

Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be “used for any purpose other than private study, scholarship, or research.” If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of “fair use” that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select “Pages from: first page # to: last page #” on the print dialog screen

2)

RECYCLED PLASTICS AS FILLERS //

IN

POLYMER CEMENT CONCRETE COMPOSITES

By

) Shian-Jong Liu //

Thesis submitted to the Faculty of The Graduate School of
the New Jersey Institute of Technology in partial fulfillment of
the requirements for the degree of
Master of Science in Chemical Engineering
1988


APPROVAL SHEET

Title of Thesis : Recycled Plastics as Fillers in Polymer
Cement Concrete Composites.

Name of Candidate : Shian-Jong Liu

Master of Science in Chemical Engineering
1988

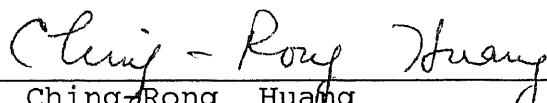
Thesis and Abstract Approved by:



Dr. Chen-Chong Lin
Research Professor
Department of Chemical Engineering

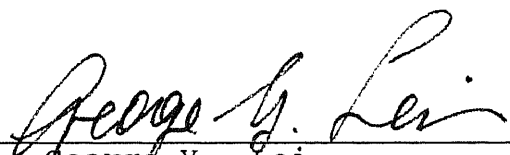
5/11/88
Date

Signatures of other members of the thesis committee :



Dr. Ching-Rong Huang
Professor & Assistant Chairperson
Department of Chemical Engineering

5/11/88
Date



Dr. George Y. Lei
Associate Professor
Department of Chemistry

5/11/88
Date

VITA

Name : Shian-Jong Liu

Permanent address: Third Floor, No. 441, Ying-Taur Road,
Ying-Ko Chen, Taipei Hsien,
Taiwan, Republic of China, 23917

Degree and date to be conferred : Master of Science in
Chemical Engineering,
1988.

Date of birth : April 7, 1958.

Place of birth : Taoyuan Hsien, Taiwan, Republic of China.

Collegiate institutions	Dates	Degree	Date of Degree
attended :			

<u>New Jersey Inst. of Tech.</u>	<u>1986-88</u>	<u>M.S.Ch.E</u>	<u>May 1988</u>
----------------------------------	----------------	-----------------	-----------------

<u>Chen-Kung University</u>	<u>1975-79</u>	<u>B.S.Ch.E.</u>	<u>June 1979</u>
-----------------------------	----------------	------------------	------------------

Position held : Research Assistant,

Department of Chemical Engineering,
New Jersey Institute of Technology.

ABSTRACT

Title of Thesis: Recycled Plastics as Fillers in Polymer
Cement Concrete Composites.

Shian-Jong Liu, Master Science in Chemical Eng., 1988.

Thesis directed by : Dr. Chen-Chong Lin

Research Professor

Department of Chemical Engineering

KEYWORDS:

plastic waste; polyethylene terephthalate(PET); compressive strength; flexural strength; tensile strength; polymer Portland cement concrete(PPCC); recycled plastics.

How to handle the plastic waste is a big task for the modern society in environmental protection. People already focus on it, especially in PET soft drink bottles. Although PET bottle can be reclaimed, its usages are restricted due to the limitation in color and difficulty in purification.

On the other side, concrete is the most common material for human beings to used in construction. Concrete has good compressive strength, but⁴ very poor in flexural and tensile strengths, which limits its applications. So, scientists try to improve its properties by adding the polymer into the conventional concrete, to enhance its strengths, chemical resistance and ductility.

In this study, the behaviors of the PPCC in corporation of the recycled plastics as filler, without causing any problem of color and purity, has been investigated on tensile, flexural and compressive strengths, weight reduction and weathering test. The reason to chose the unsaturated polyester polymer Portland cement concrete(UP-PPCC) system is to develop a novel method to transfer the plastics waste to valuable product and to solve the problem about dumping the million tons of plastic waste.

