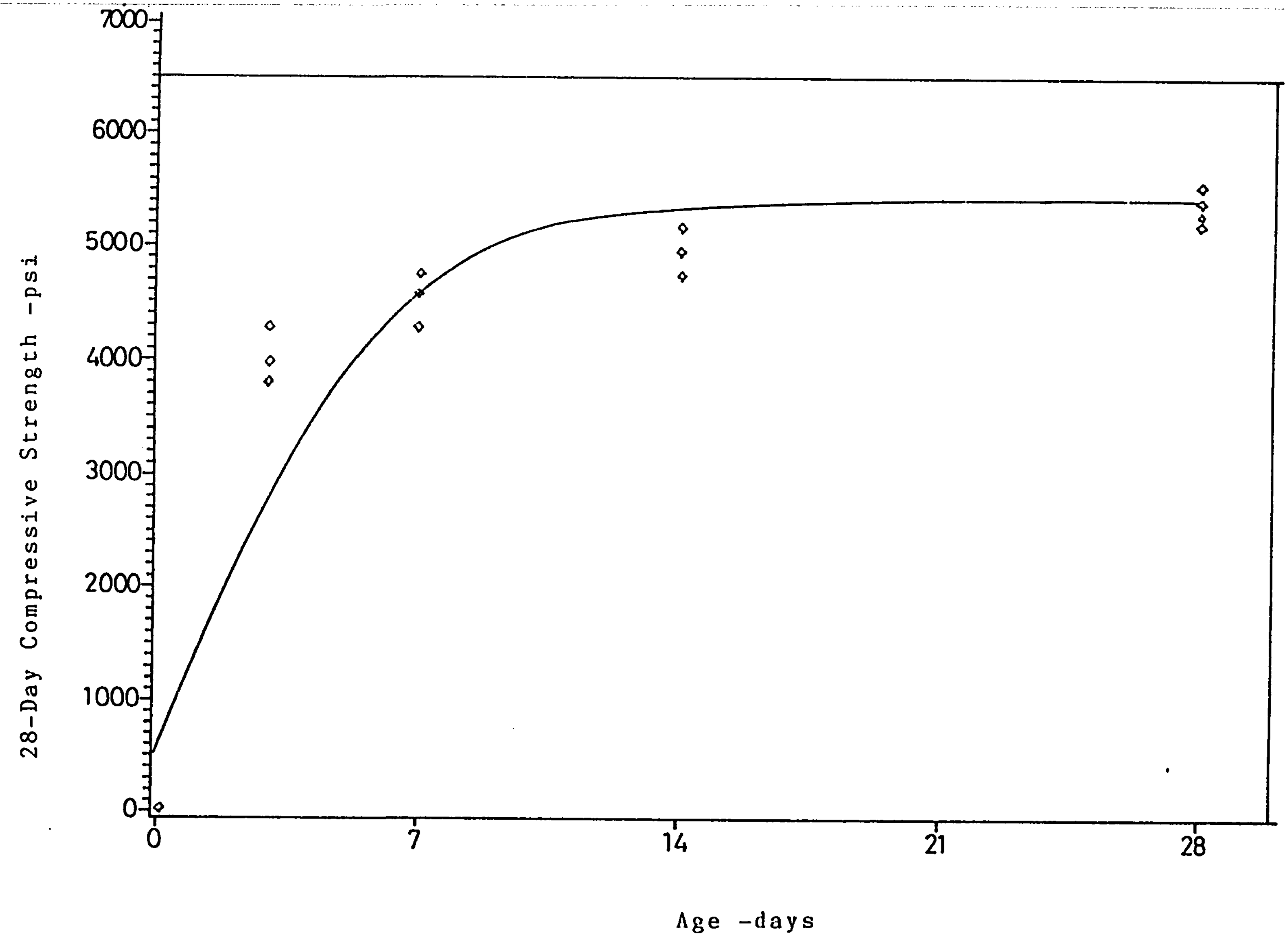


Figure A.8 : Variation of Compressive Strength with Age for Mix B2

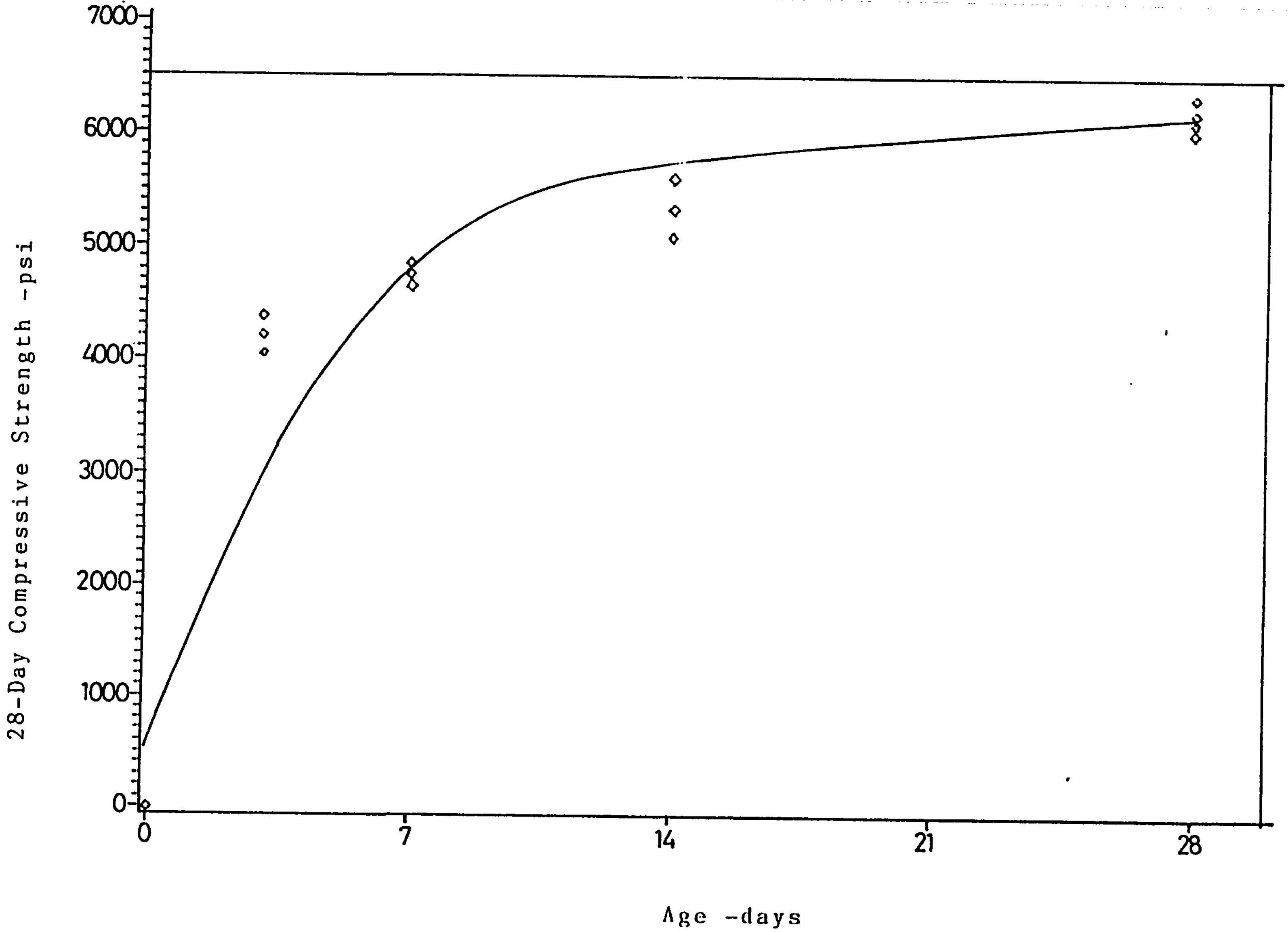


Figure A.9 : Variation of Compressive Strength with Age for Mix B3

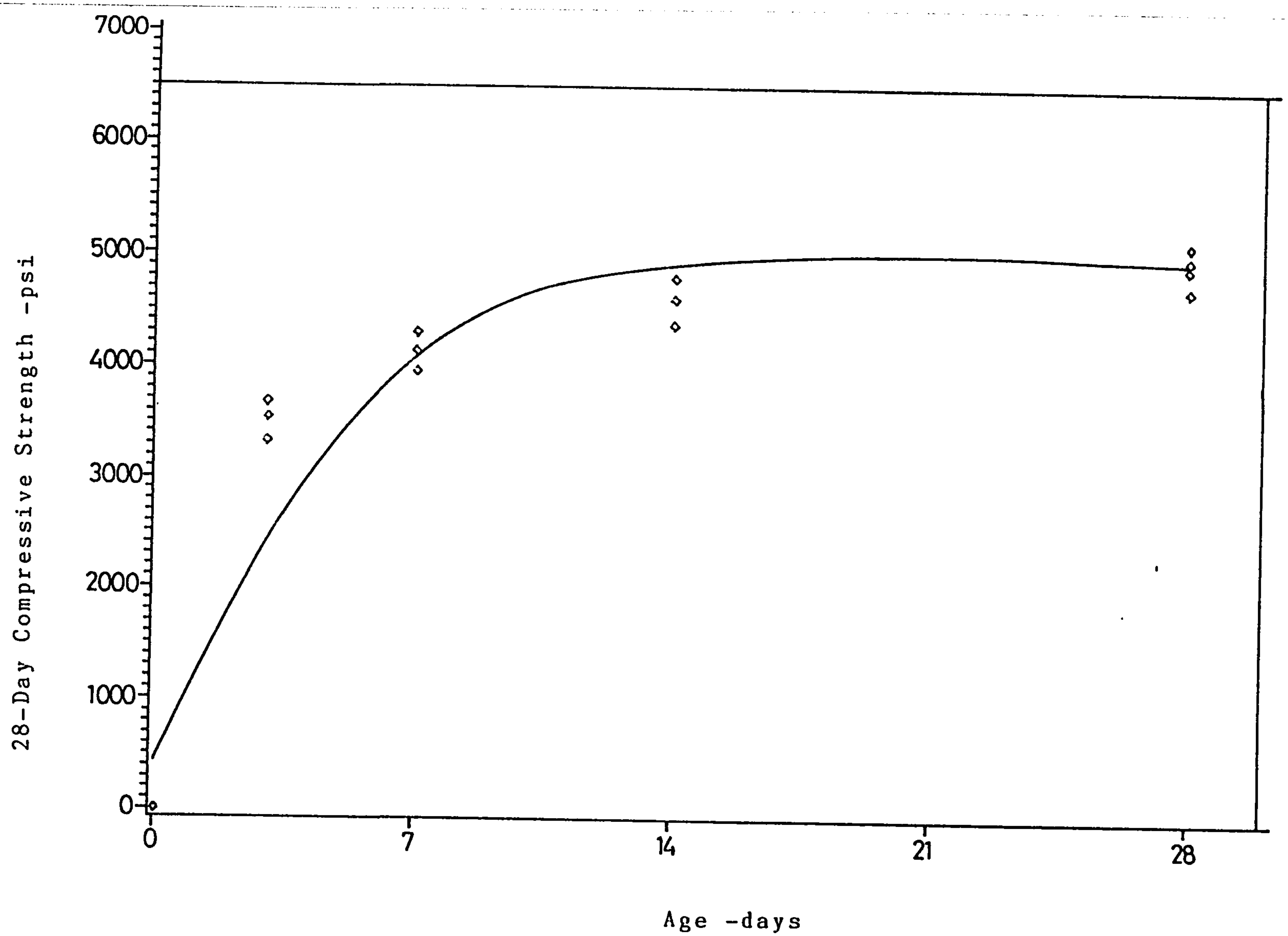
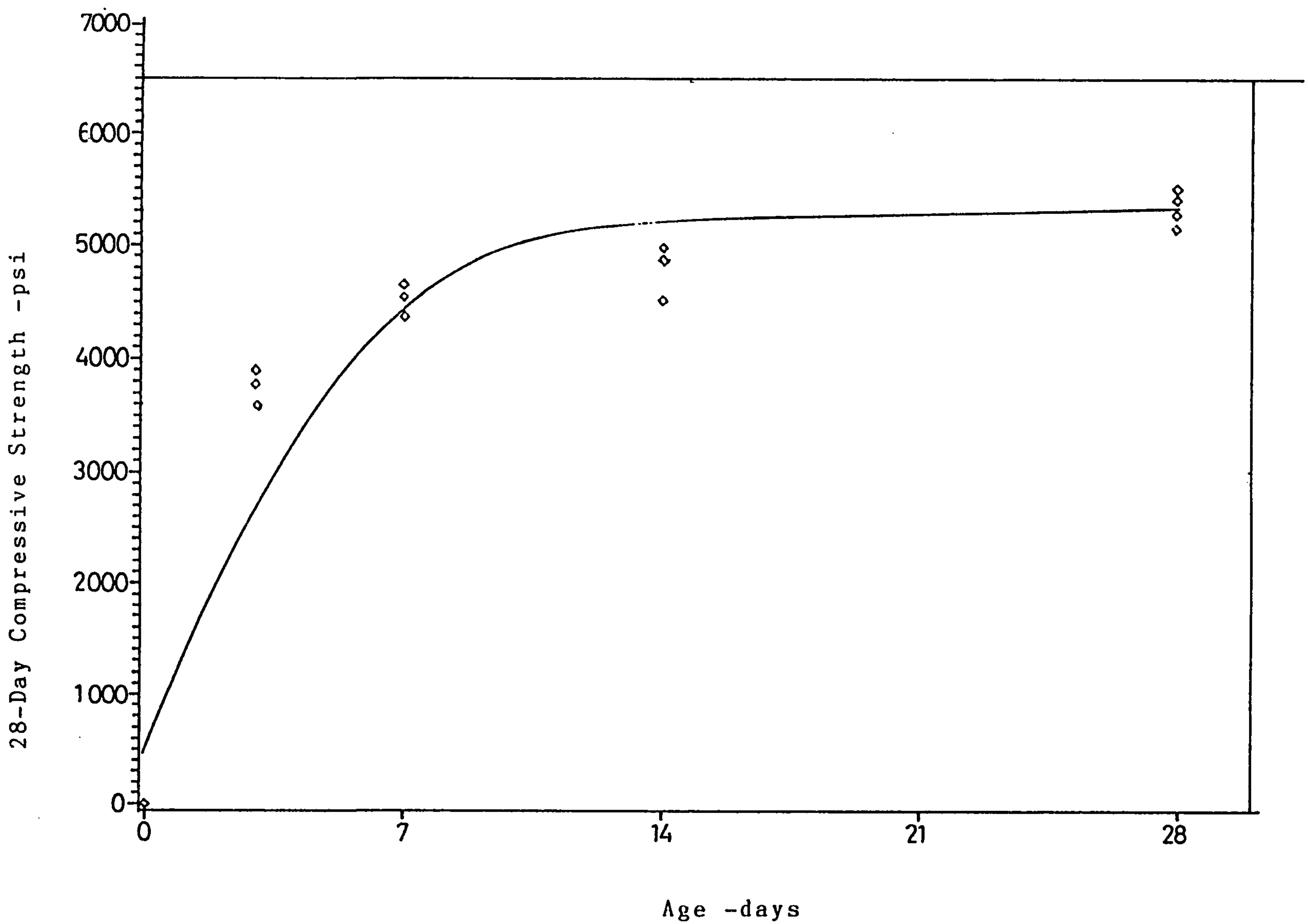