The results of experiments show that UP-PPCC system has very good adhesive ability to bind the flakes of plastics with polymer-concrete matrix and the light-weighing plastic concrete can cut down the cost of transportation.

ACKNOWLEDGMENTS

I would like to express my appreciation and gratitude to my advisor, Dr. Chen-Chong Lin, for his guidance and assistance in the accomplishment of this study. I would like to thank Dr. Wing Wong and Dr. Methi Wecharatana with all the staffs in the Concrete Laboratory of Civil Engineering Department, for their permitting and helping to use several instruments which were essential necessity for the experimentation conducted in this work.

I would also like to express my love to my family, my wife, and my baby, for their encouragement, understanding, and support to make this possible.

TABLE OF CONTENTS

CHAPTER	PAGE
ACKNOWLEDGMENTS	ii
List of Tables	iii
List of Figures	iv
I. INTRODUCTION	1
1.1 General Viewpoint	1
1.2 Plastics Recycling System of PET Bottle	4
1.3 Types of Concrete	6
II. THEORETICAL BACKGROUND	9
2.1 Literature Review	9
2.2 Polymer Concrete	10
2.3 Unsaturated Polyester Portland Cement Concrete(UP-PPCC)	14
2.4 Fillers	18
III. EXPERIMENTAL PROGRAM	20
3.1 Types of Test	20
3.2 Materials	21
3.3 Experimental Procedure	23
3.4 Test Procedure	26
IV. RESULTS AND DISCUSSIONS	31
V. CONCLUSIONS	53
APPENDIX A. TABLES	56
APPENDIX B. TEMPERATURE RISING CURVES	61
APPENDIX C. STRESS-STRAIN CURVES	65
SELECTED BIBLIOGRAPHY	81

LIST OF TABLES

TABLES	PAGE
1-1 Recovery Rates from Post-Consumer Waste in 1984. . .	2
1-2 Advantages and Disadvantages of Conventional Concrete.	7
1-3 Compare the Typical Properties of Conventional Concrete and Polymer Concrete.	8
3-1 The Configurations of Specimen for each Test. . .	20
3-2 Mixing Proportion.	24
I Main Compounds of Portland Cement.	57
II Typical Values of Compound Composition of Portland Cements, Type I.	57
III Chemical Composition, Physical and Mechanical Characteristics of Fly Ash.	58
IV Properties of Sand.	59
V Properties of Unsaturated Polyester Latex.	59
VI The General Informations about Sika Series. . . .	60

LIST OF FIGURES

FIGURES	PAGE
1-1 PET Wet Reclamation System.	5
2-1 Structures of Three Types Polymer Concrete. . . .	11
3-1 Compressive Strength Test.	27
3-2 Flexural Strength Test.	28
3-3 Tensile Strength Test.	29
4-1 Compressive Strengths, PET as Filler.	34
4-2 Compressive Strengths, PE as Filler.	35
4-3 Compressive Strengths, Coarse Aggregate as Filler	36
4-4 Flexural Strengths, PET as Filler.	38
4-5 Flexural Strengths, PE as Filler.	39
4-6 Flexural Strengths, Coarse Aggregate as Filler. .	40
4-7 Tensile Strengths, PET as Filler.	42
4-8 Tensile Strengths, PE as Filler.	43
4-9 Tensile Strengths, Coarse Aggregate as Filler. .	44
4-10 Specific Gravities, PET as Filler.	46
4-11 Specific Gravities, PE as Filler.	47
4-12 Specific Gravities, Coarse Aggregate as Filler. .	48
4-13 Weight Reduction Effectiveness, PET as Filler. .	49
4-14 Weight Reduction Effectiveness, PE as Filler. . .	50
4-15 Weight Reduction Effectiveness, Coarse Aggregate as Filler.	51

LIST OF FIGURES(continued)