Figure A.10: Variation of Compressive Strength with Age for Mix B4



FigureA.11 : Variation of Compressive Strength with Age for Mix B5

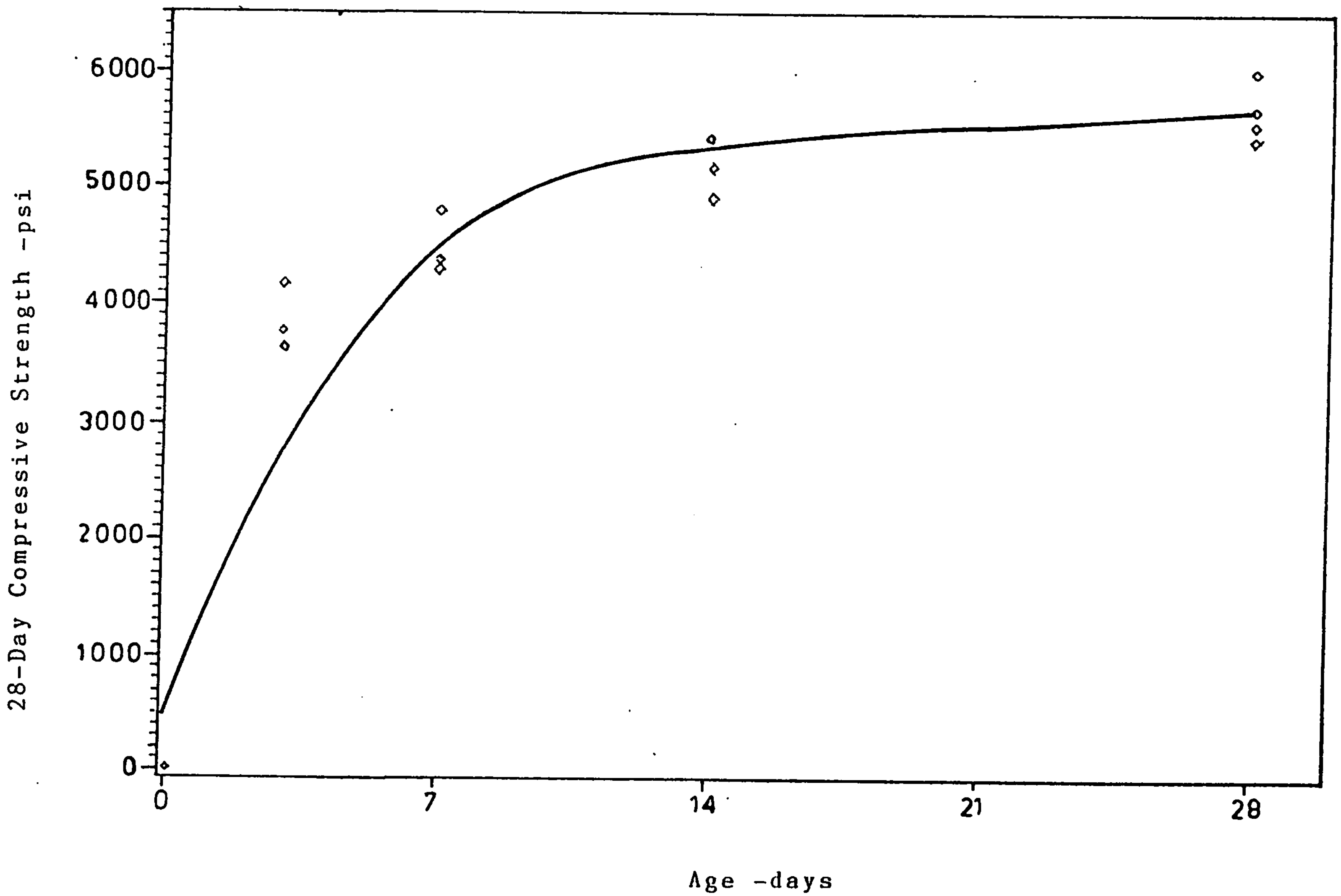


Figure A.12 :Variation of Compressive Strength with Age for Mix B6

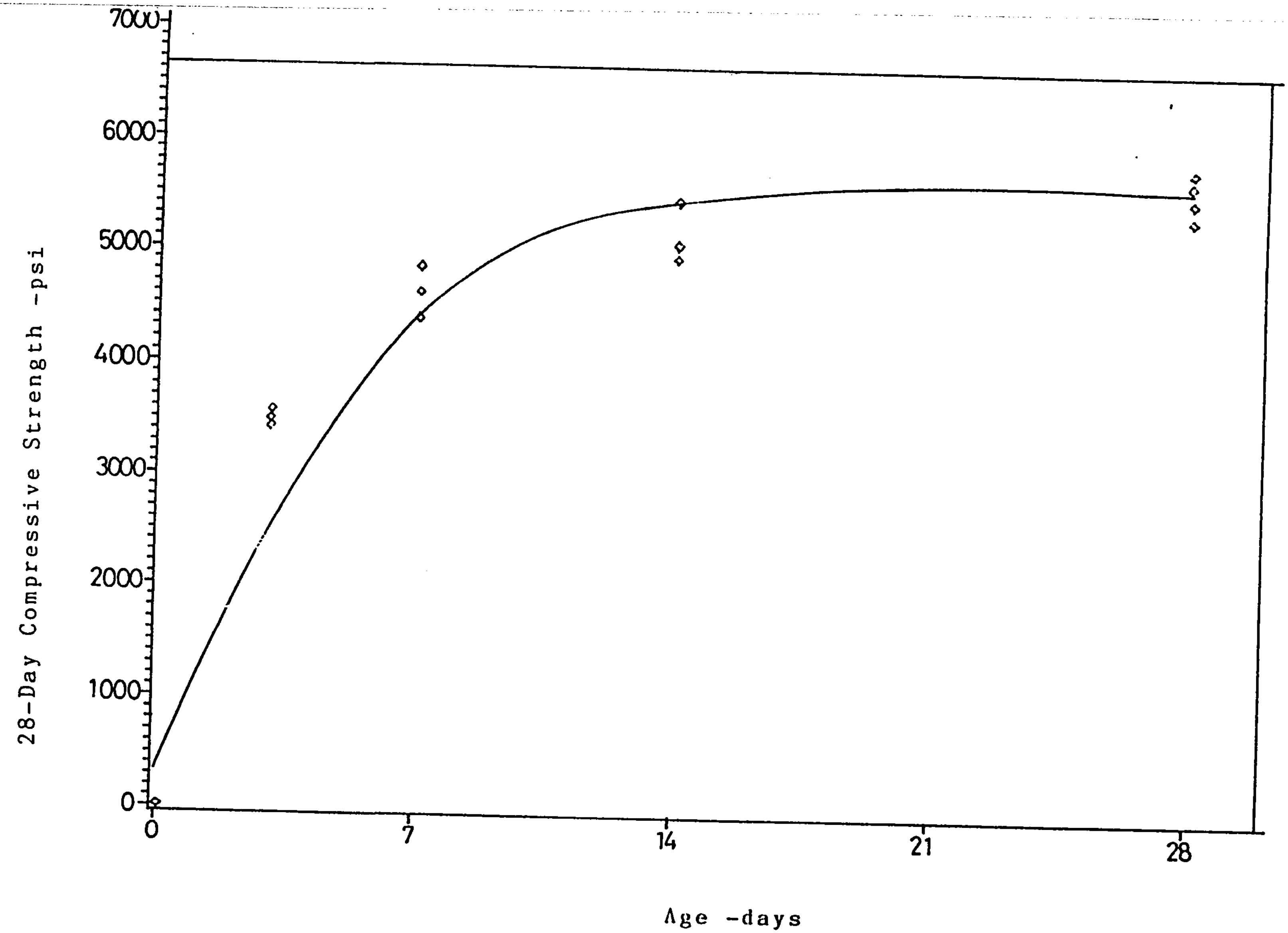


Figure A.13: Variation of Compressive Strength with Age for Mix C1

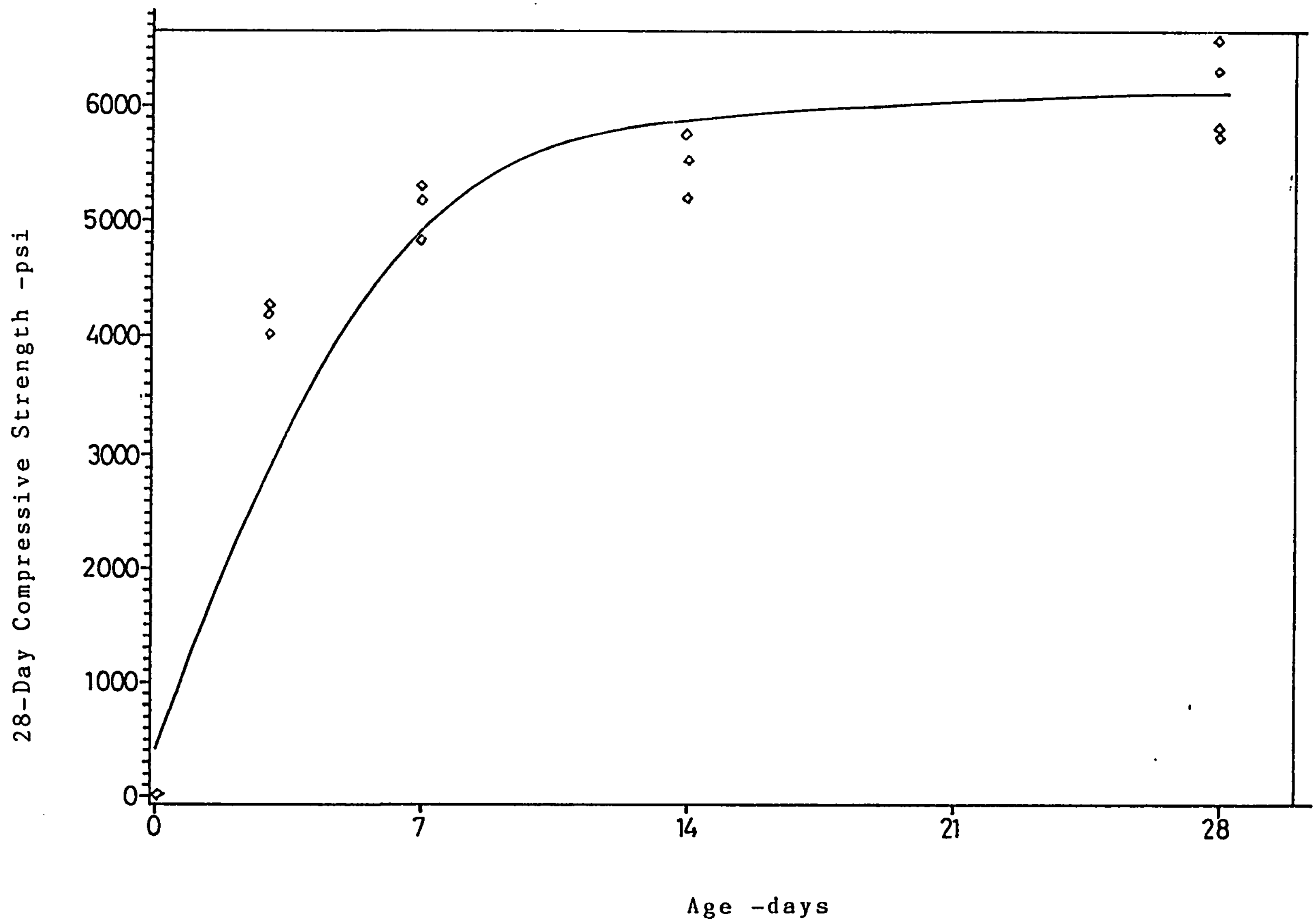


Figure A.14 : Variation of Compressive Strength with Age for Mix C2

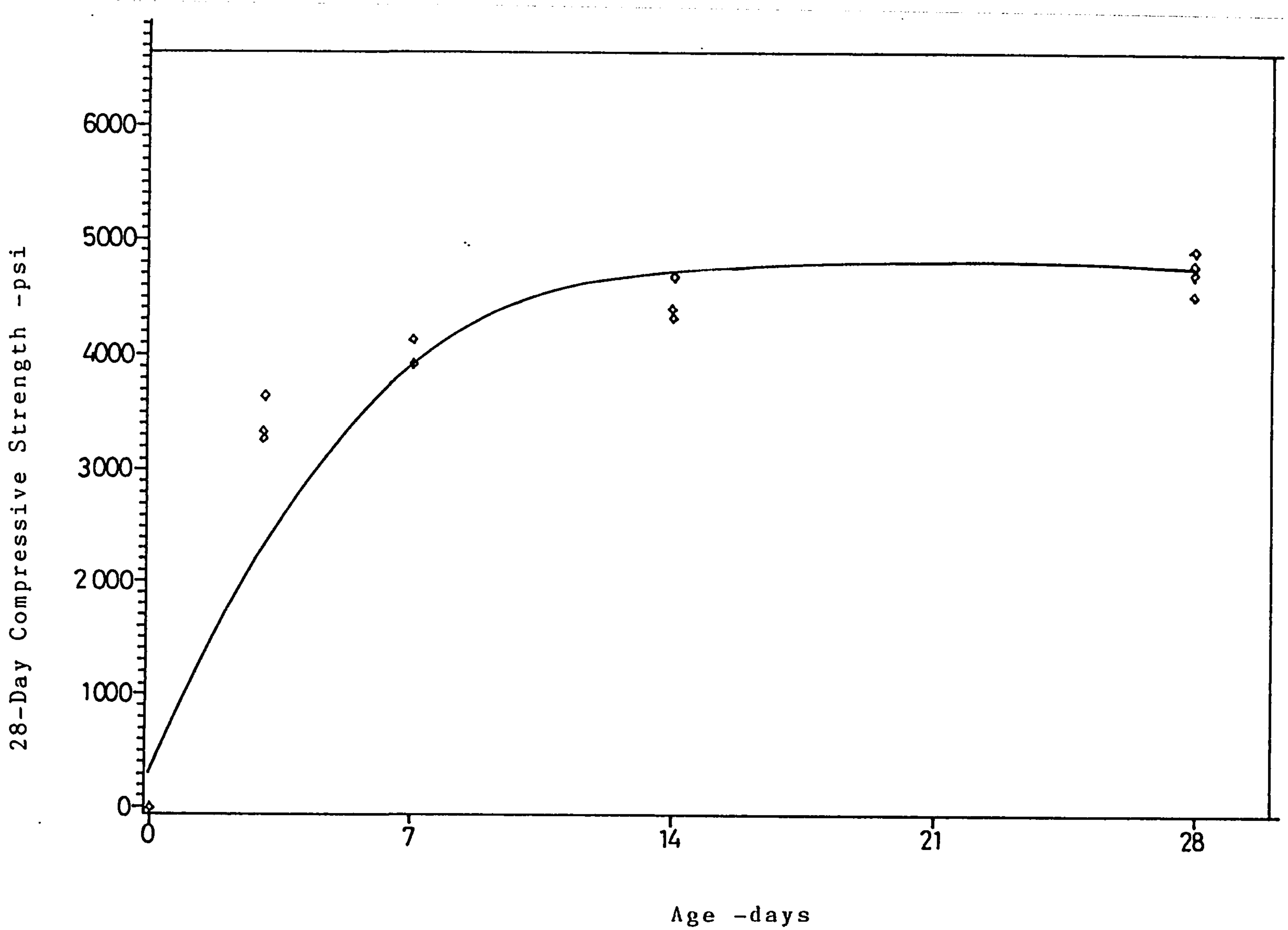


Figure A.15 : Variation of Compressive Strength with Age for Mix C3

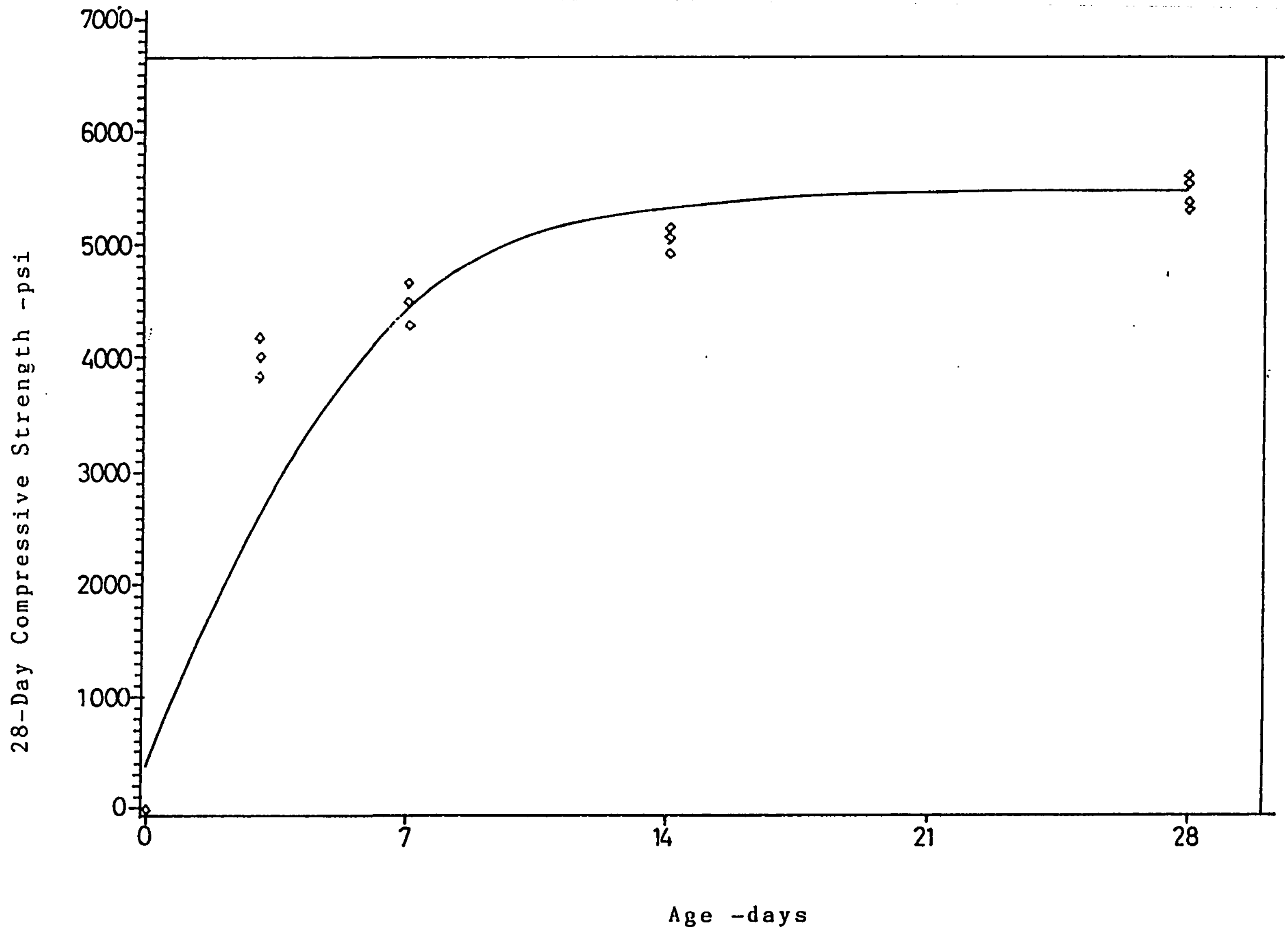


Figure A.16 : Variation of Compressive Strength with Age for Mix C4

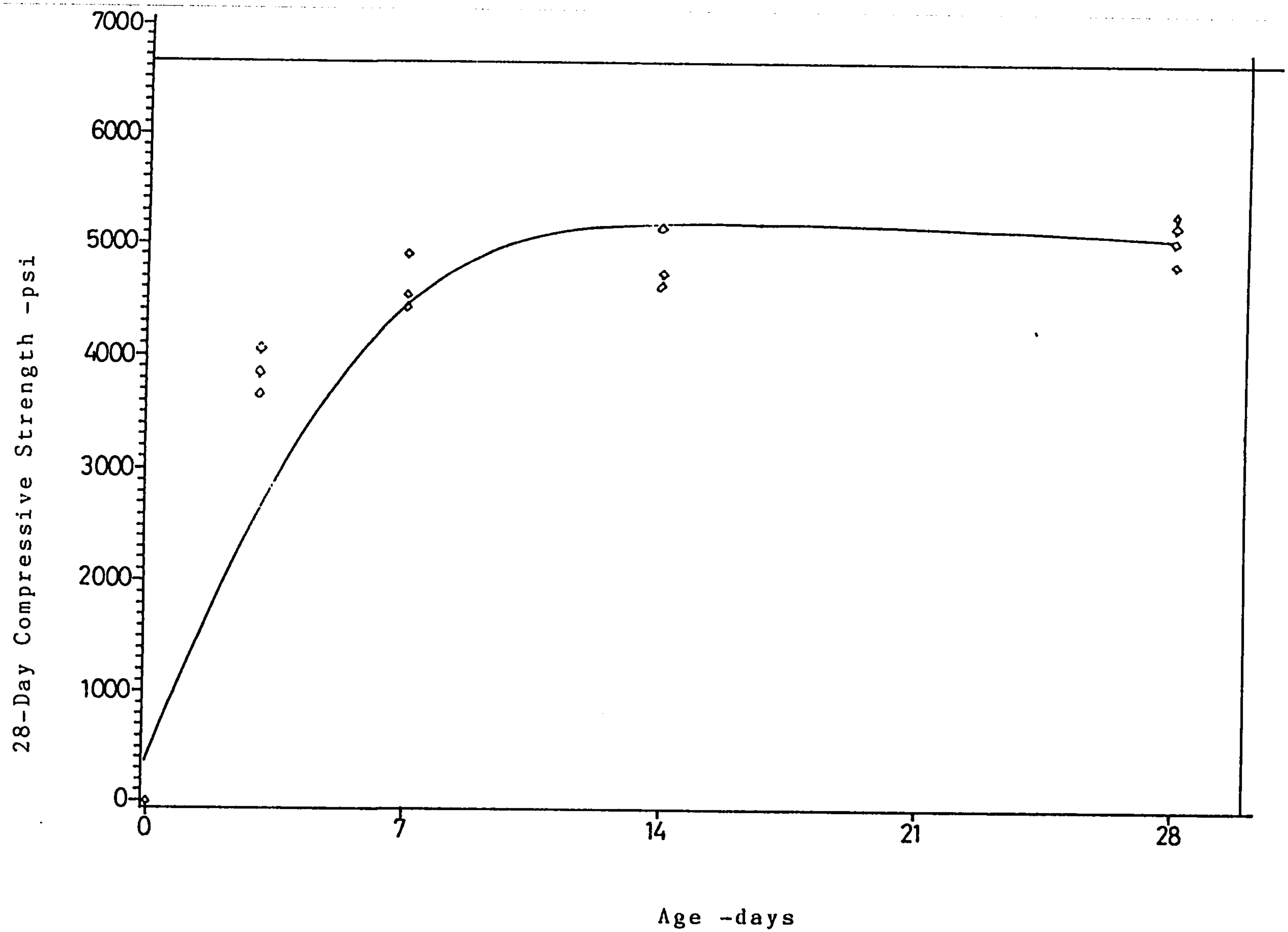


Figure A.17 : Variation of Compressive Strength with Age for Mix C5

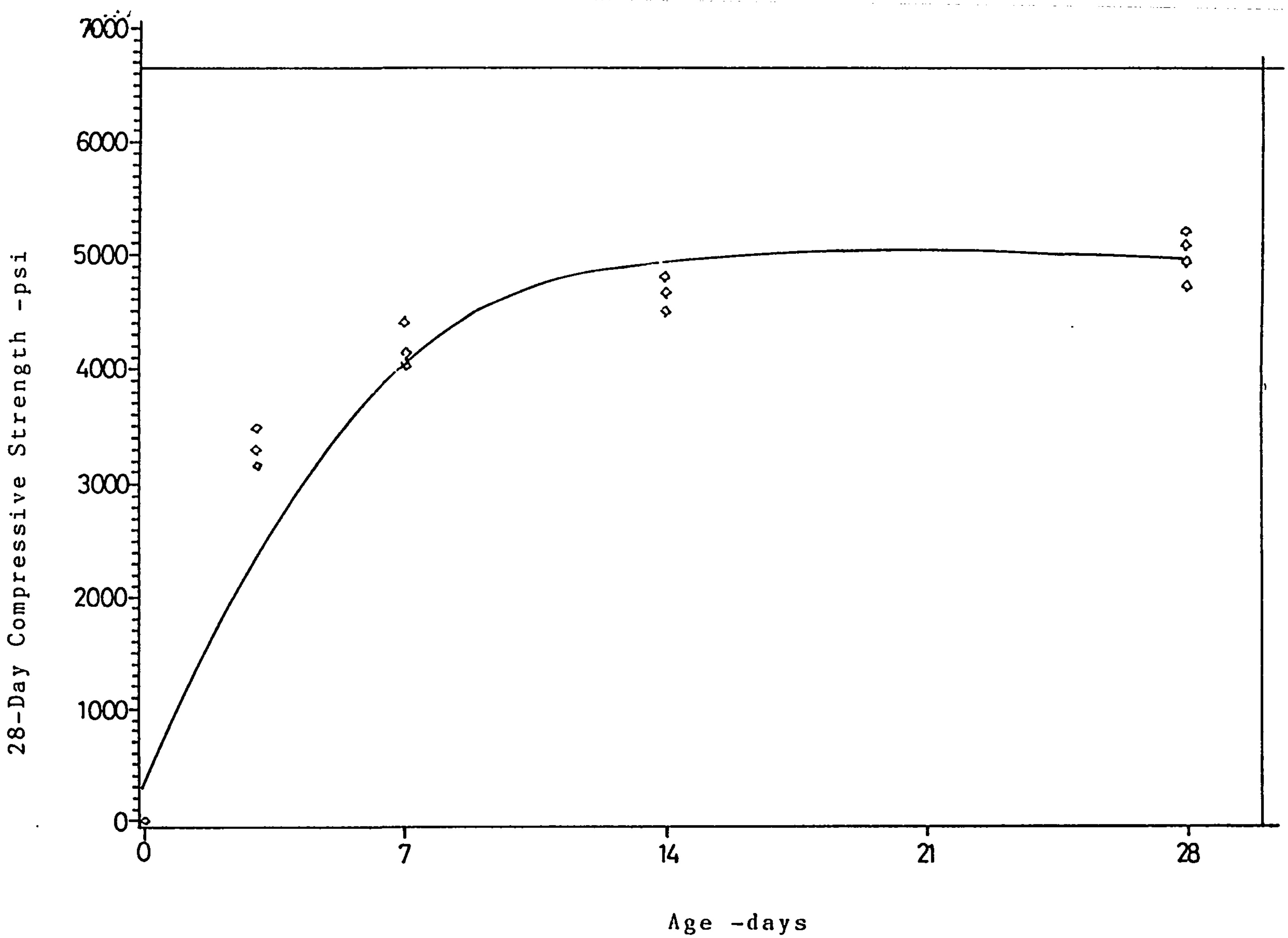


Figure A.18 : Variation of Compressive Strength with Age for Mix C6

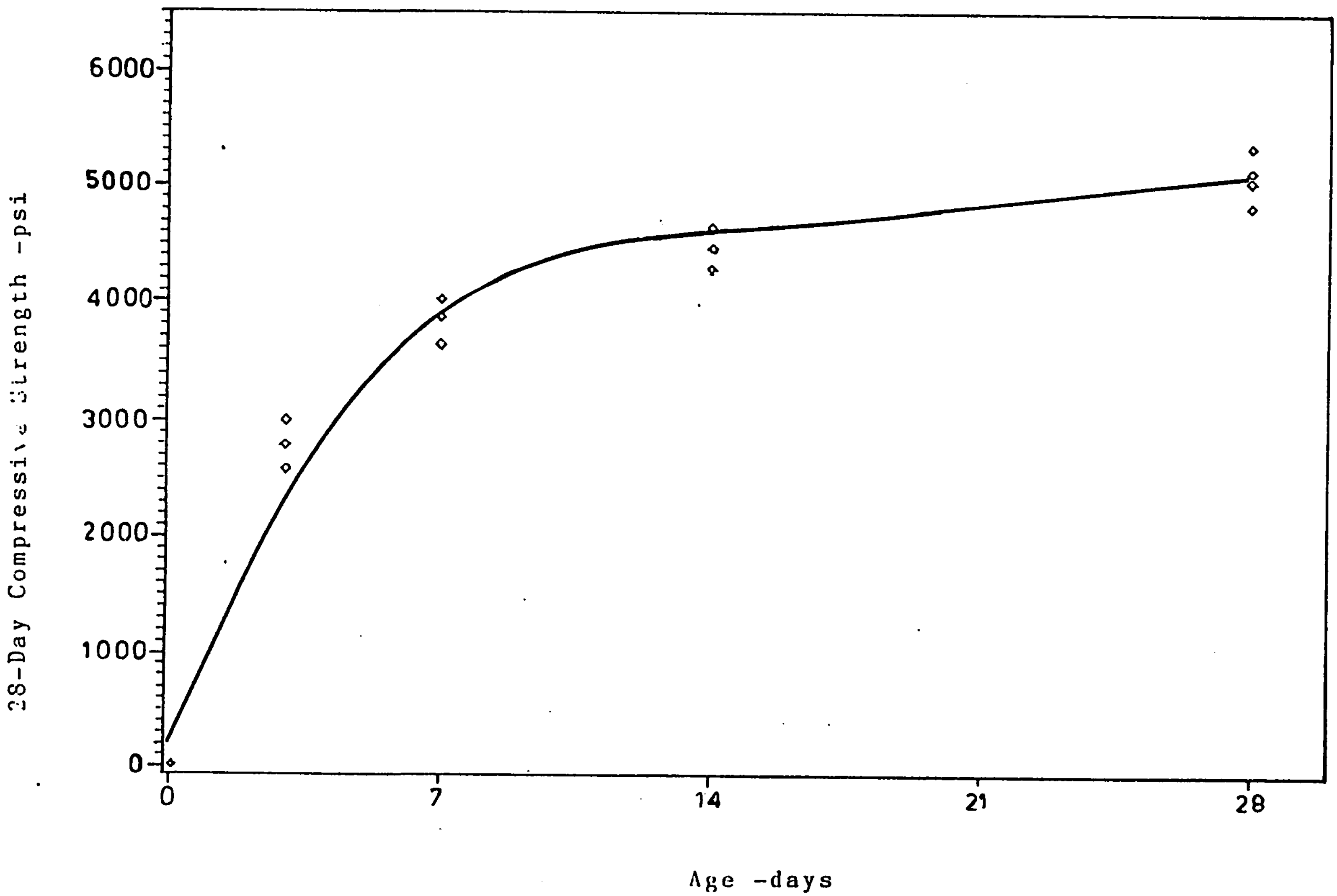


Figure A.19 Variation of Compressive Strength with Age for Mix D1

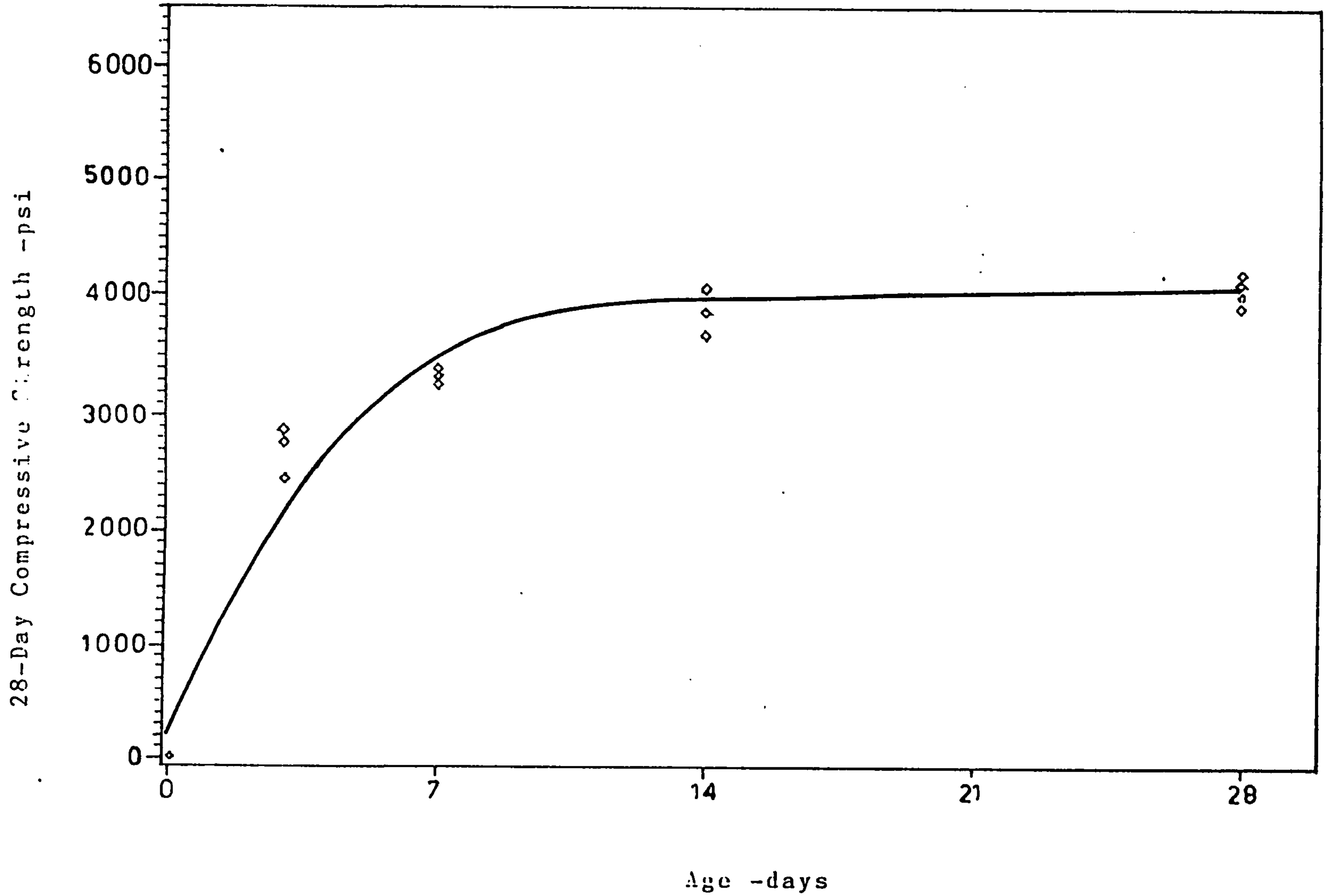


Figure A.20: Variation of Compressive Strength with Age for Mix D2

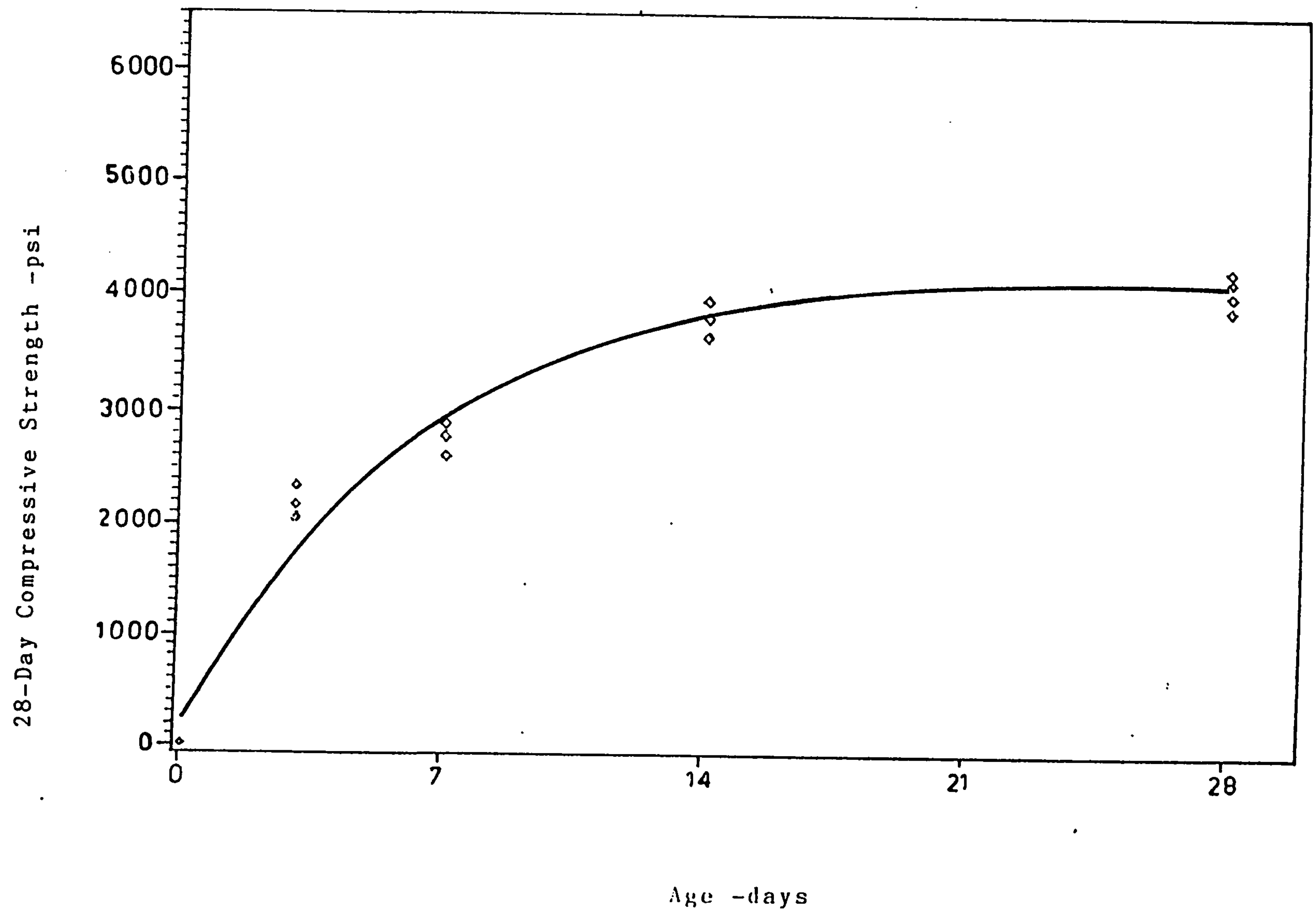


Figure A.21 : Variation of Compressive Strength with Age for Mix D3

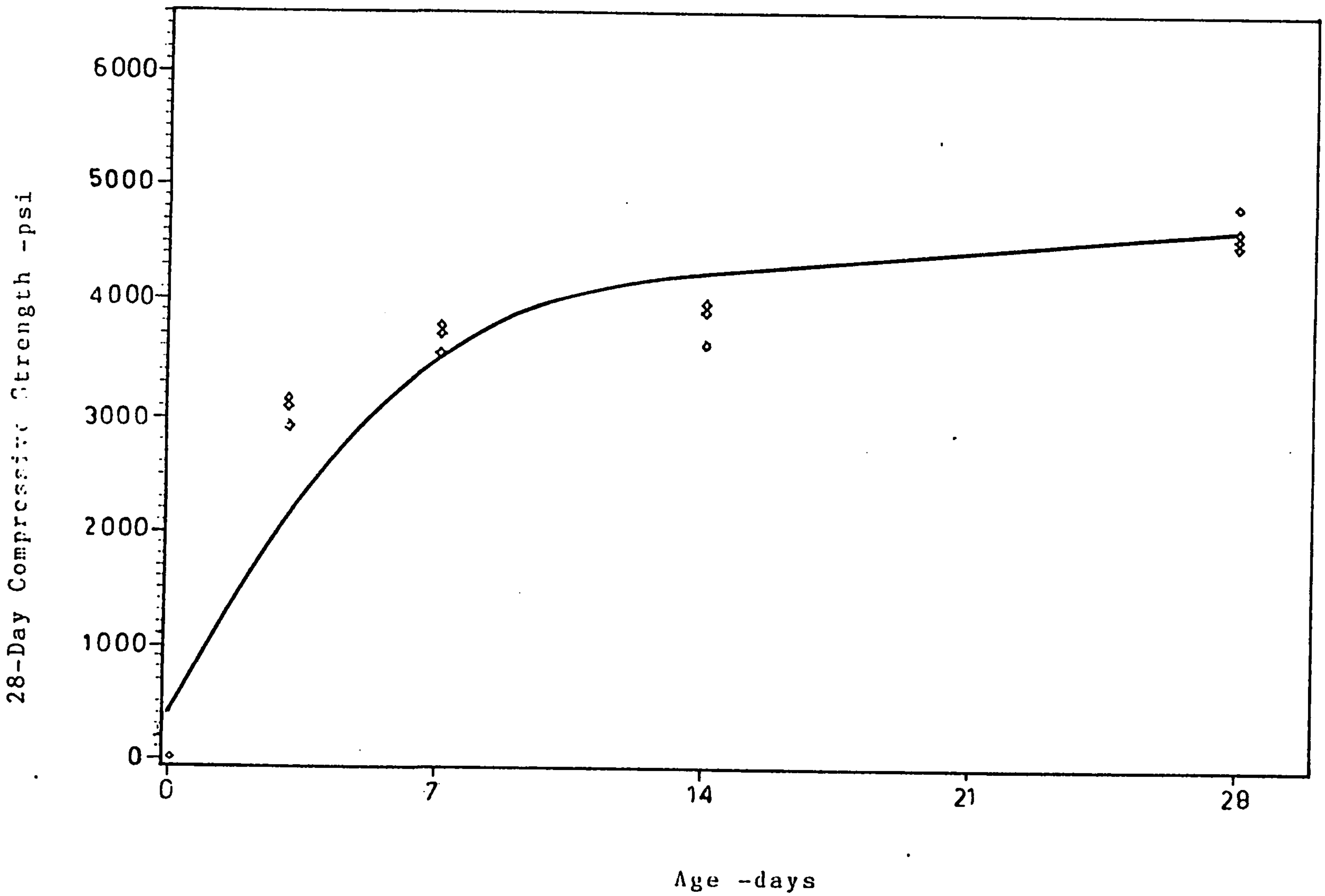


Figure A.22 : Variation of Compressive Strength with Age for Mix D4

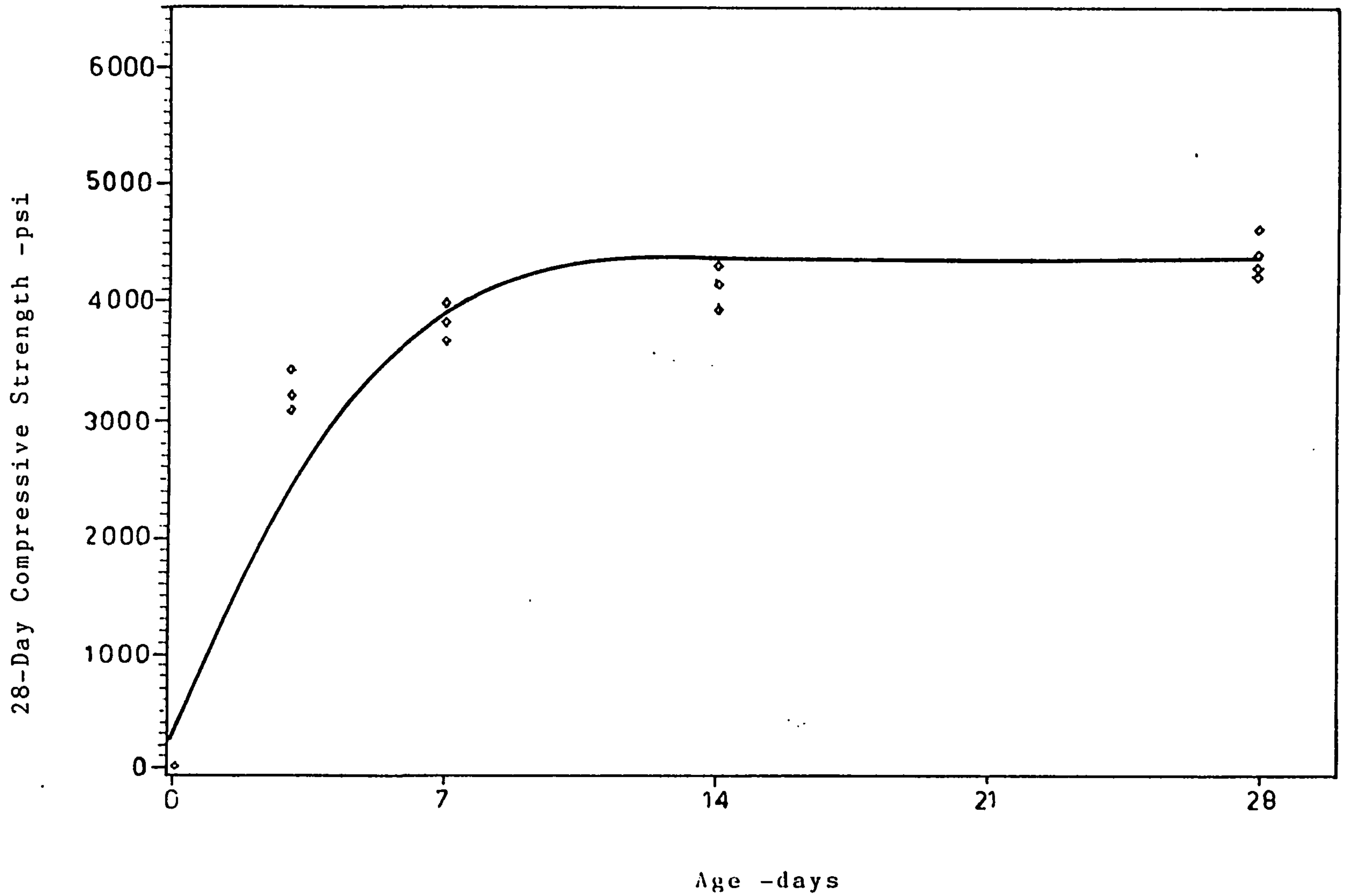


Figure A.23 : Variation of Compressive Strength with Age for Mix D5

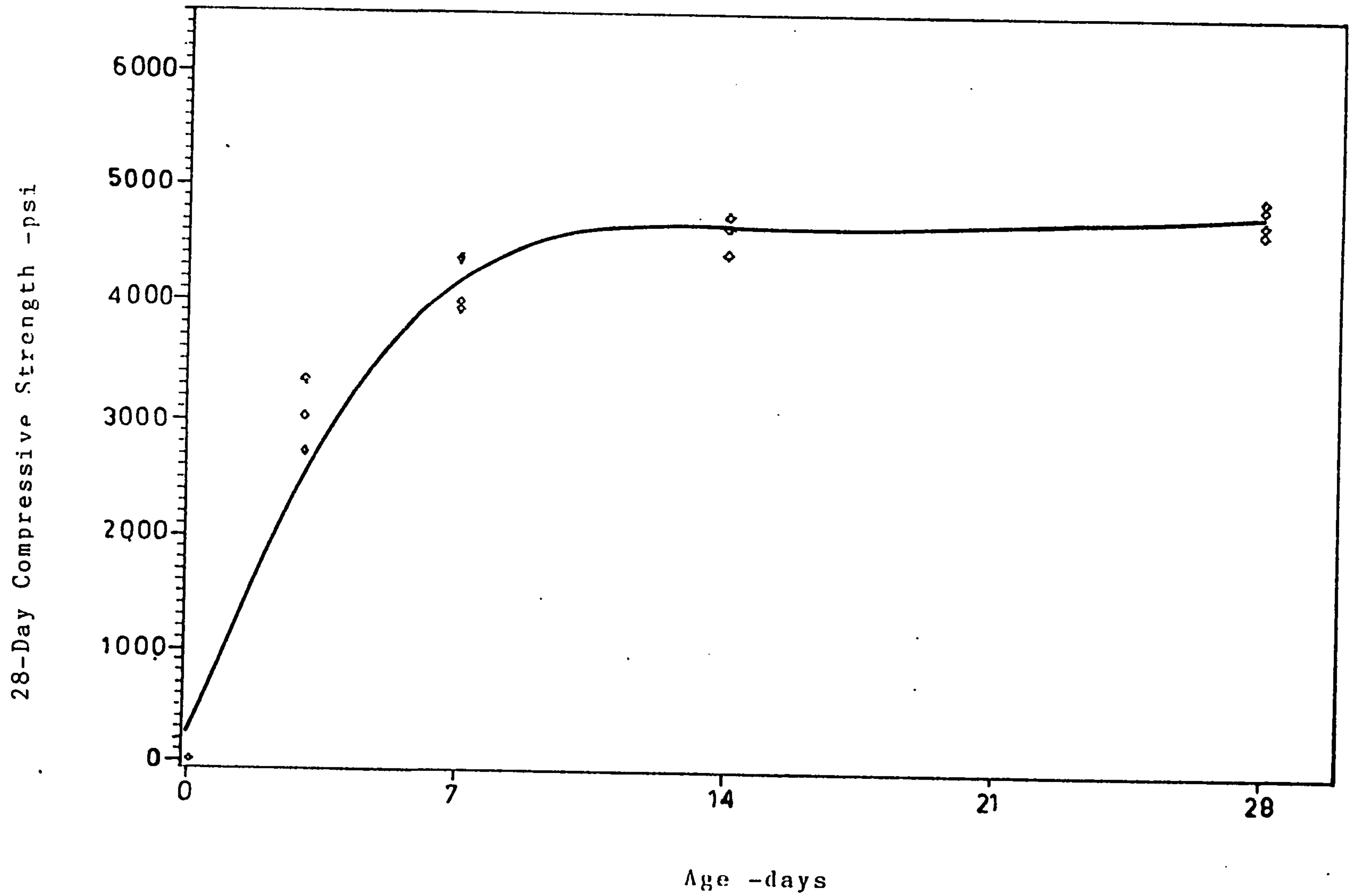


Figure A.24 : Variation of Compressive Strength with Age for Mix D6

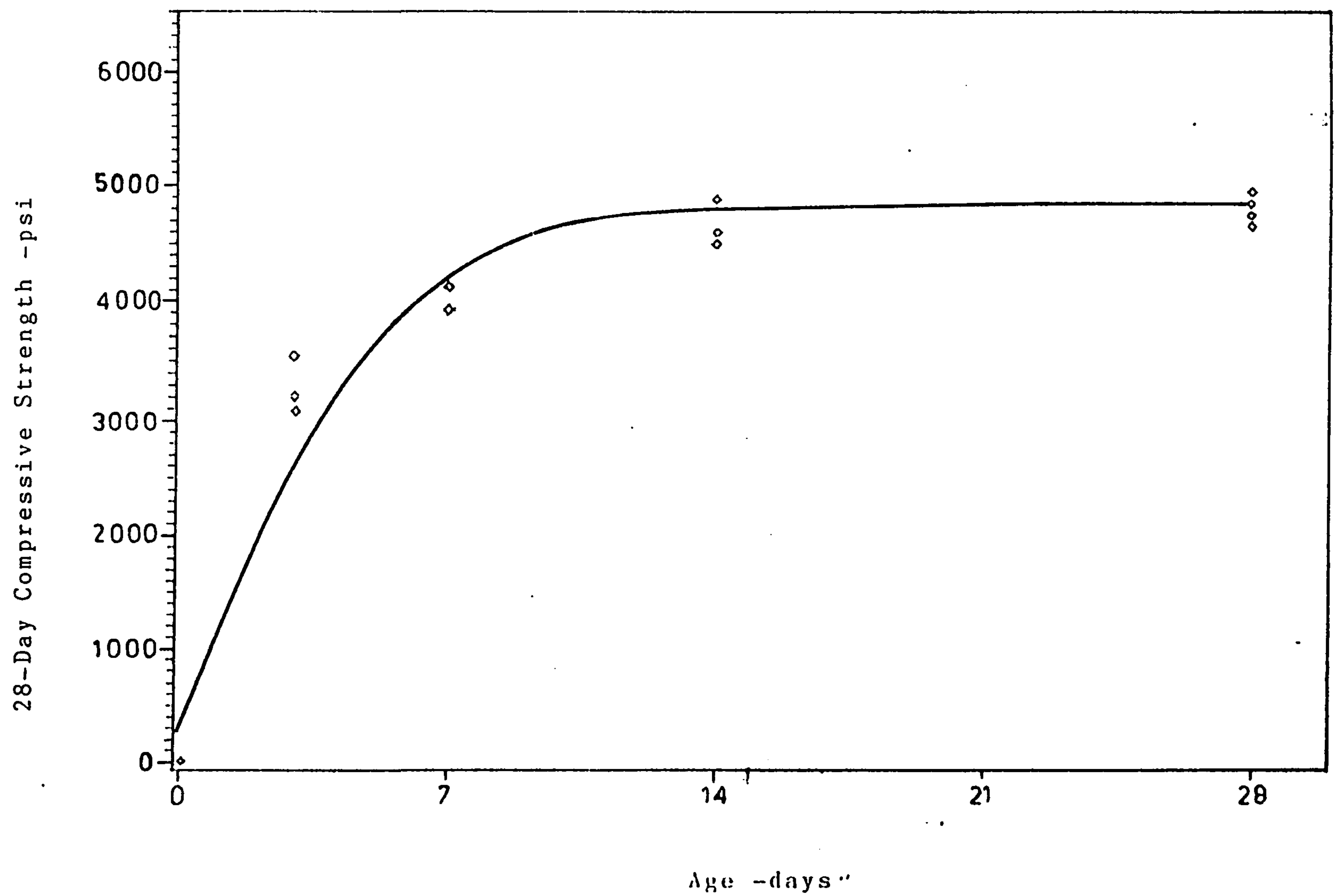


Figure A.25 : Variation of Compressive Strength with Age for Mix E1

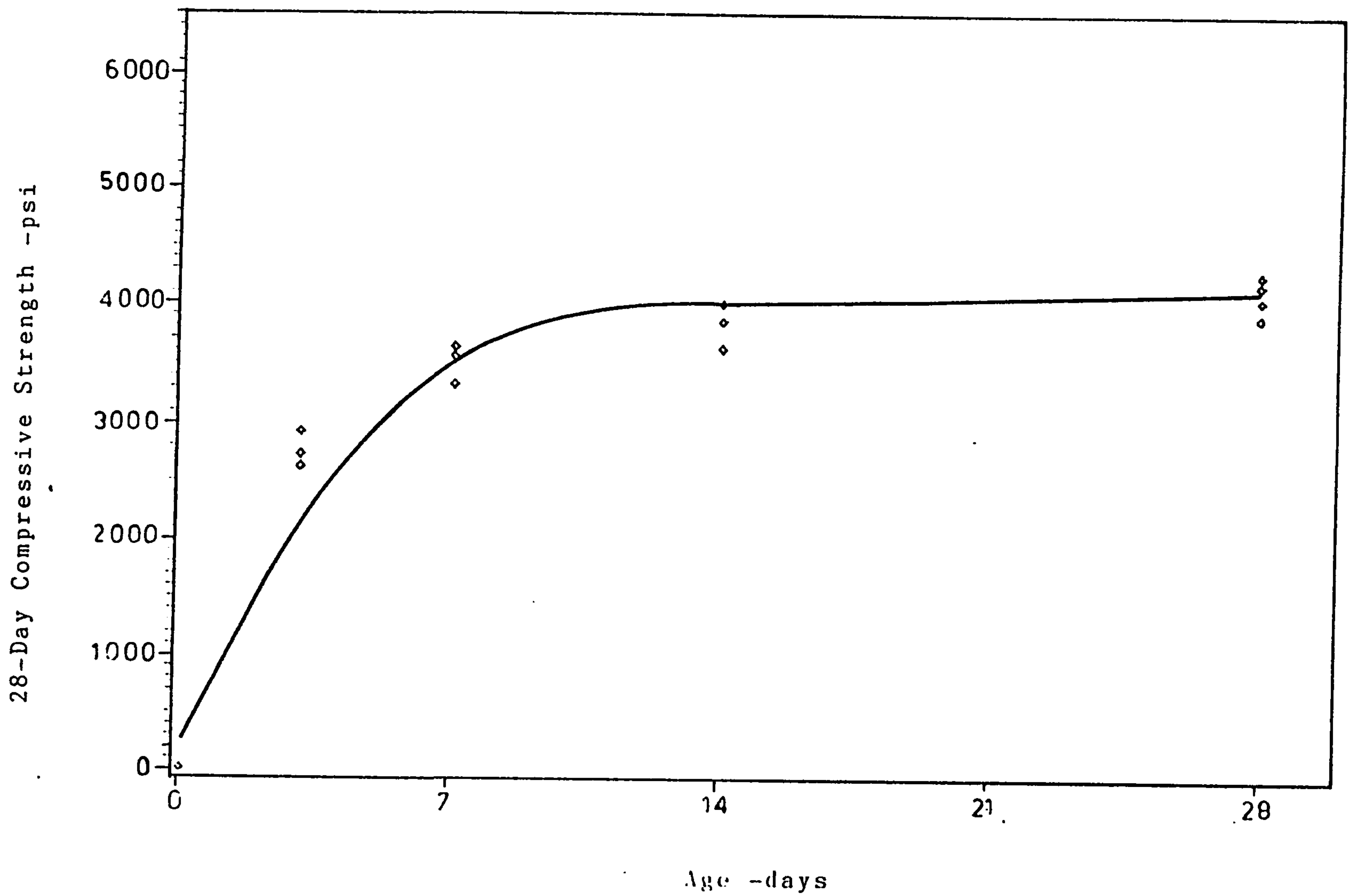


Figure A.26 : Variation of Compressive Strength with Age for Mix E2

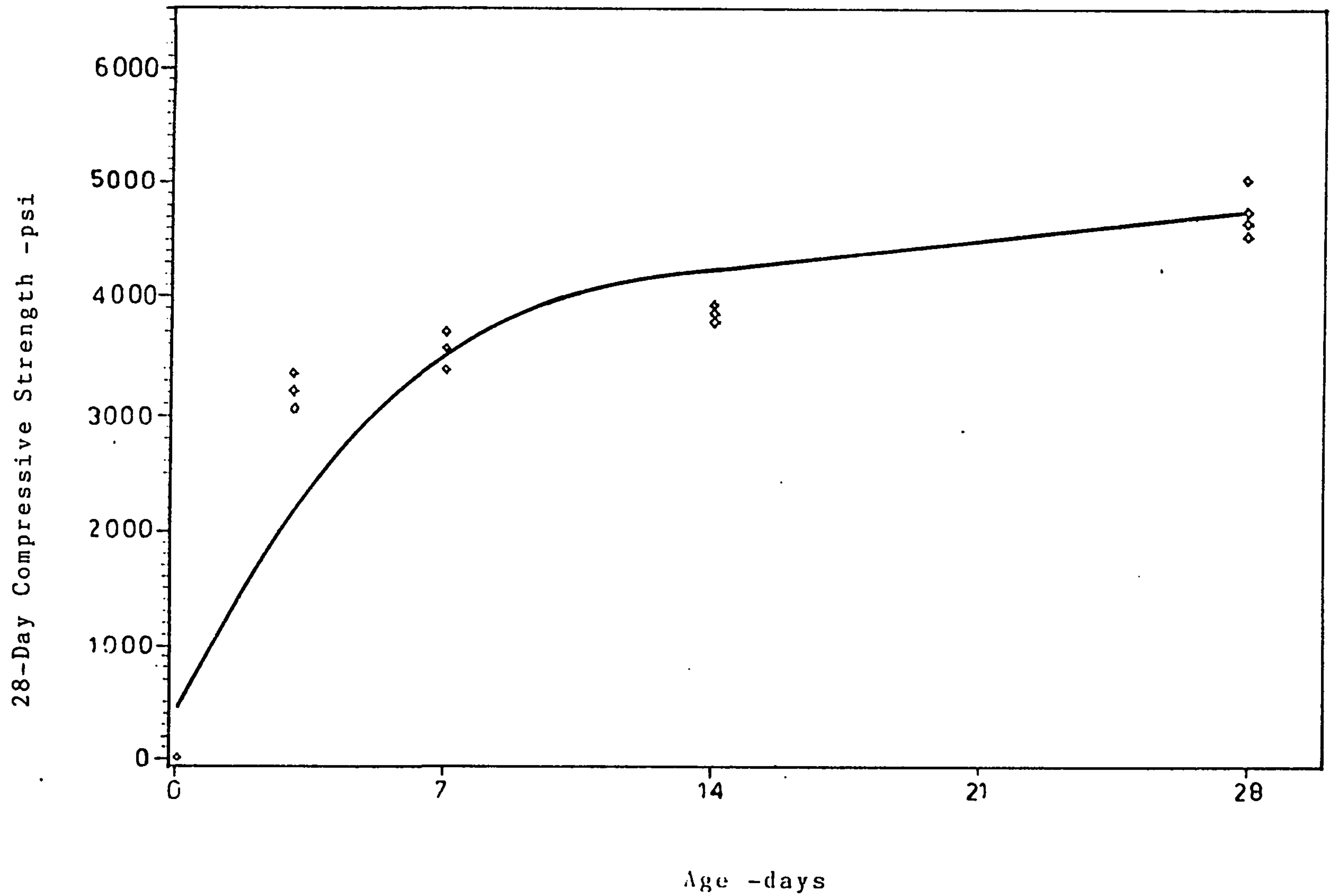


Figure A.27 : Variation of Compressive Strength with Age for Mix E3

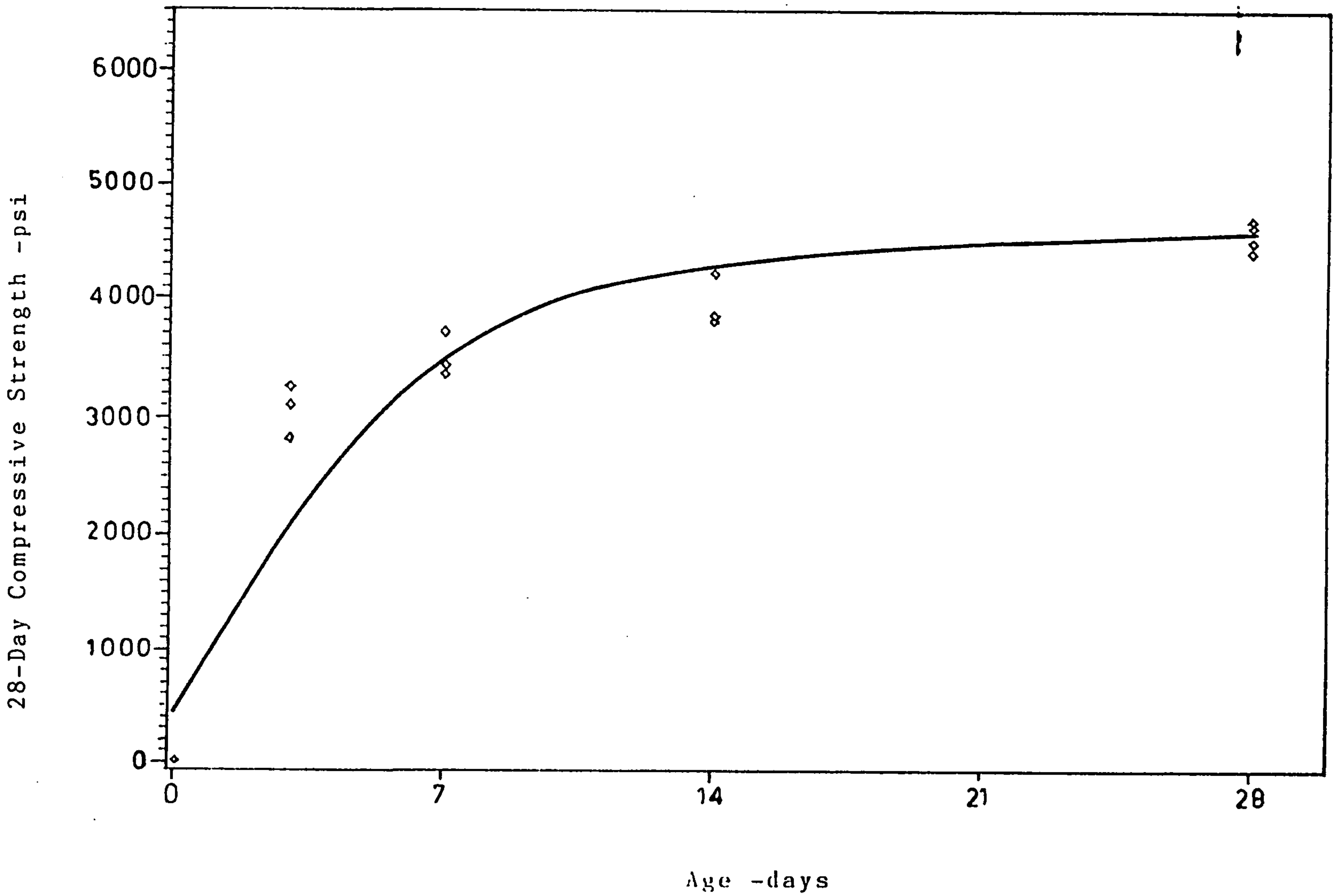


Figure A.28 : Variation of Compressive Strength with Age for Mix E4

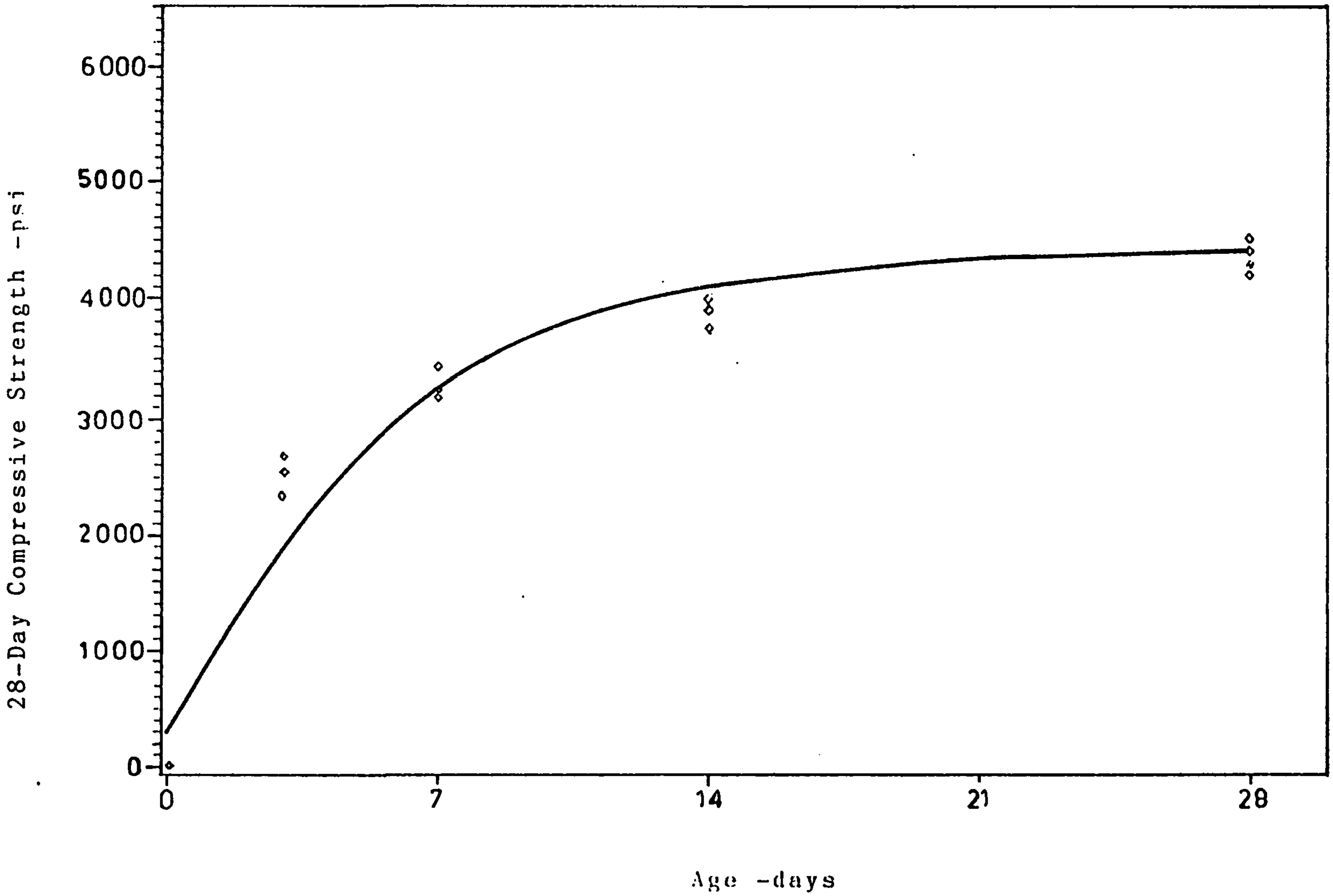


Figure A.29 : Variation of Compressive Strength with Age for Mix E5

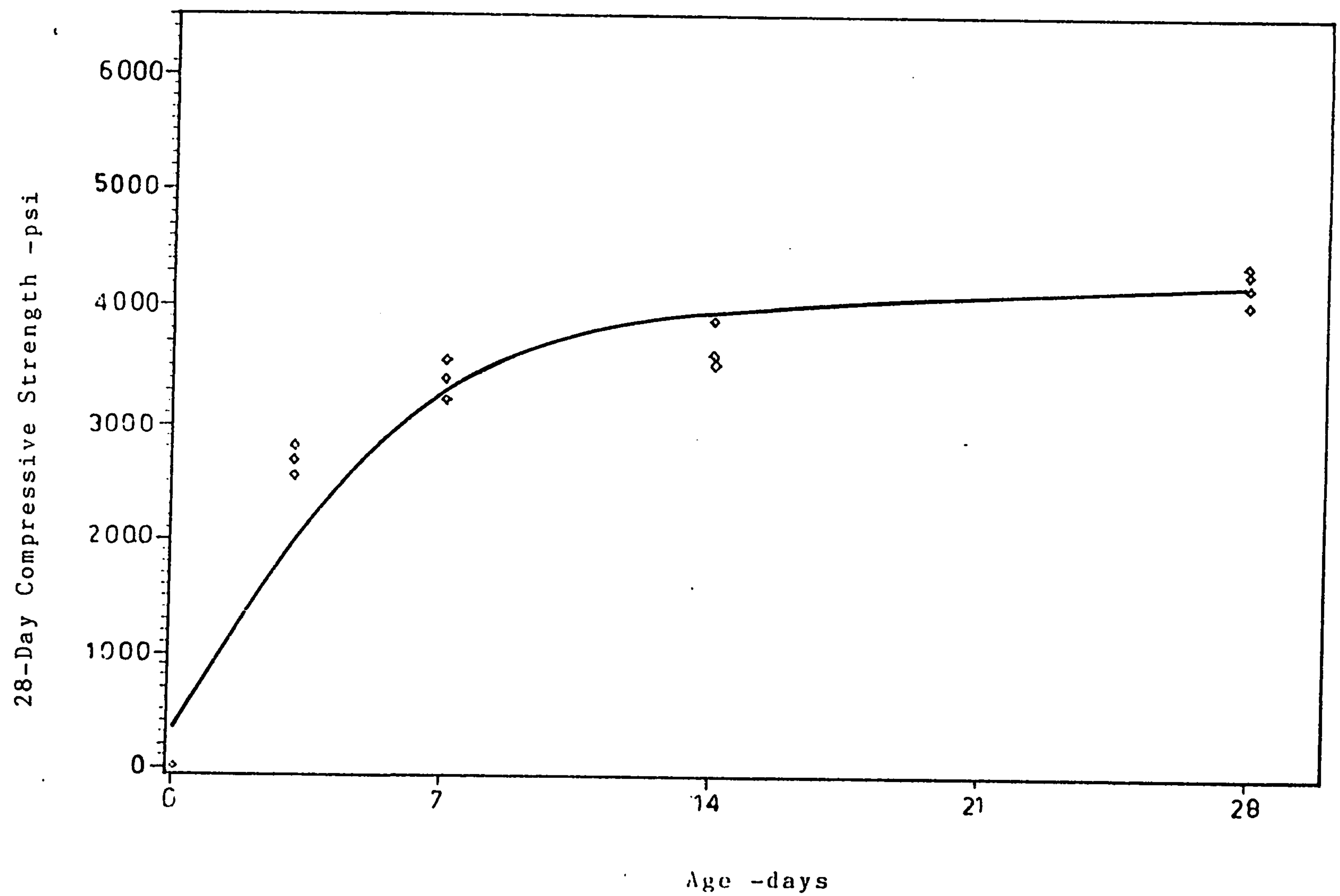


Figure A.30 : Variation of Compressive Strength with Age for Mix E6

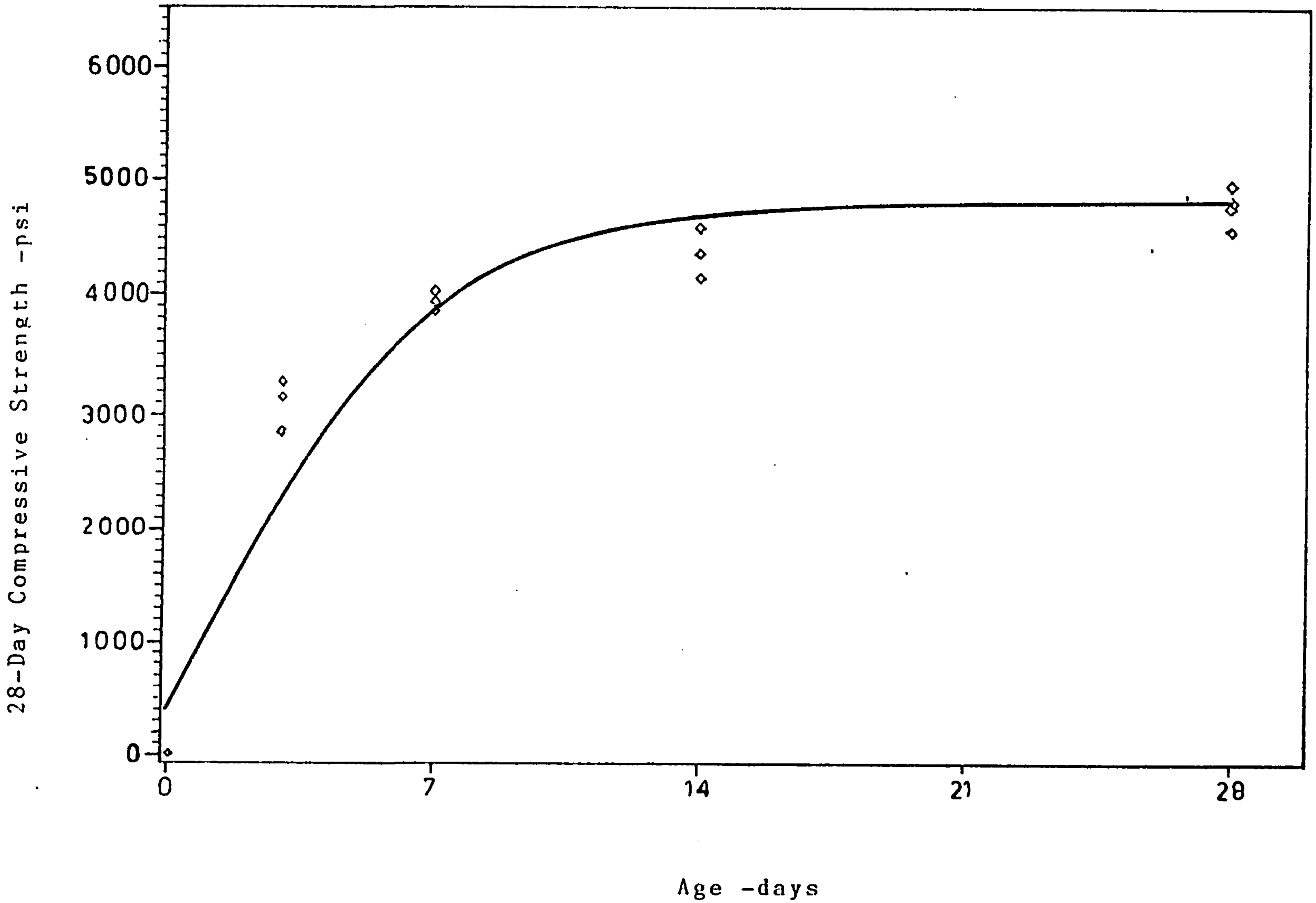


Figure A.31 : Variation of Compressive Strength with Age for Mix F1

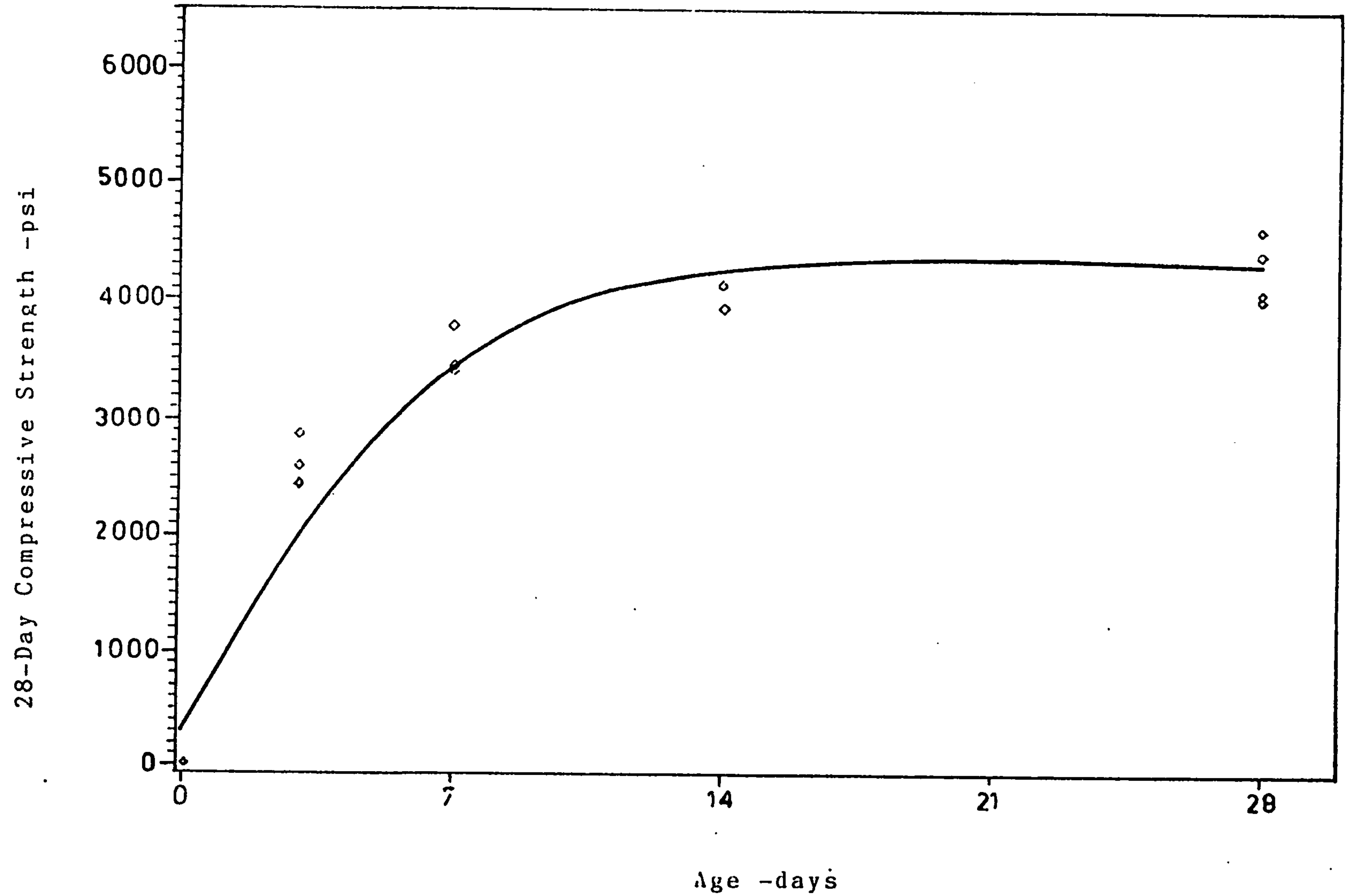


Figure A.32 : Variation of Compressive Strength with Age for Mix F2

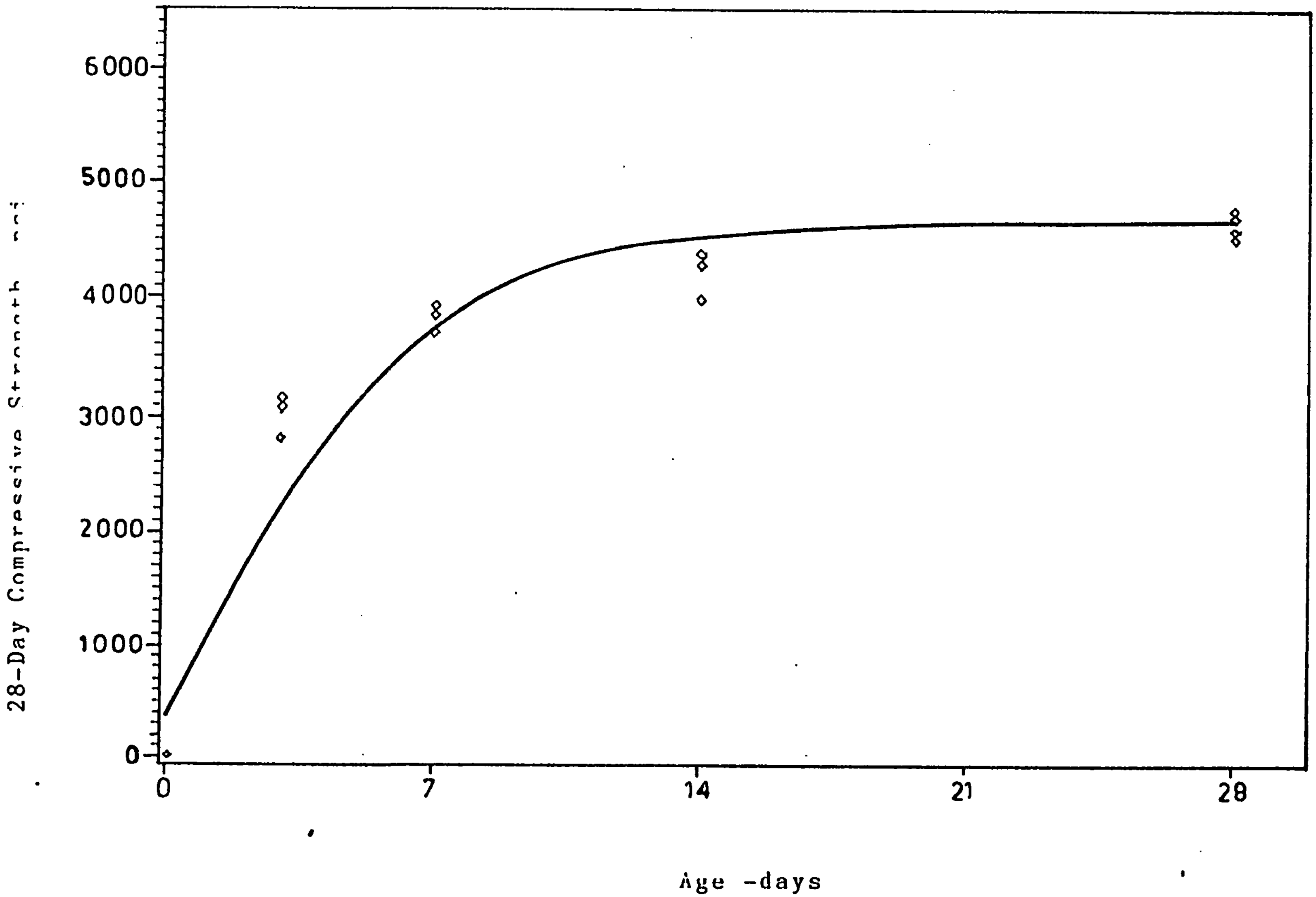
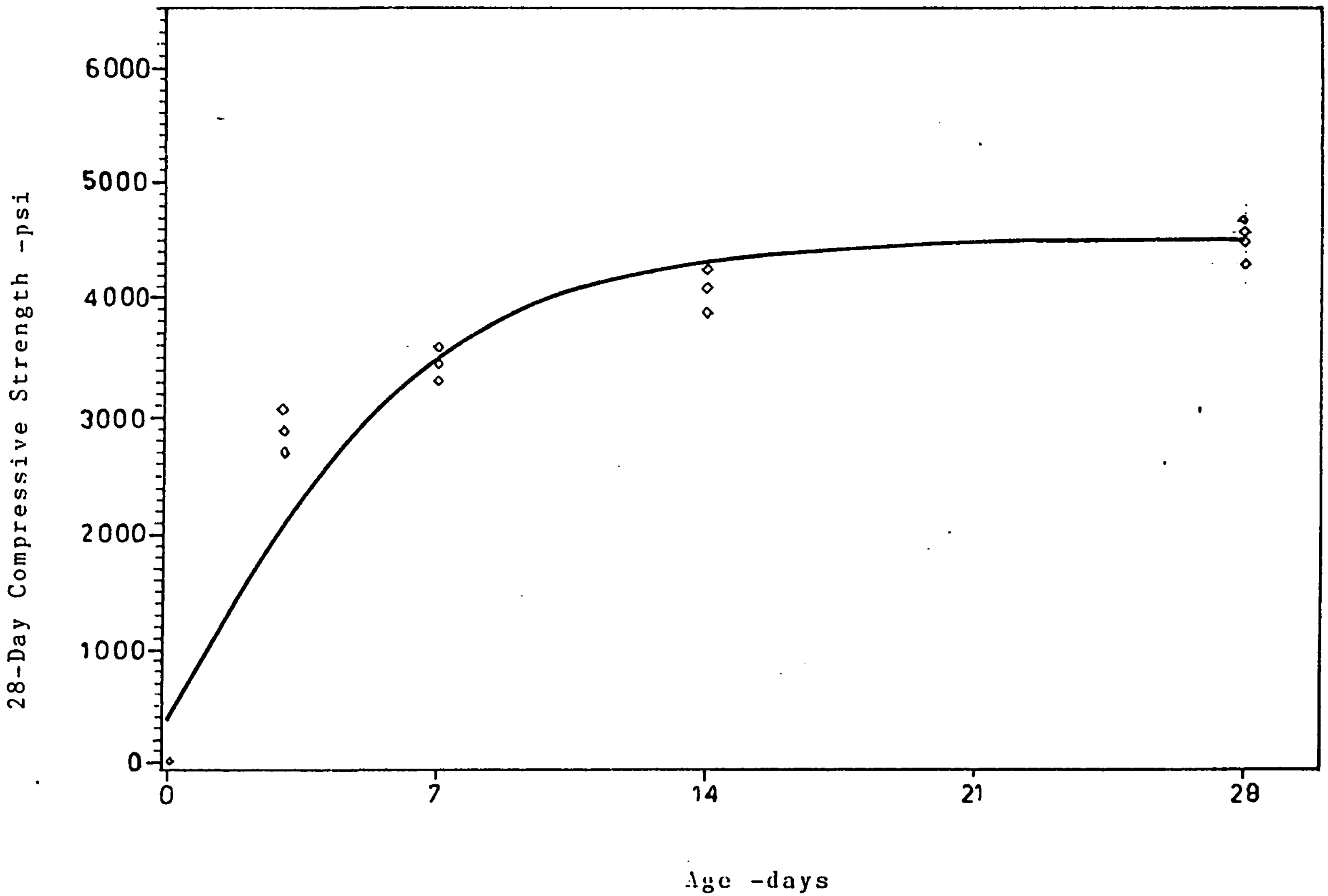


Figure A.33 : Variation of Compressive Strength with Age for Mix F3



FigureA.34 : Variation of Compressive Strength with Age for Mix F4

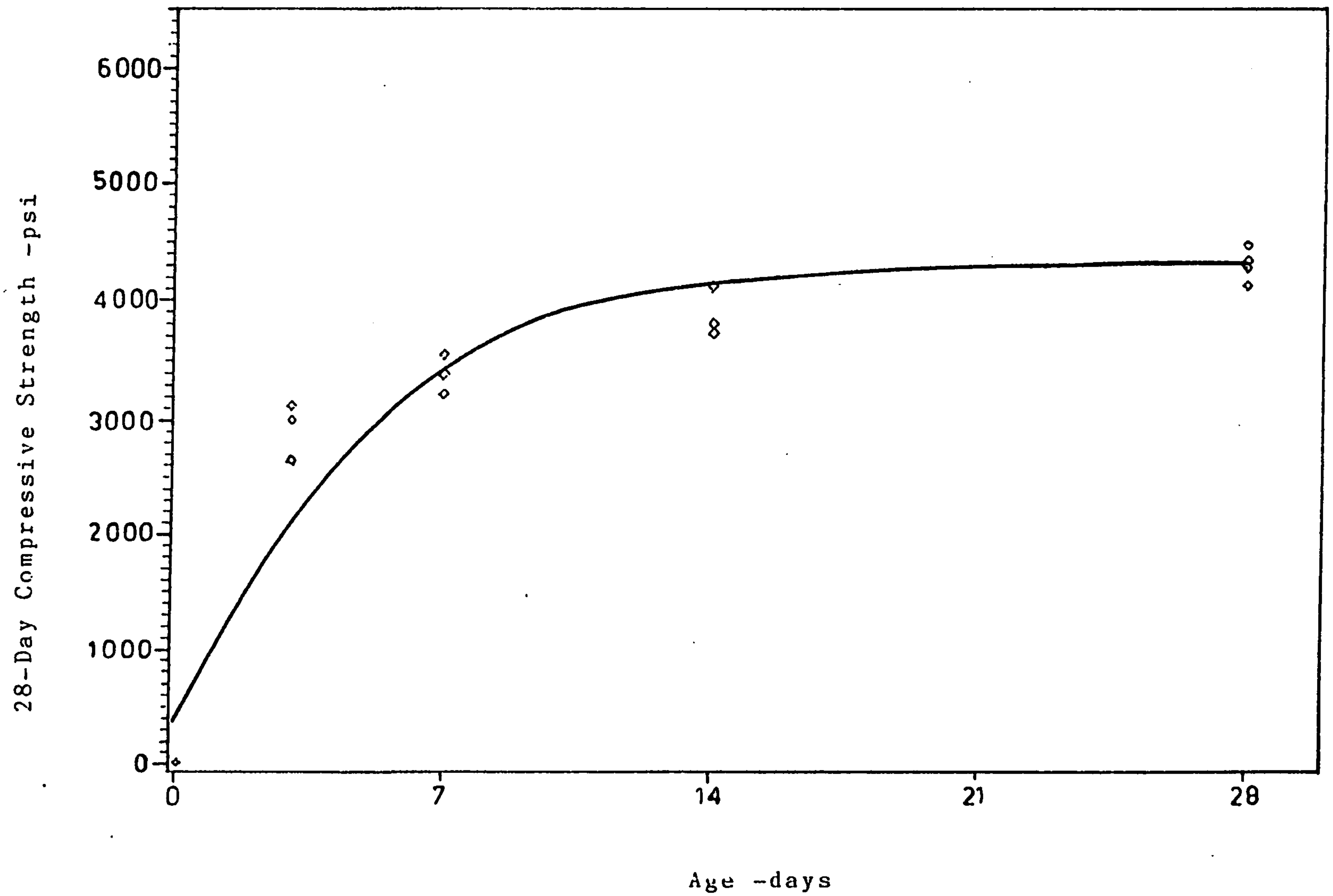
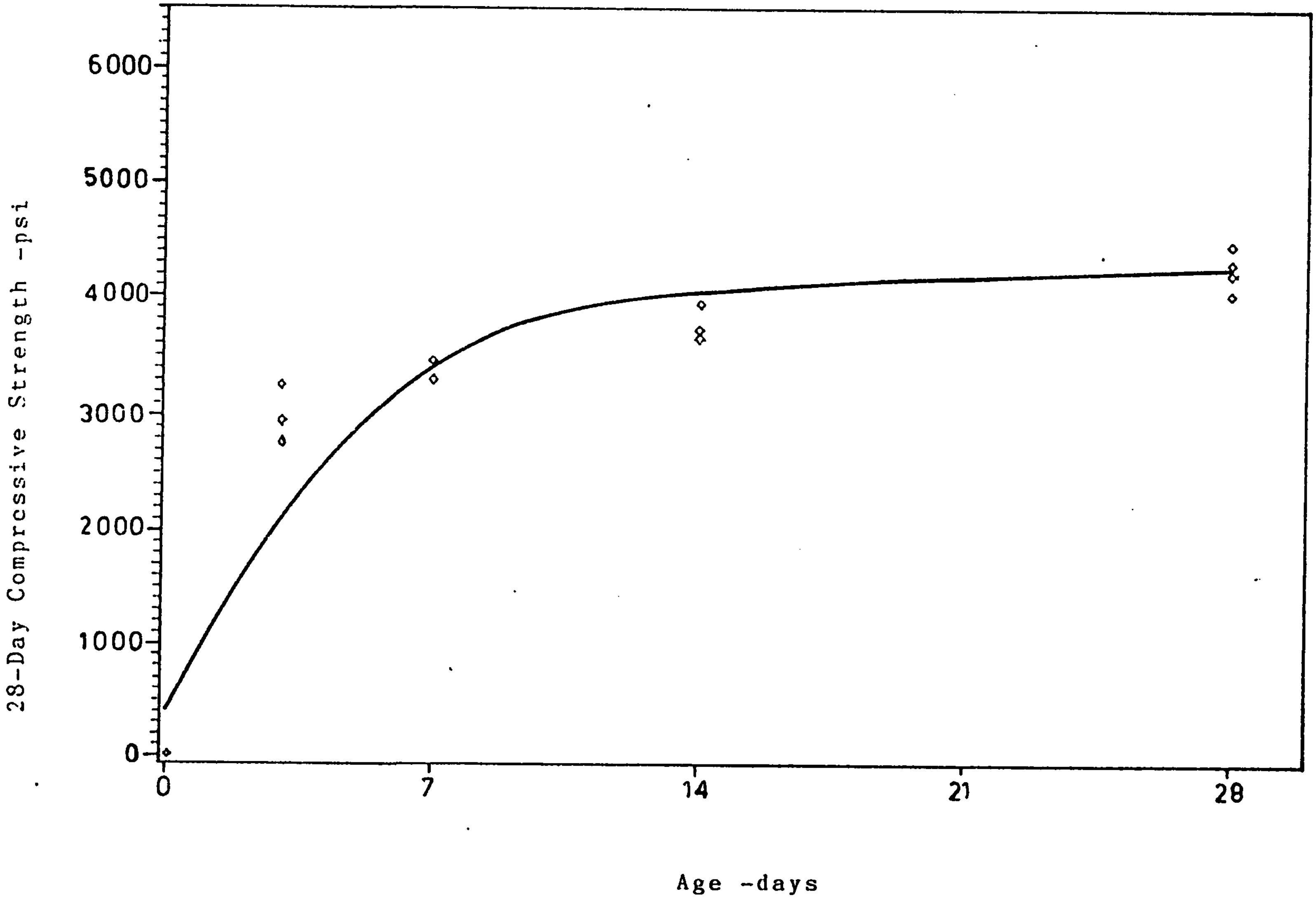


Figure A.35 : Variation of Compressive Strength with Age for Mix F5



FigureA.36 : Variation of Compressive Strength with Age for Mix F6

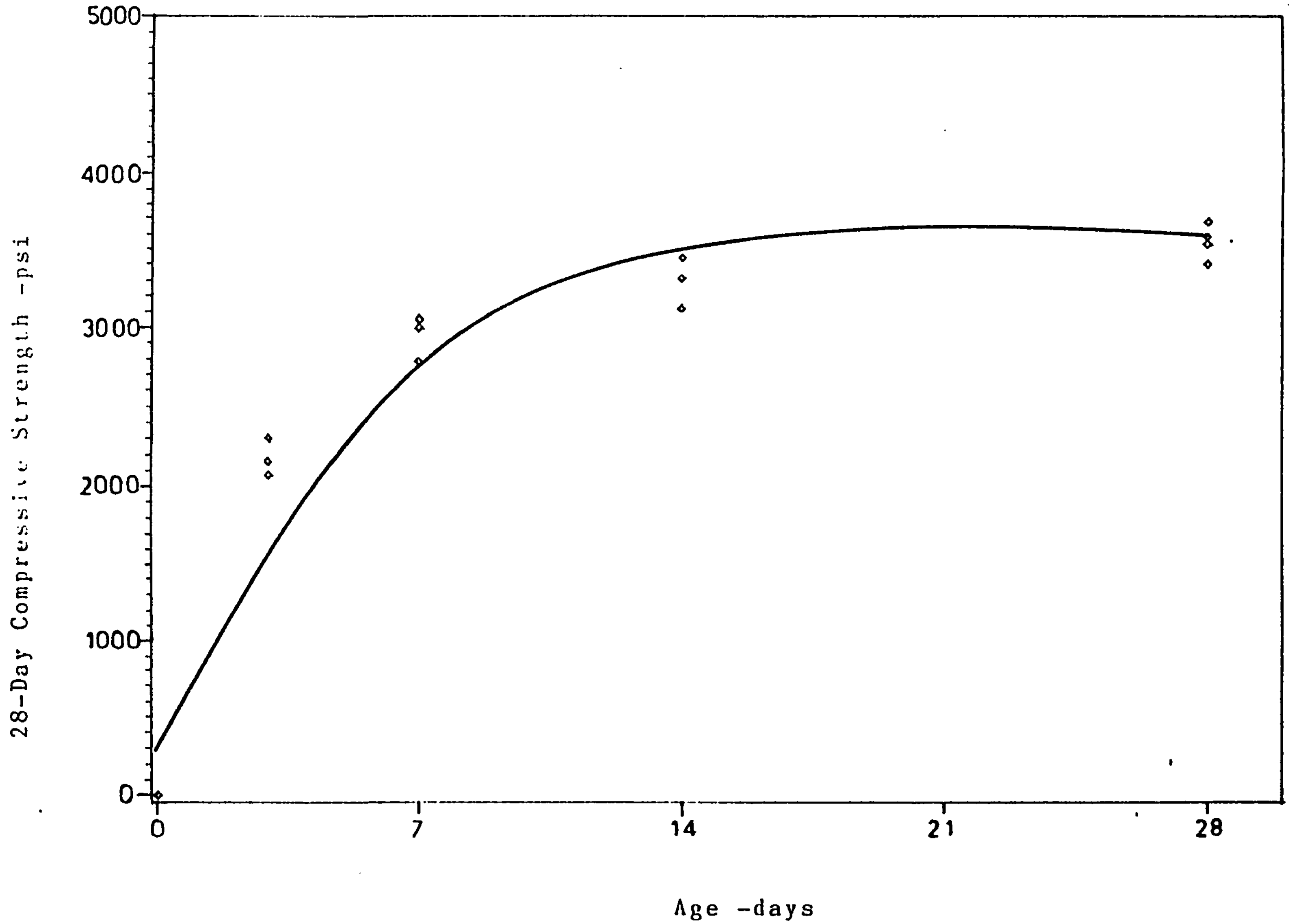


Figure A.37: Variation of Compressive Strength with Age for Mix G1

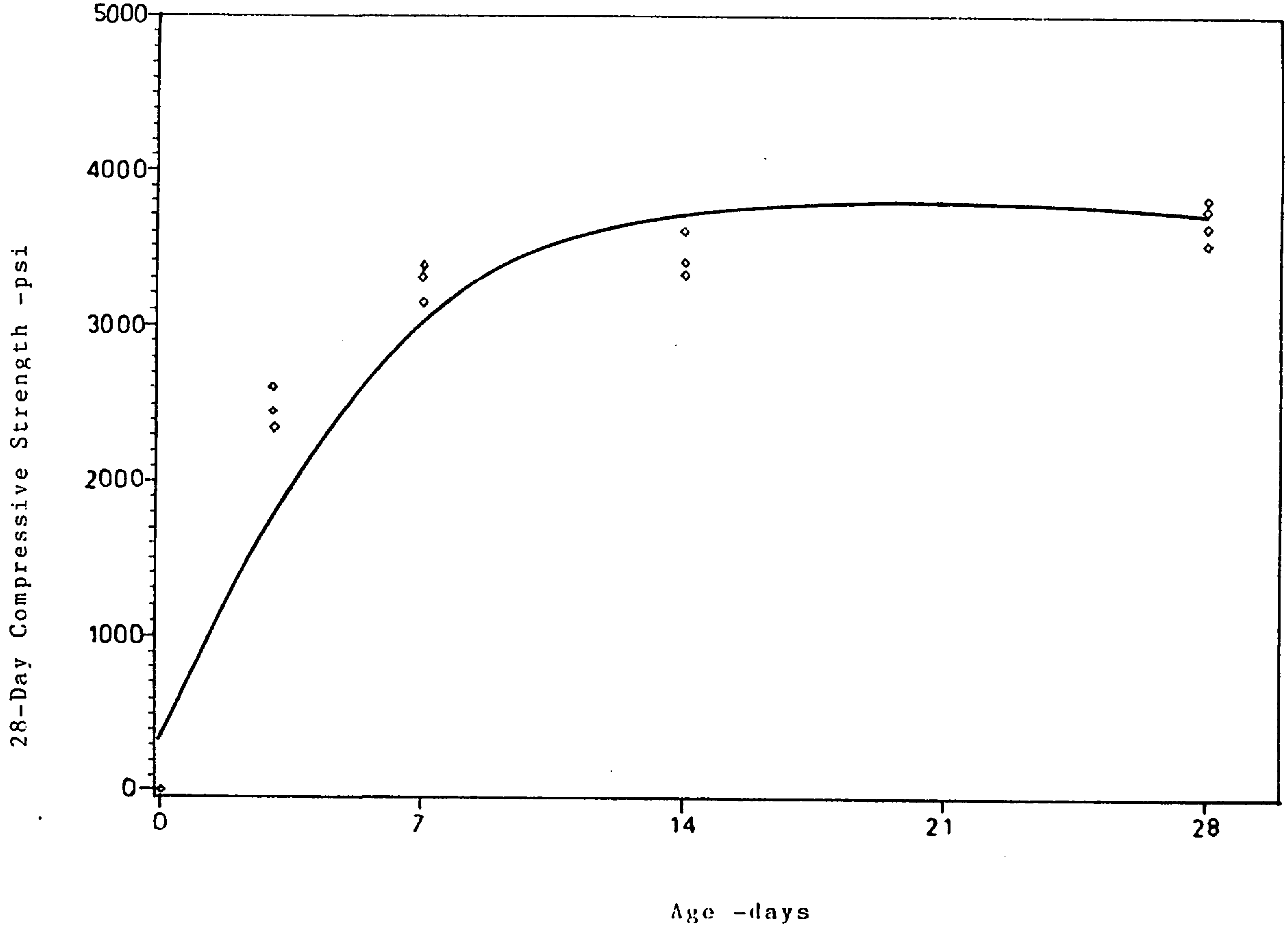


Figure A.38 : Variation of Compressive Strength with Age for Mix G2

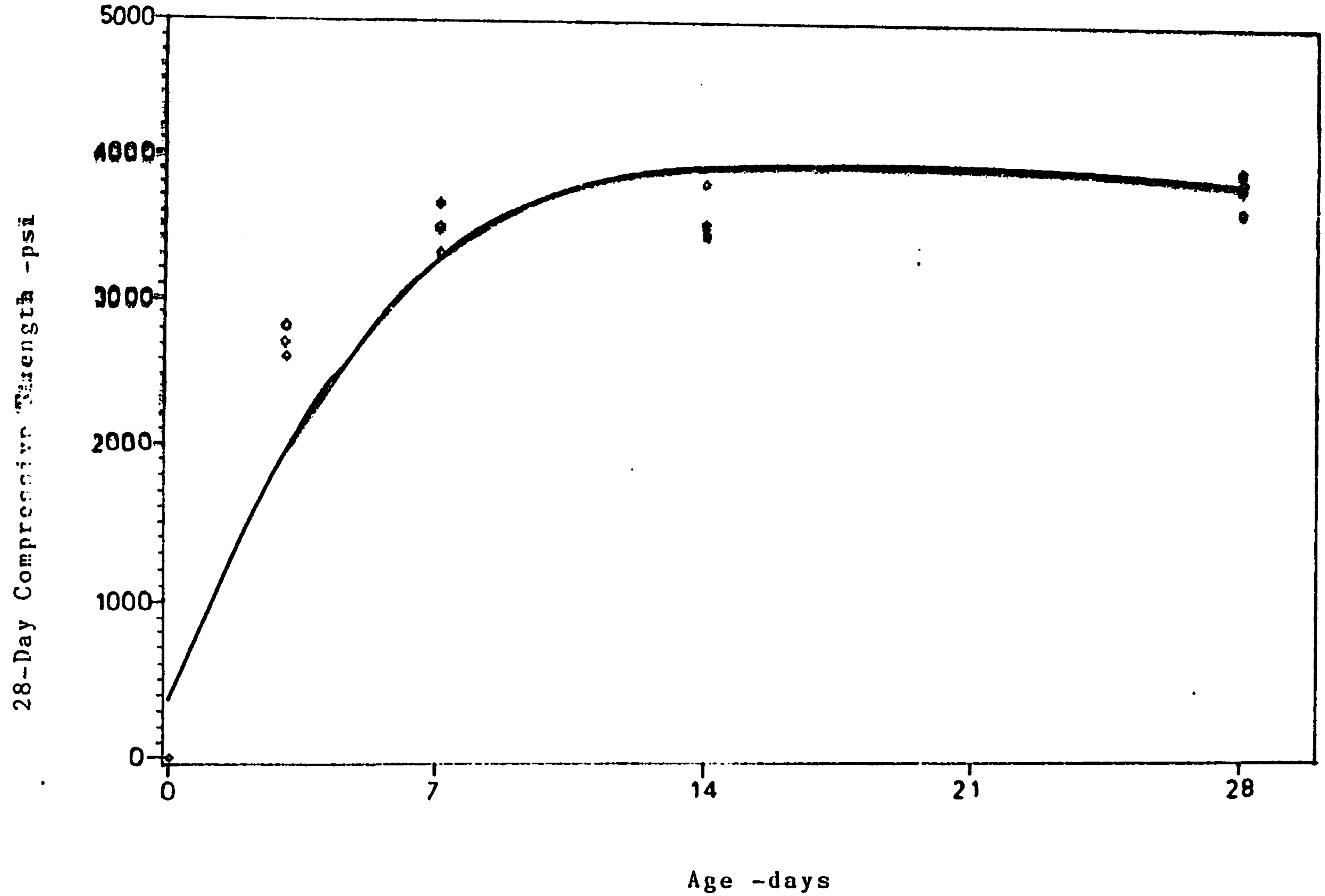


Figure A.39: Variation of Compressive Strength with Age for Mix G3

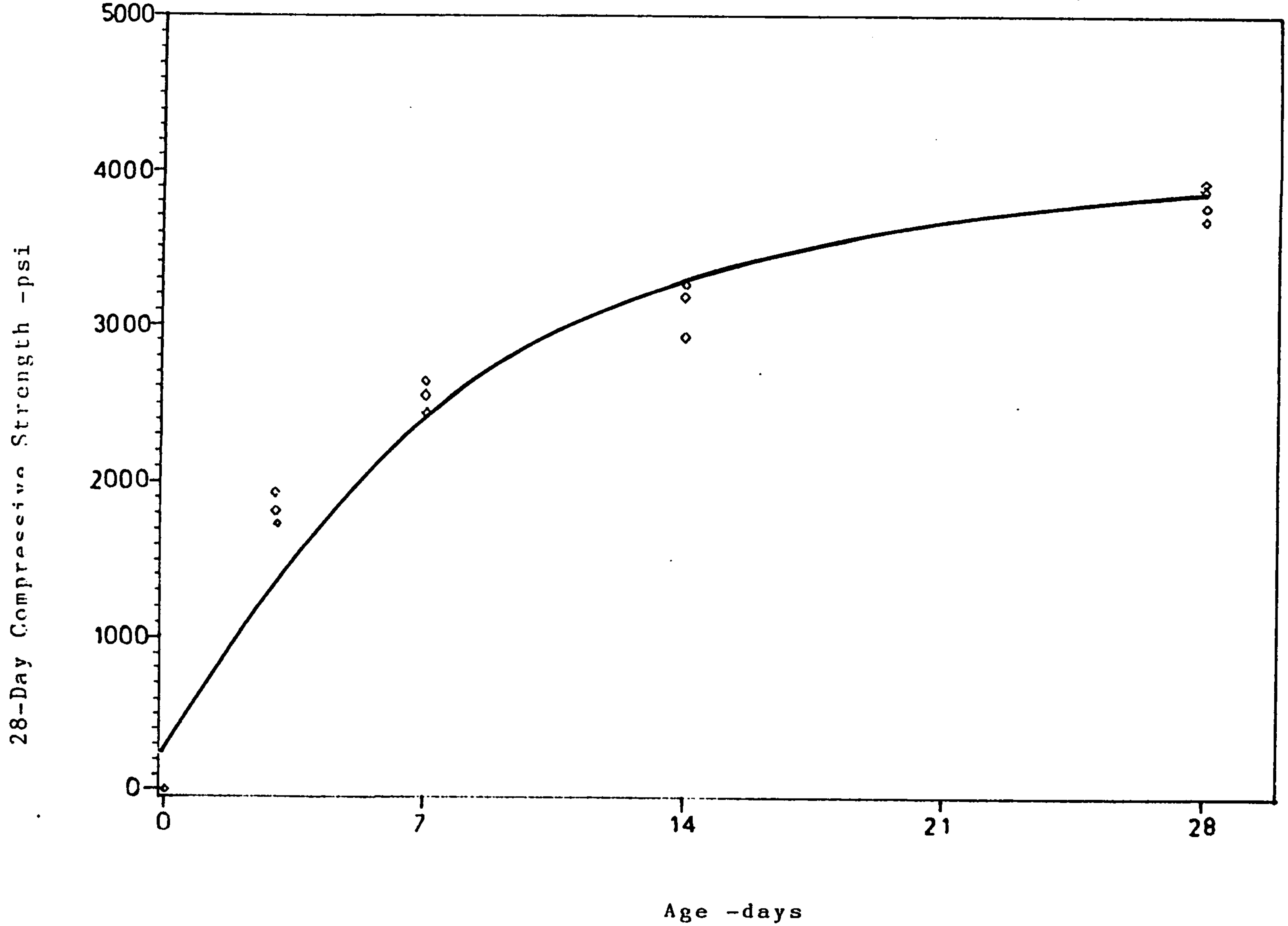


Figure A.40 : Variation of Compressive Strength with Age for Mix G4

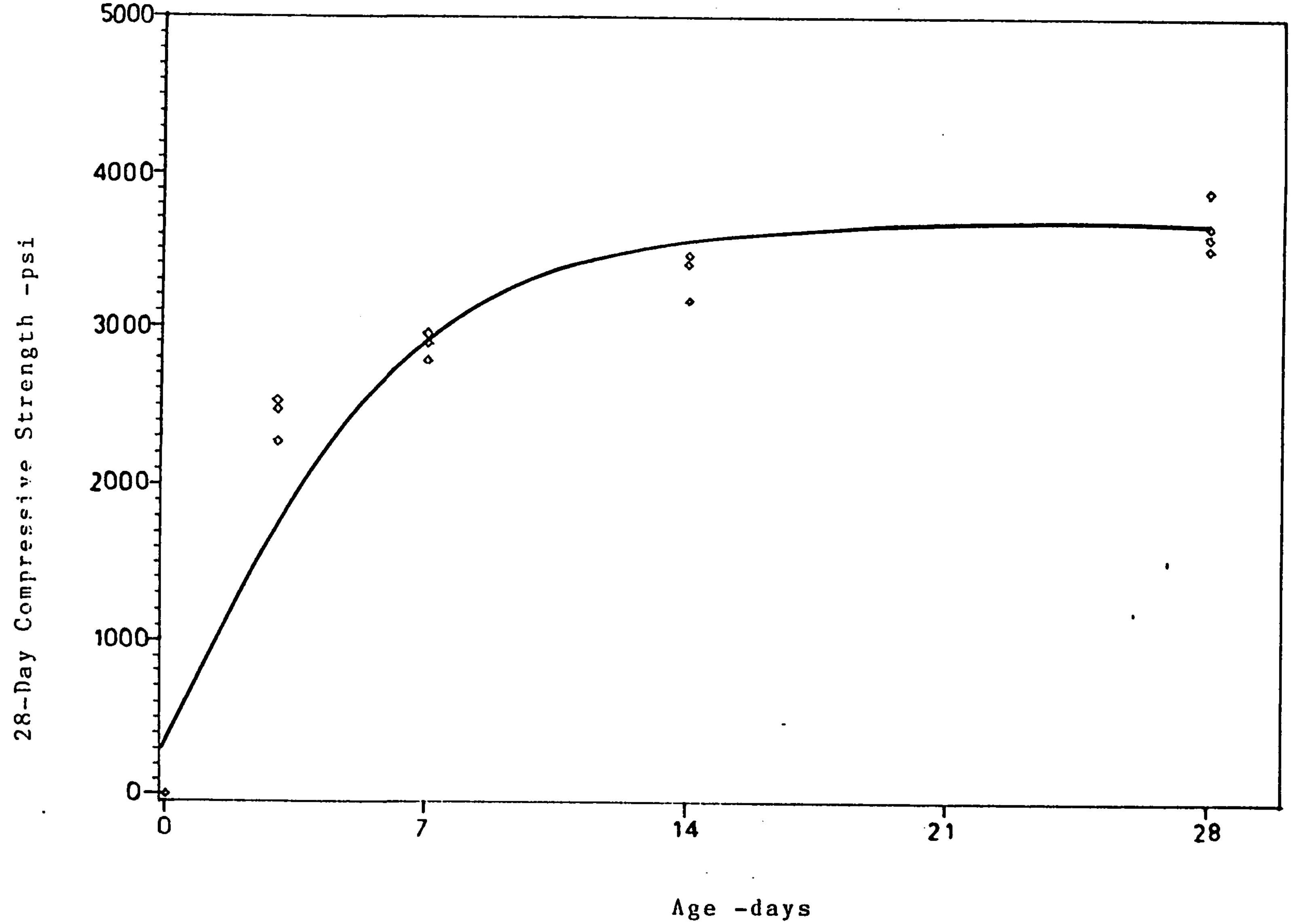


Figure A.41 : Variation of Compressive Strength with Age for Mix G5

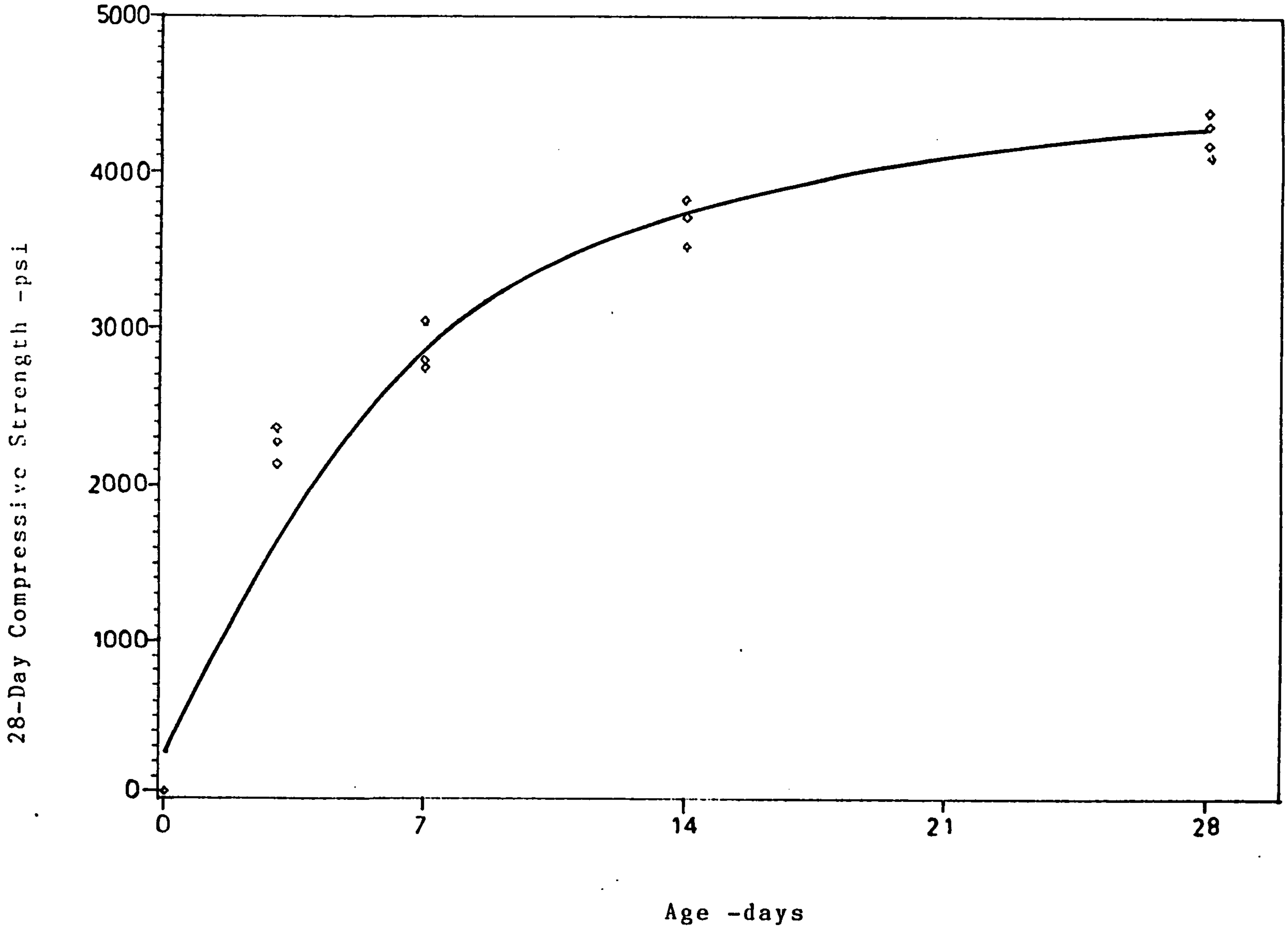


Figure A.42 : Variation of Compressive Strength with Age for Mix G6

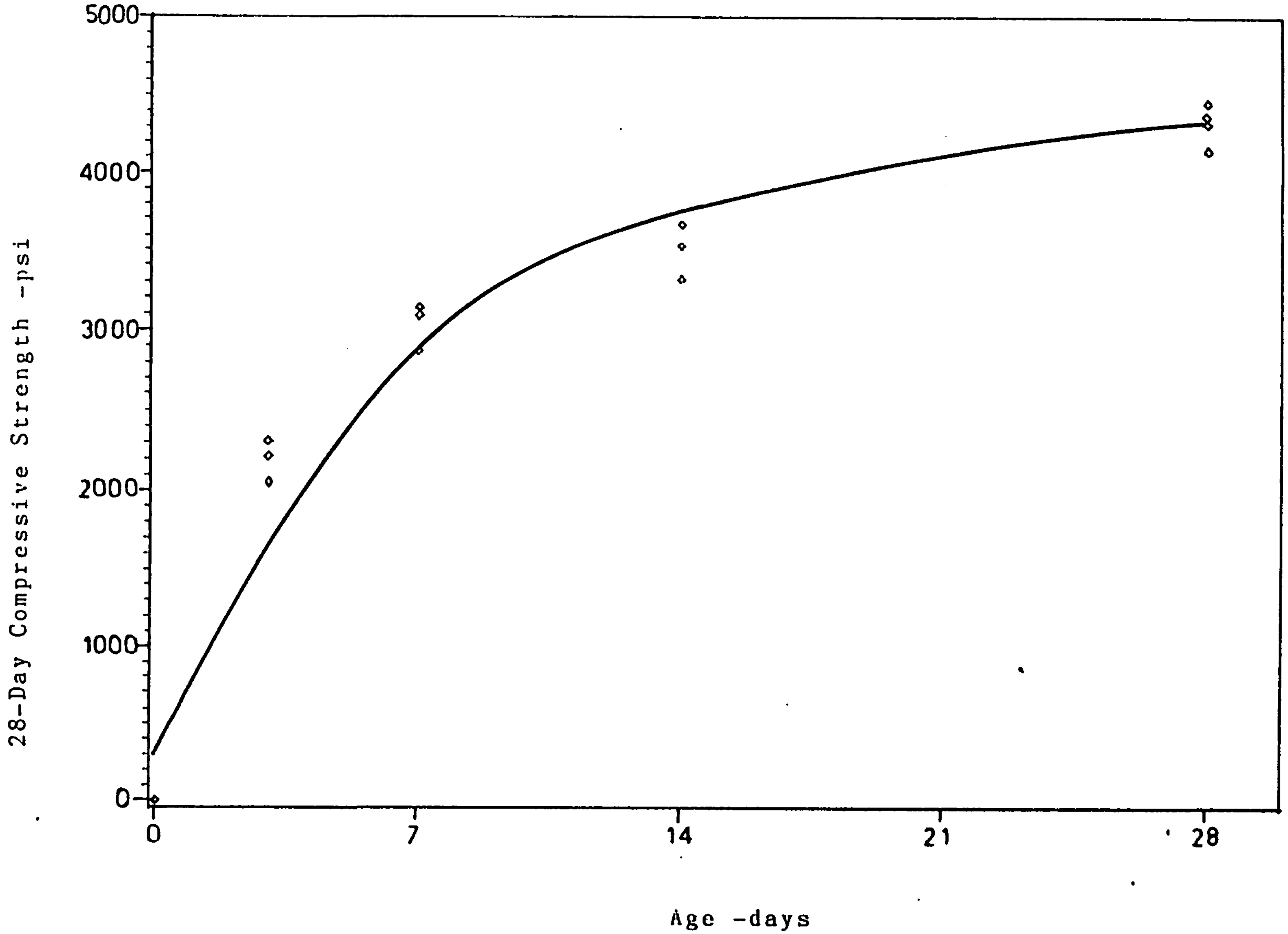


Figure A.43: Variation of Compressive Strength with Age for Mix H1

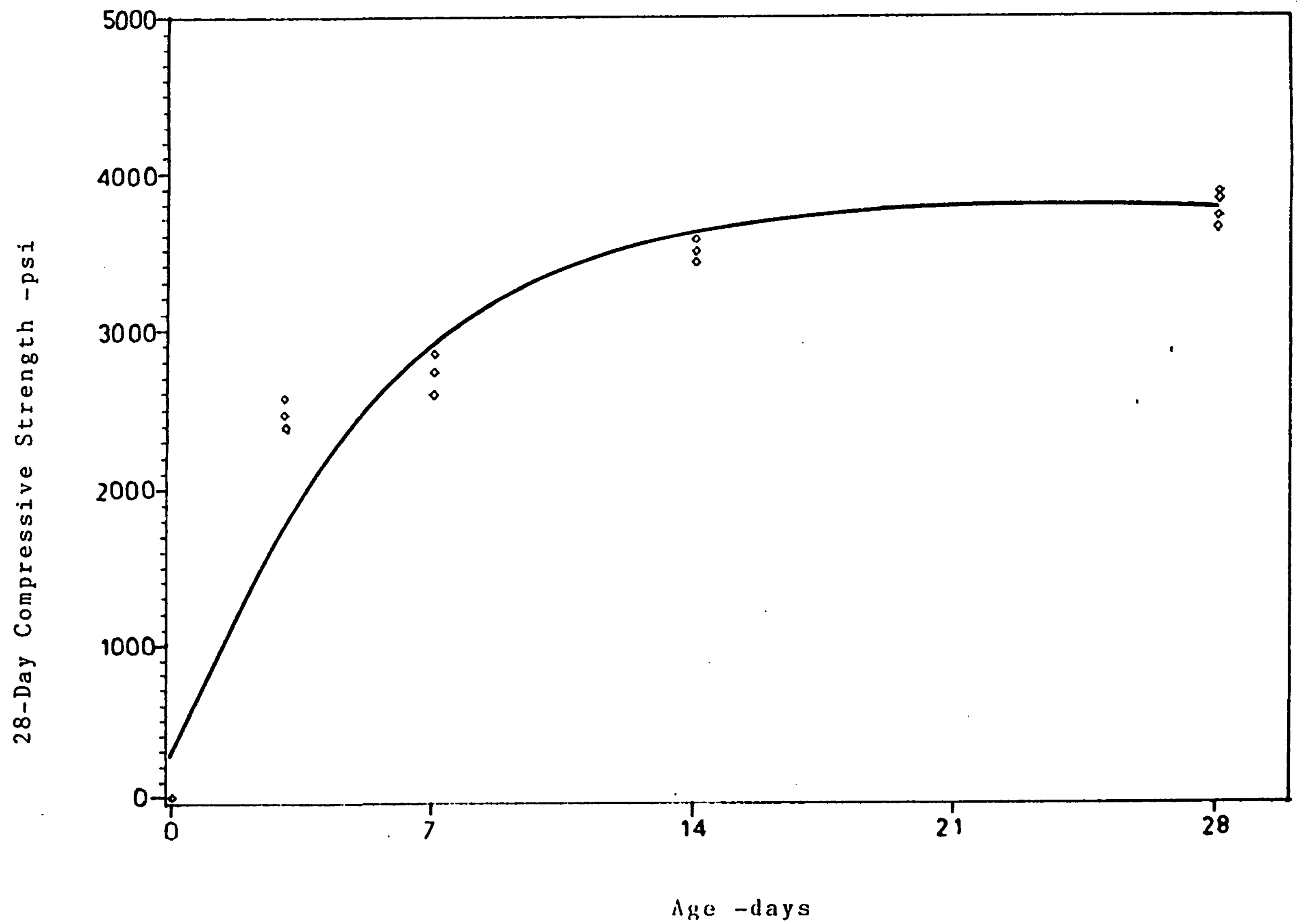


Figure A.44 : Variation of Compressive Strength with Age for Mix H2

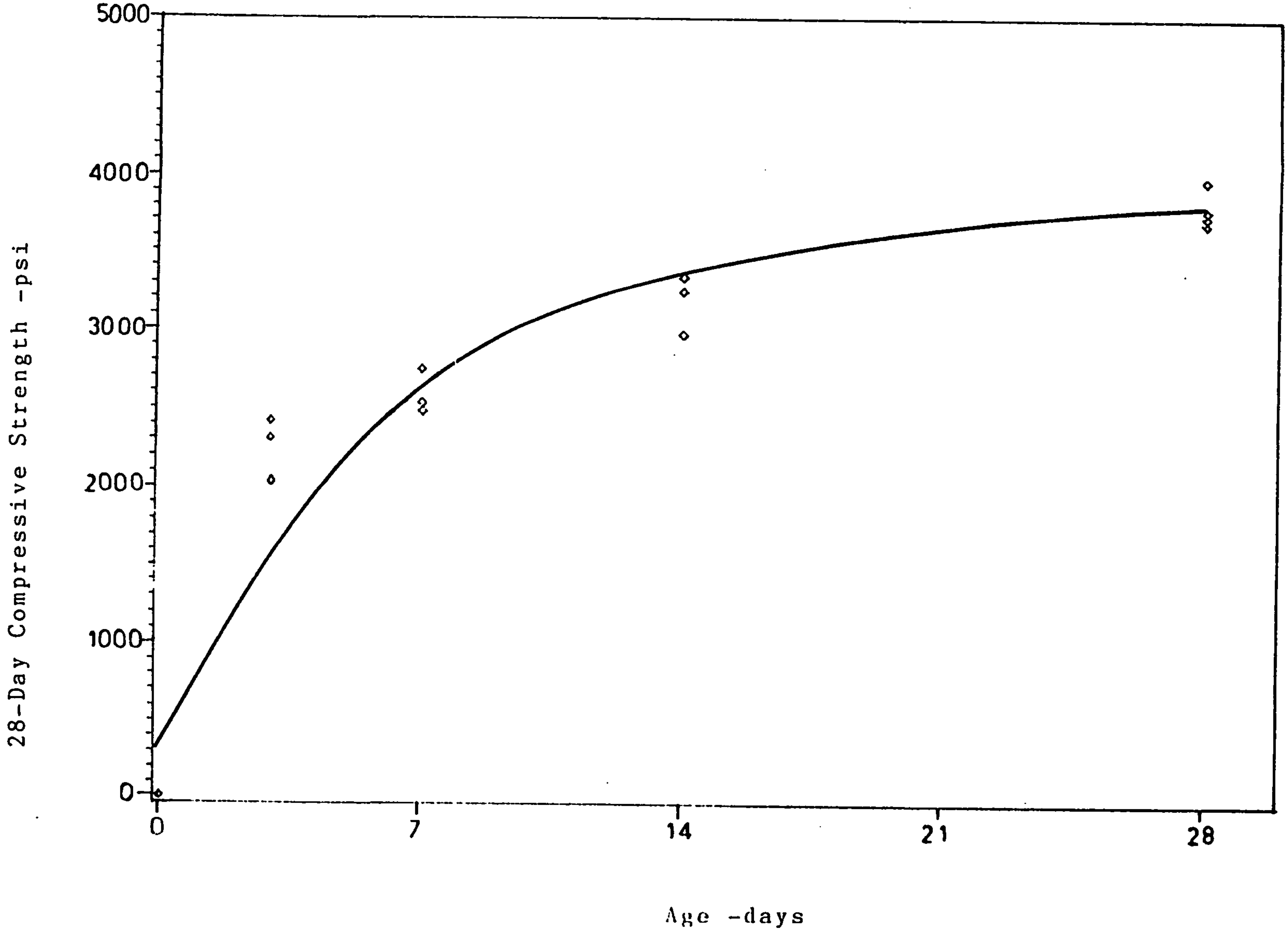


Figure A.45 : Variation of Compressive Strength with Age for Mix H3

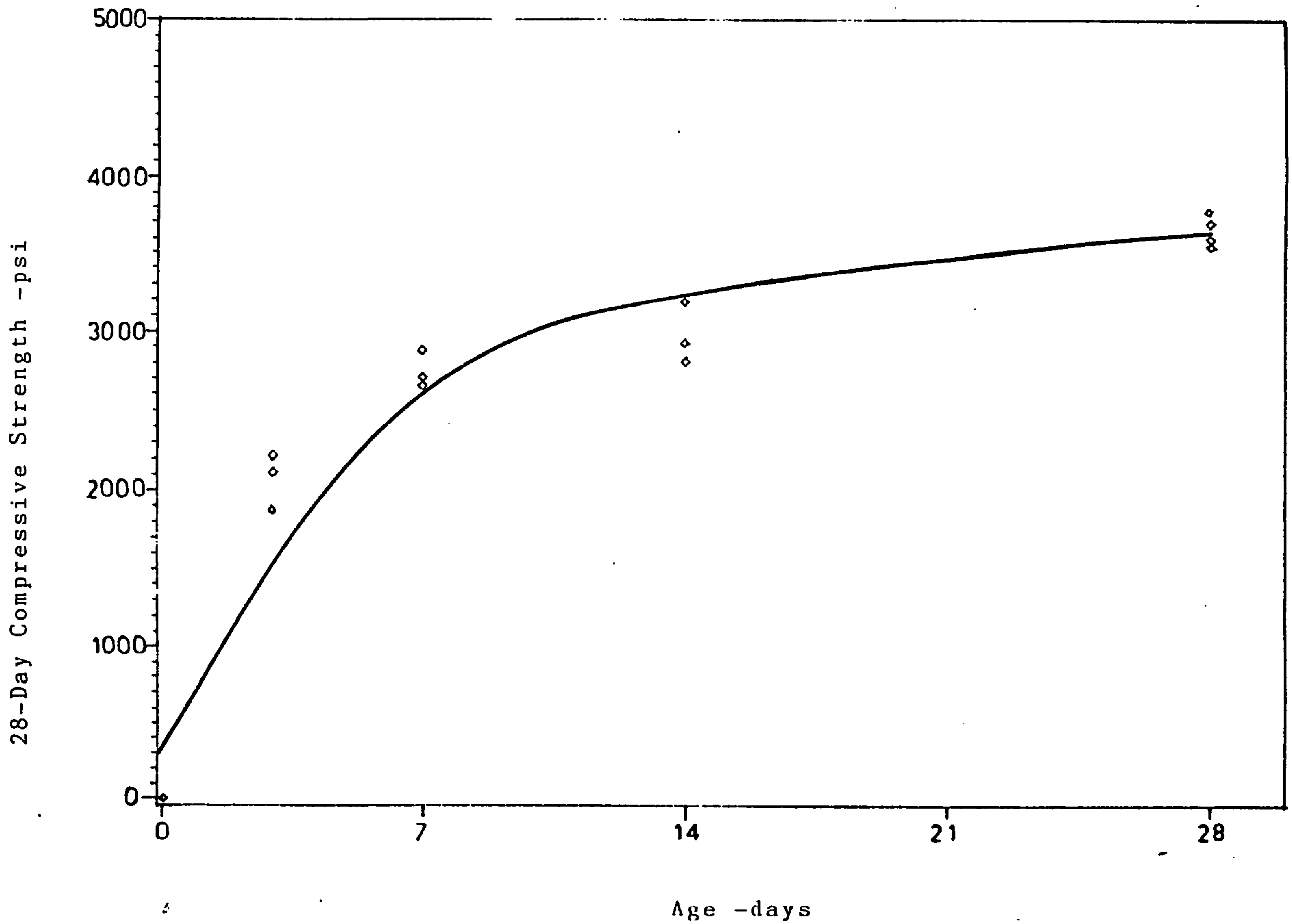


Figure A.46: Variation of Compressive Strength with Age for Mix H4

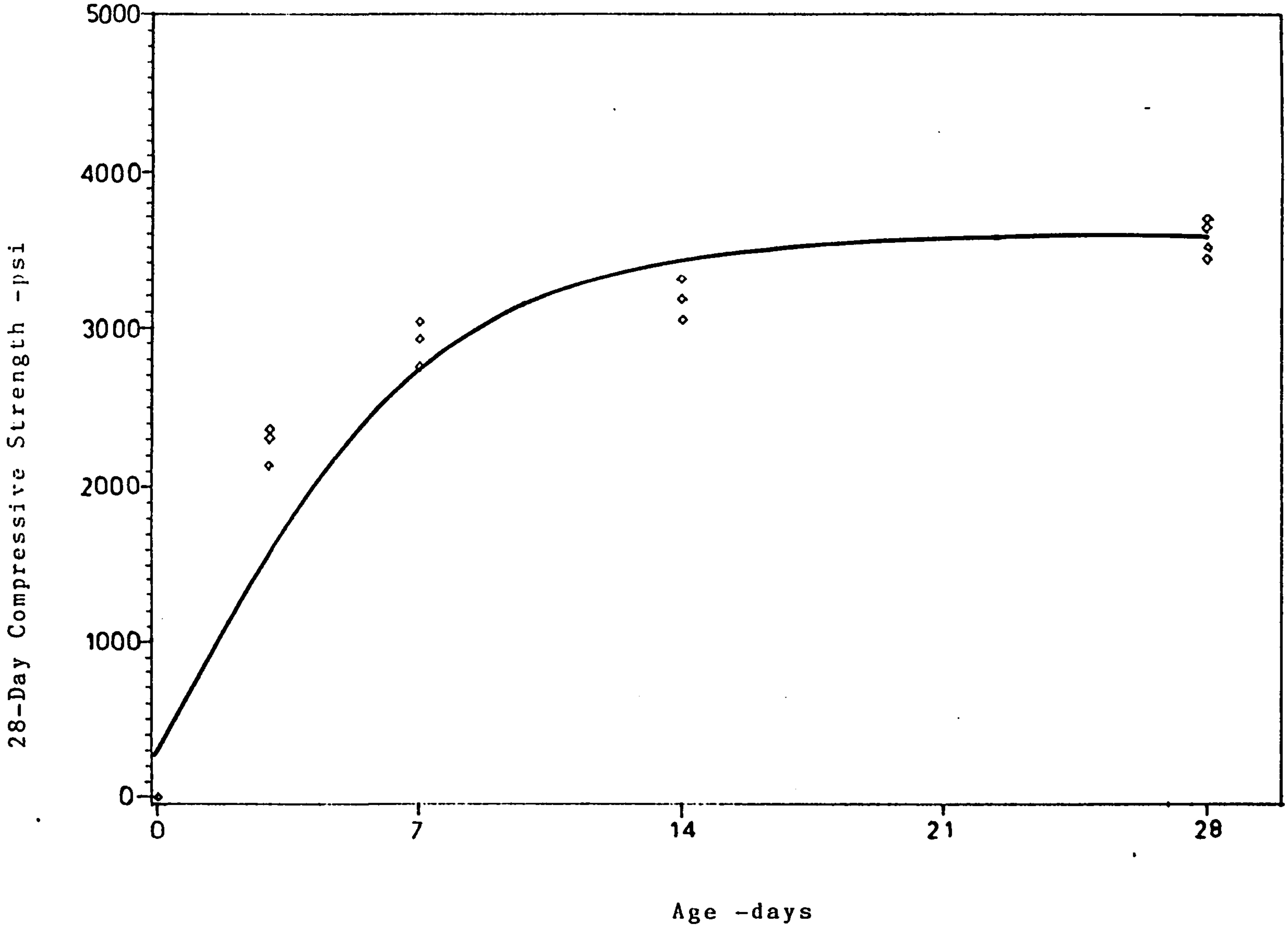


Figure A.47 : Variation of Compressive Strength with Age for Mix H5

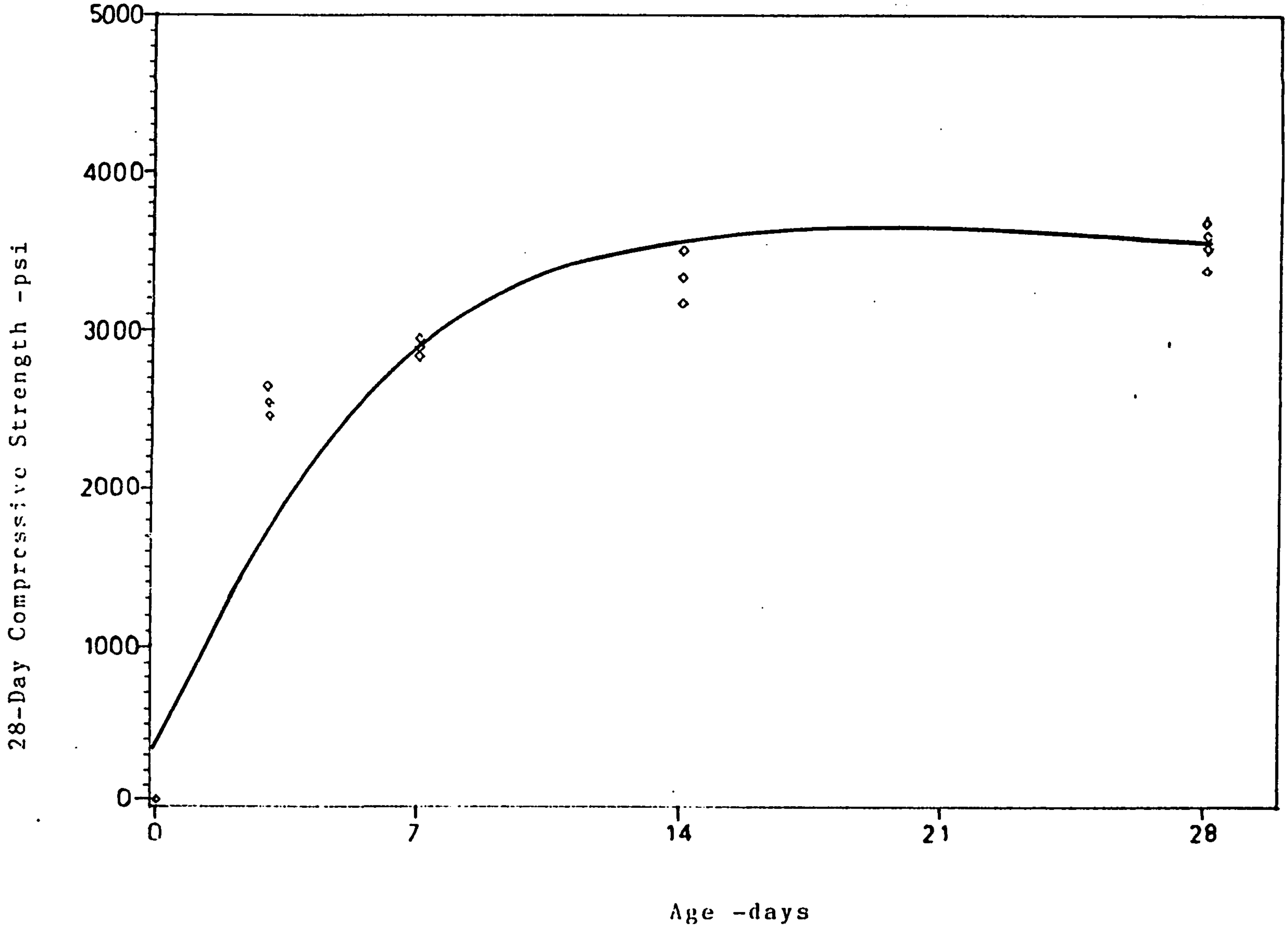


Figure A.48 : Variation of Compressive Strength with Age for Mix H6

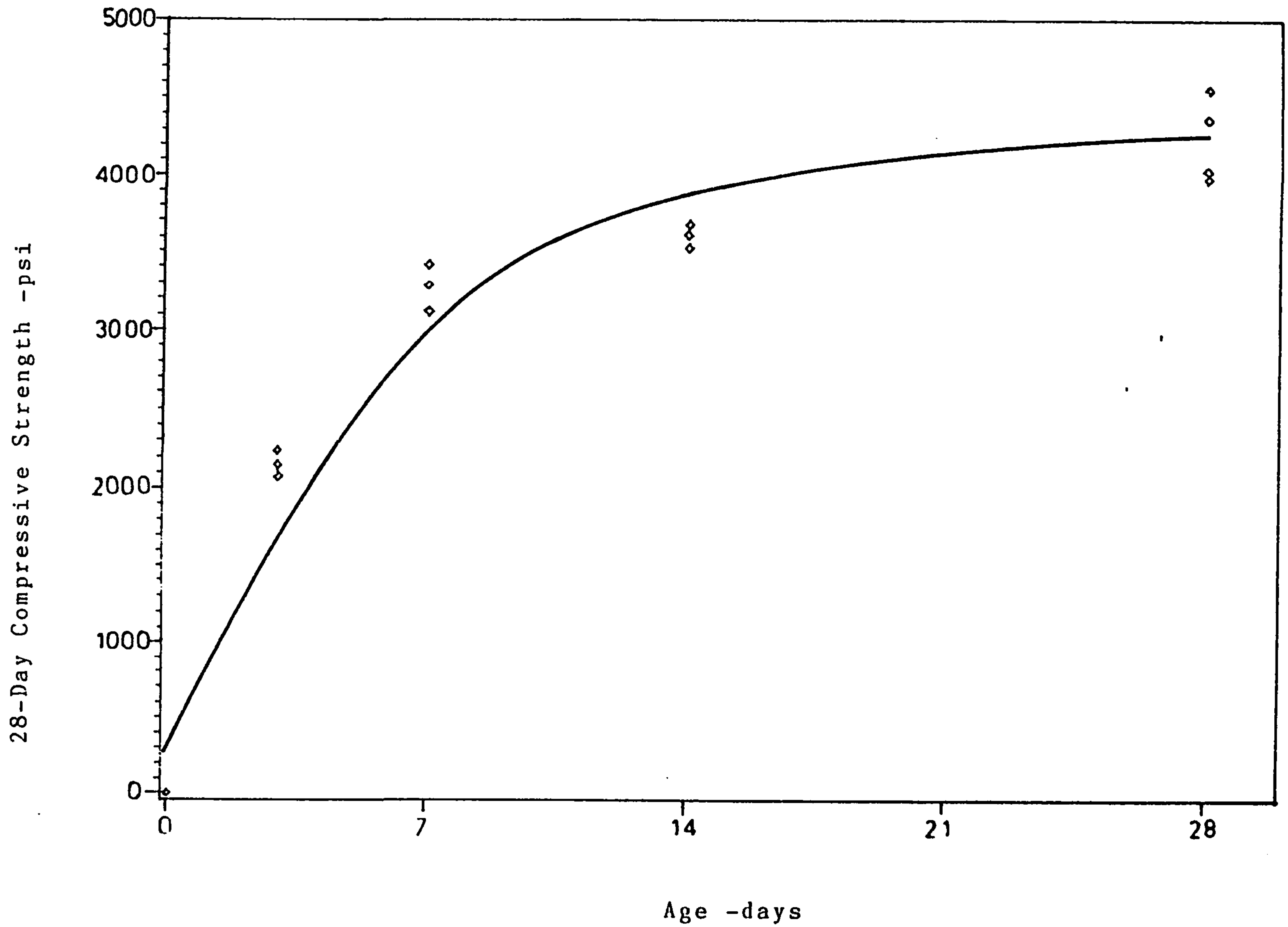


Figure A.49 : Variation of Compressive Strength with Age for Mix I1

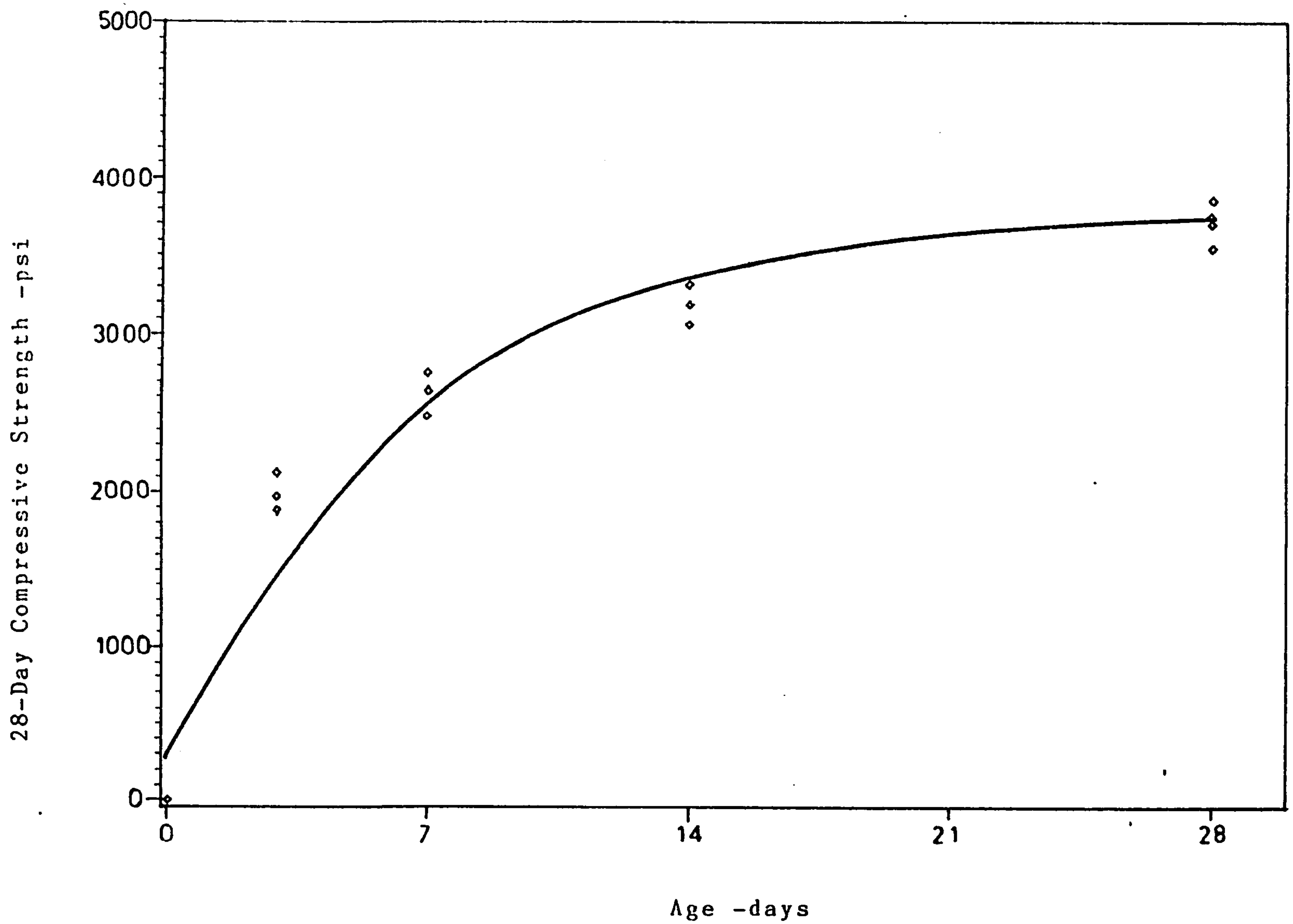


Figure A.50 :Variation of Compressive Strength with Age for Mix I2

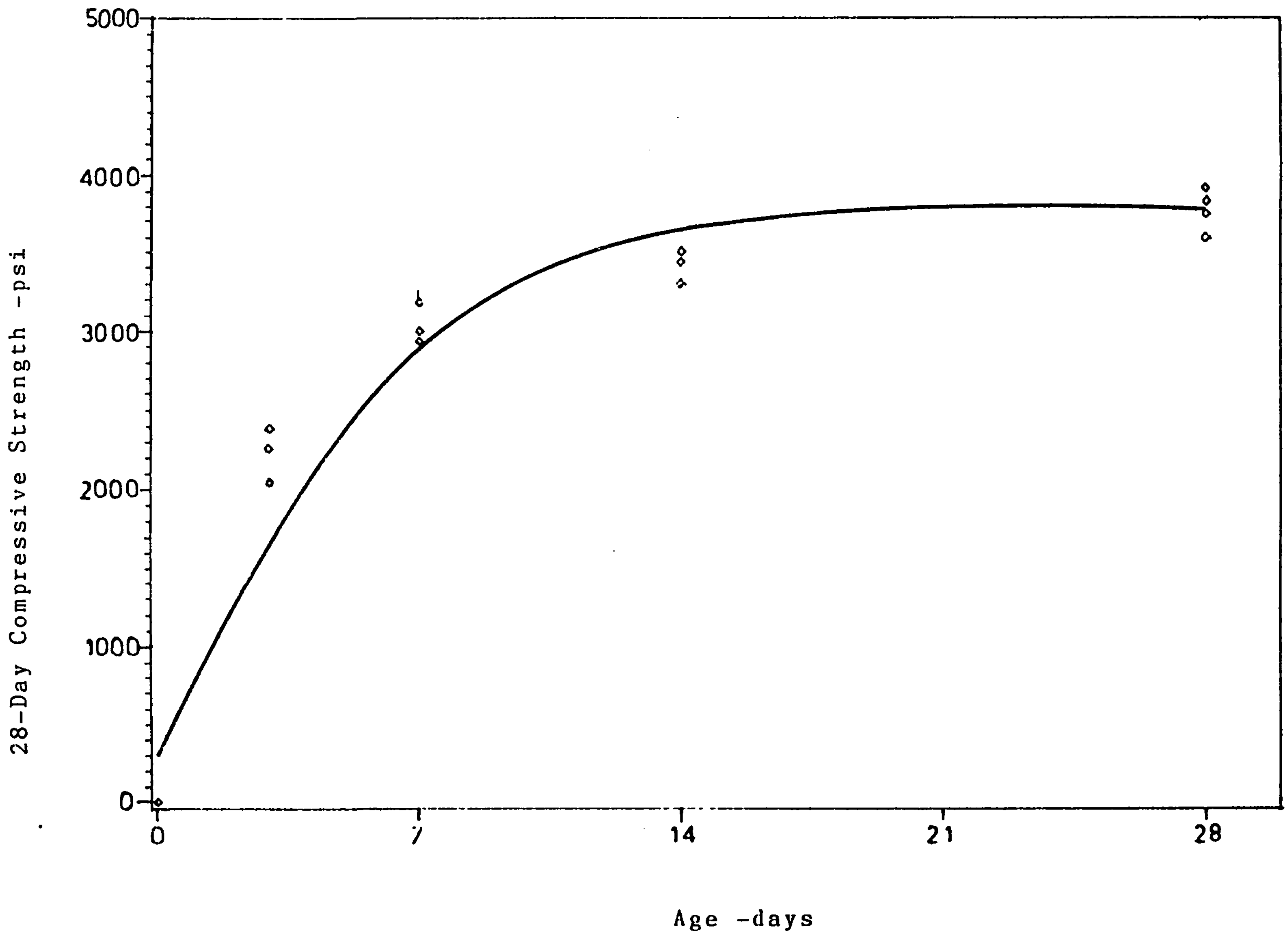


Figure A.51: Variation of Compressive Strength with Age for Mix I3

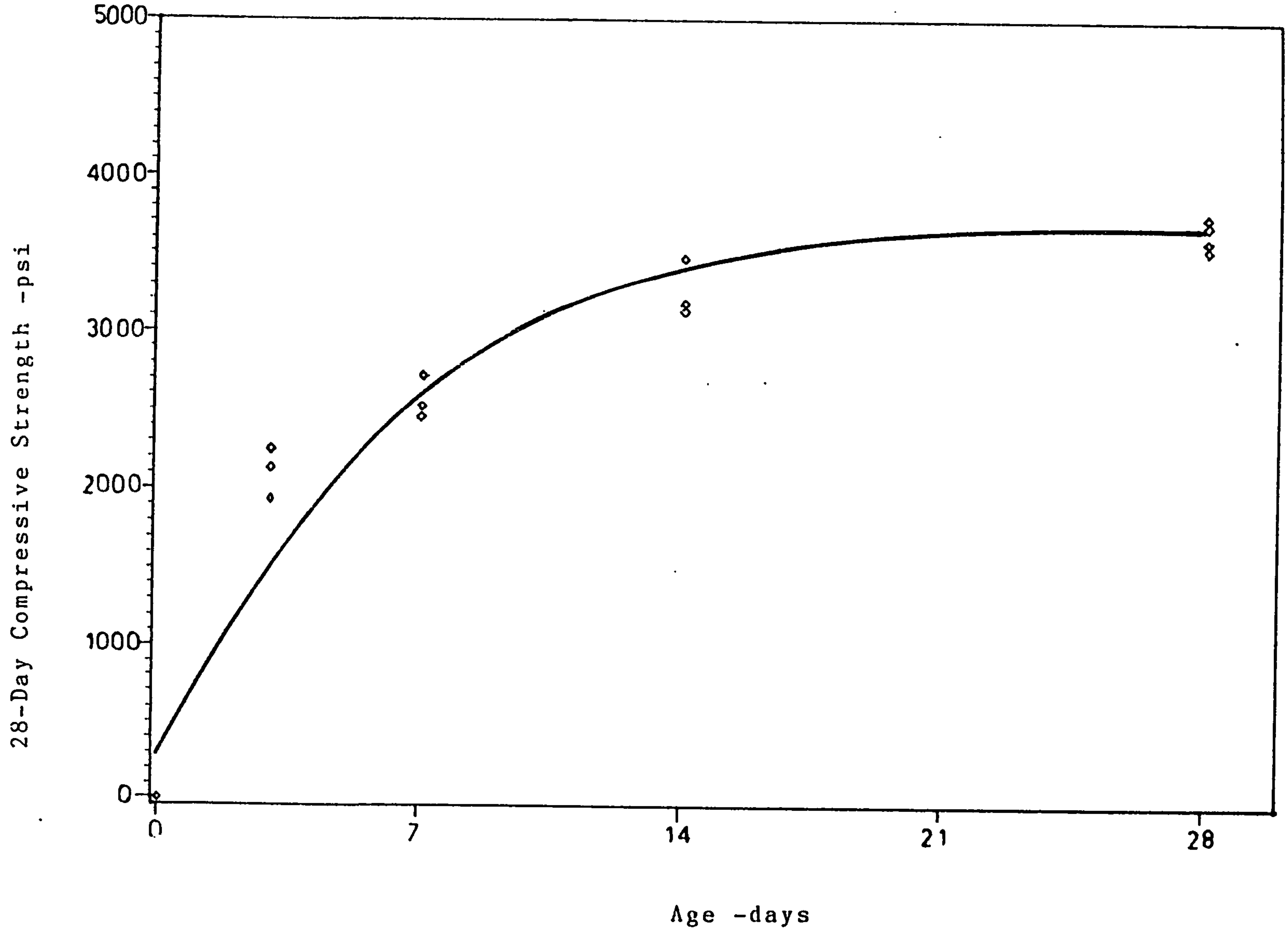


Figure A.52 : Variation of Compressive Strength with Age for Mix I4

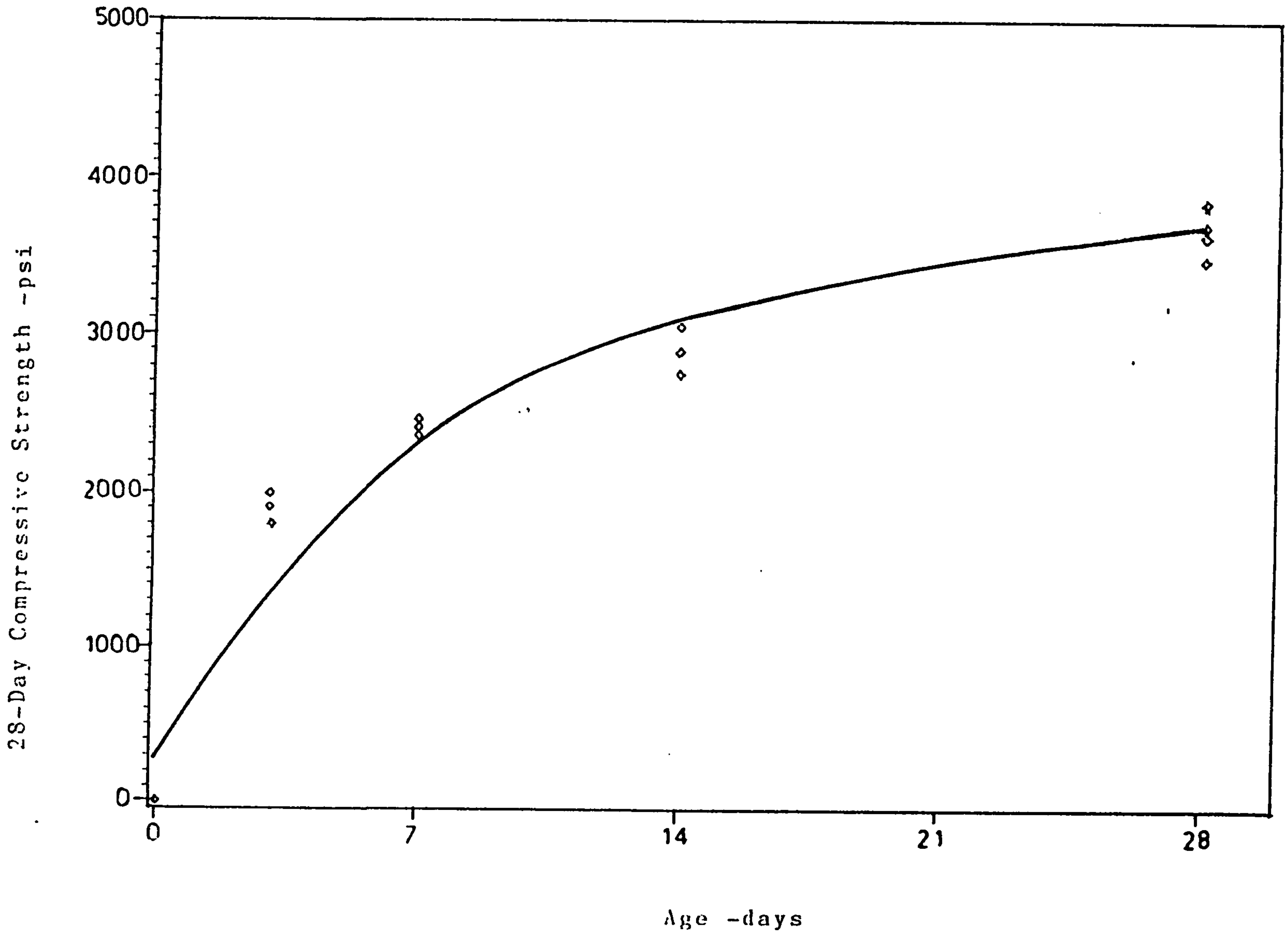


Figure A.53 : Variation of Compressive Strength with Age for Mix I5

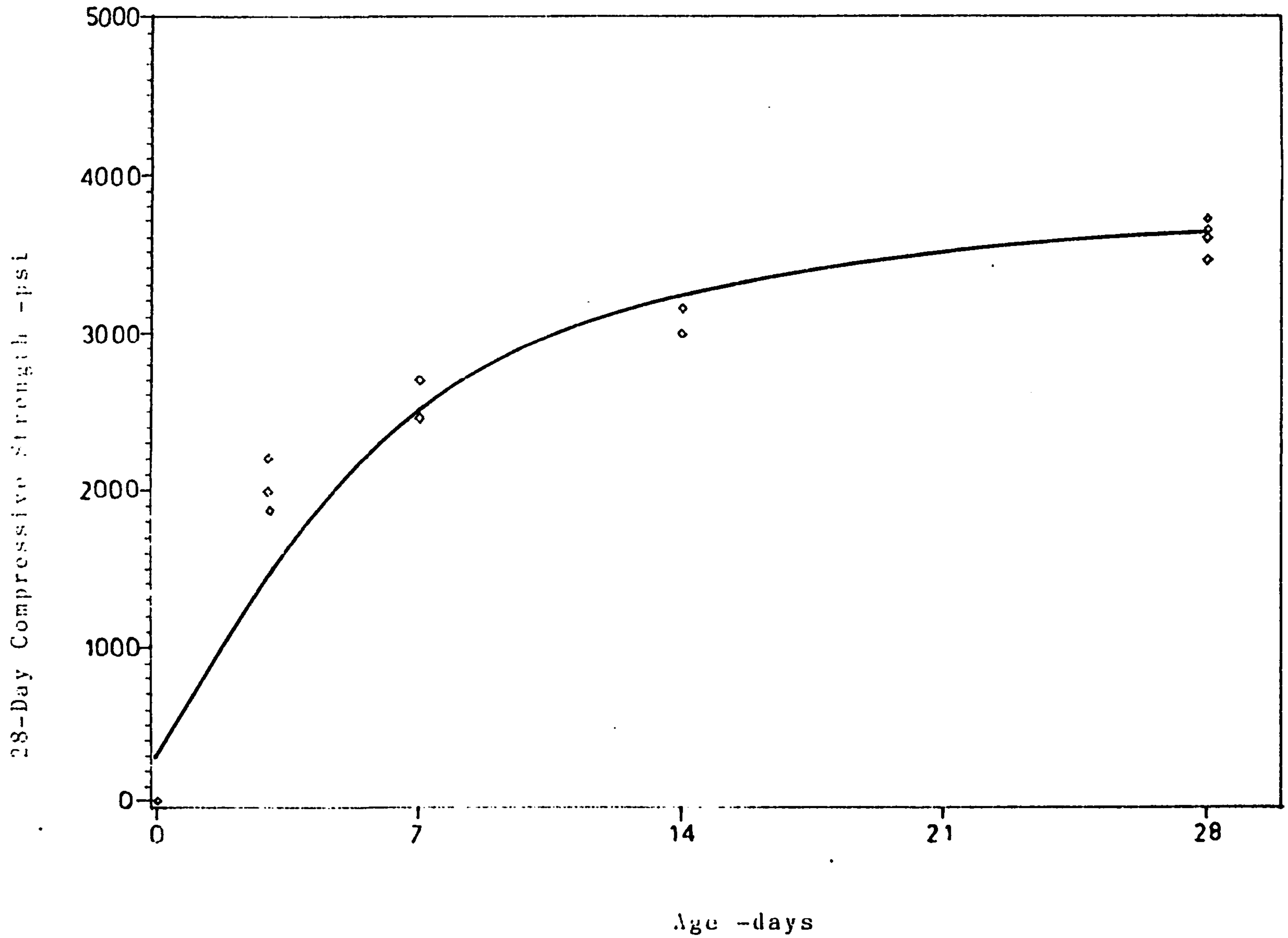
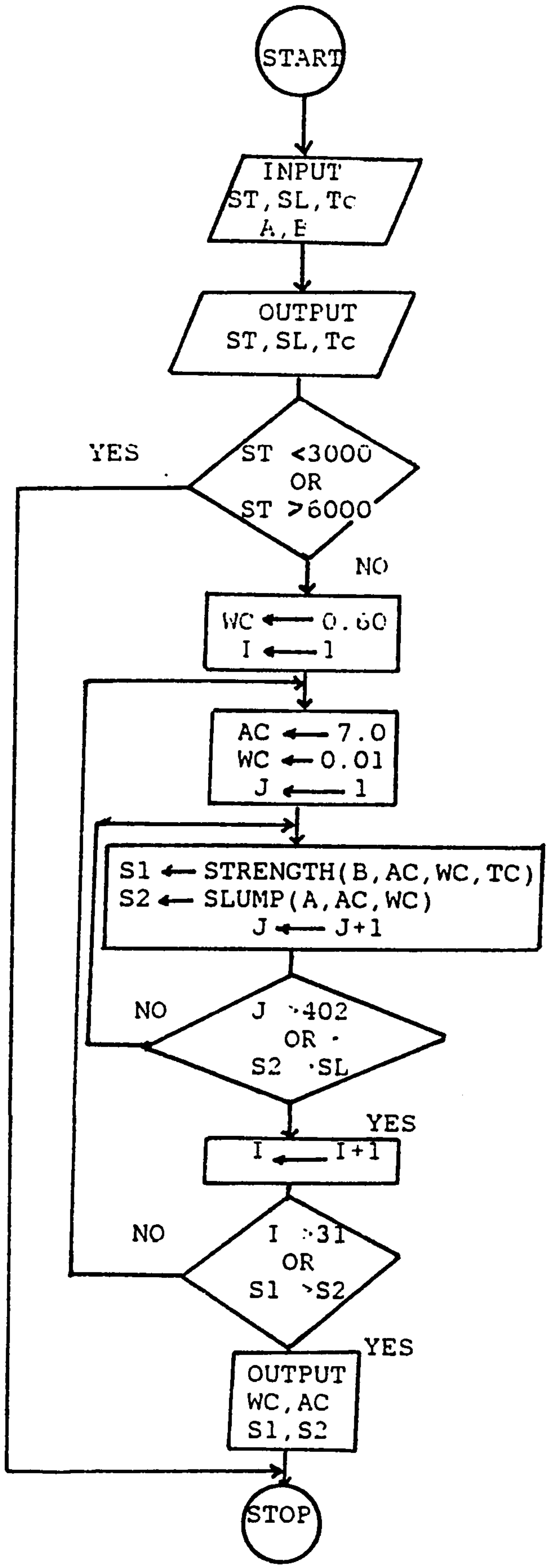


Figure A.54 : Variation of Compressive Strength with Age for Mix I6

APPENDIX B

Flow Chart and Listing of the Computer Program

Flow Chart of the Computer Program



Computer Program Listing

```
$JOB
      DIMENSION A(6),B(9)
      INTEGER T
C   A(I) AND B(I) ARE THE VECTORS FOR VALUES OF REGRESSION CONSTANTS
C   TO BE USED  FOR WORKABILITY  AND STRENGTH  EQUATIONS
C   READS THE DATA
C   'ST' STANDS FOR THE REQUIRED COMPRESSIVE STRENGTH IN PSI
C   'SL' STANDS FOR THE REQUIRED CONCRETE SLUMP IN INCHES
C   'T'  STANDS FOR THE FRESH CONCRETE TEMPERATURE IN DEGREES CENTIGRAL
      READ, ST, SL, T
C   READS THE VALUES OF REGRESSION CONSTANTS
      READ, (A(I),I=1,6)
      READ, (B(I),I=1,9)
      WRITE (6,5) ST, SL, T
C   PRINTS THE GIVEN DATA
  5   FORMAT('1','REQUIRED STRENGTH =',F8.0,' PSI',//,'REQUIRED SLUMP
     * ',F5.2,' INCHES',//,'FRESH CONCRETE TEMP =',I4,'C',////)
C   IF THE GIVEN STRENGTH IS OUTSIDE THE RANGE 3000 TO 6000, THE
C   PROGRAM ENDS
      IF (ST .LT. 3000.0 .OR. ST .GT. 6000.0) GOTO 200
C   CALCULATES VALUES OF WATER-CEMENT RATIO, TOTAL AGGREGATE-CEMENT
C   RATIO THAT GIVE THE REQUIRED COMPRESSIVE STRENGTH AND SLUMP
      WC=0.60
      DO 20 I=1,40
      AC=8.0
      WC=WC-0.01
      DO 15 J=1,120
      AC=AC-0.05
      S1=B(1)+B(2)*WC+B(3)*AC+B(4)*T+B(5)*WC*AC+B(6)*WC*T+B(7)*AC**2
     * +B(8)*T**2+B(9)*WC*T**2
      S2=A(1)+A(2)*WC+A(3)*AC+A(4)*AC*WC+A(5)*WC**2+A(6)*AC*WC**2
      IF(S2.GT. SL) QUIT
  15  CONTINUE
      IF(S1.GT. ST ) QUIT
  20  CONTINUE
      WRITE(6,100) WC,AC,S1,S2
C   PRINTS THE CALCULATED DATA
 100  FORMAT(//,'WATER-CEMENT RATIO =',F6.2,//,'TOTAL AGGREGATE-CEME
     * RATIO =',F6.2,//,'CALCULATED COMP STRENGTH =',F7.0,' PSI',//,'
     * CALCULATED SLUMP =',F5.1,' INCHES',////)
      GOTO 33
 200     WRITE (6,10)
C   PRINTS THE FOLLOWING LINE IF THE REQUIRED STRENGTH IS OUTSIDE
C   THE RANGE
  10  FORMAT(3X,'"RANGE OF GIVEN STRENGTH  IS OUTSIDE THE RANGE
     * 3000 TO 6000 PSI"',////)
  33  STOP
      END
$ENTRY
```

```
5500 3 40
1238.13
-5138.75
-212.00
870.00
5375.00
-900.00
69340.902
-125404
-953.656
-1905.587
4013.699
3459.704
-103.180
17.083
-31.481
```

Note : To use this program change the first line after $ENTRY to give desired values of strength in psi, slump in inches and concrete temperature in degrees centigrade.

APPENDIX C

Example for Mix Design

Calculate the quantities of the ingredients in 1 yd3 (3900 lb) of concrete for a required compressive strength of 4000 psi, a required slump of 3 inches and an expected concr--ete temperature at placement of 38°C.

Using Tables 4.25 for the given data of strength, slump and concrete temperature, the required mix proportions can be obtained :

$W/C = 0.53$

$TA/C = 5.76$

$5.76C + 0.53C + C = 3900$ lb

$C = 3900/7.29 = 535$ lb

$W=(0.53)(535) = 284$ lb

$TA=(5.76)(535) = 3081$ lb

Since $FA/TA = 0.37$ in this investigation

$FA = (0.37)(3081)$

$= 1140$ lb

$CA = 3081 - 1140$

$= 1941$ lb

Note that the calculated quantity of water above is only for the effective W/C ratio. Required amounts of water to com--pensate for evaporation and for the absorption of the aggreg--ate should be added to the above calculated value.