FIGURE	PAGE
1. Temperature Rising Curve, UP-PPCC.	62
2. Temperature Rising Curve, Sikatop-111.	63
3. Temperature Rising Curve, Sikatop-122.	64
I. Compressive Strength, UP-PPCC with PET Flakes. . .	66
II. Compressive Strength, UP-PPCC with HDPE Flakes. .	67
III. Compressive Strength, Sika-111 without Filler. . .	68
IV. Compressive Strength, Sika-111 with PET Flakes. .	69
V. Compressive Strength, Sika-111 with HDPE Flakes. .	70
VI. Flexural Strength, UP-PPCC without Filler.	71
VII. Flexural Strength, UP-PPCC with HDPE Flakes. . . .	72
VIII. Flexural Strength, Sika-122 with PET Flakes. . . .	73
IX. Flexural Strength, Sikabond without Filler. . . .	74
X. Flexural Strength, Conventional concrete with PET Flakes as Filler.	75
XI. Tensile Strength, UP-PPCC with PET Flakes.	76
XII. Tensile Strength, UP-PPCC with HDPE Flakes. . . .	77
XIII. Tensile Strength, Sika-111 with HDPE Flakes. . . .	78
XIV. Tensile Strength, Sika-122 with HDPE Flakes. . . .	79
XV. Tensile Strength, Conventional Concrete with HDPE Flakes as Filler.	80

CHAPTER I

INTRODUCTION

1.1 General Viewpoint

Today, people are more and more concerned about the environmental protection, expending millions of dollars in carting and disposal their waste. In the United States, about 130 millions tons of waste pour annually into municipal solid waste streams to be burned, buried, just little recycled. The taxpayers of New Jersey are now forking out from \$50 to more than \$120 a ton to get rid of their waste, in which including recyclable waste. That forces the New Jersey state's new source separation program established to require the residents to collect their recyclable waste to save taxpayers millions of dollars a year(1).

The recyclable waste includes aluminum, paperboard, paper, glass, rubber, iron, and plastics. Some of them being recycled, the recovery rate of each recyclable waste in 1984 is listed in Table 1-1, which according to a study by Franklin Associates, Prairie Village, KS(2).

Table 1-1 Recovery rates from post-consumer waste in 1984.

Material	Annual discards, million tons	Post-consumer recovery(M.tons)	Recovery rate, %
Aluminum	2.1	0.6	28.6
Paper and Paperboard	62.3	12.9	20.7
Glass	13.9	1.0	7.2
Rubber and Lather	3.4	0.1	3.0
Iron and Steel	11.3	0.3	2.7
Plastics	9.7	0.1	1.0

We can easily find out that the lowest recovery rate in 1984 was plastic waste. Back to 1960, the United States produced 76 million tons of municipal solid waste, less than 1% of which was plastics. But now, the plastic waste stands at about 10 million tons, or 7.2% of the total stream, and it will be increased to 15.5 billion tons(9.8%) by the year of 2000(2). So, we can predict that the plastic waste, if not recycled, will cause a big problem in environmental protection for its inherent property of durability and non-corruption.

On the other side, concrete is a major material for construction which used in large amount by human beings, about 800 million tons of concrete being utilized in the United States every year. Concrete is a composite material,

which consists of binder and aggregate phases. High quality concrete is obtained by ensuring that both the binder and the aggregate are of good quality, and the efficient bonding force occurs between two components.

The addition of filler in concrete can change the properties of concrete, such as mechanical strength, weight, durability, and workability. It is also demonstrated that standard fiberglass or polymeric fibers, such as polyester and polypropylene fibers, can reinforce the concrete(3).

The tasks of this research are to study the behaviors about recycled plastics(specialized in PET bottle recycling) as filler in concrete, to try to develop a novel method that can produce valuable material from recyclable waste of PET bottle, and to solve the problem about how to dump million tons of plastic waste every year.

The additional advantage of using polymeric material waste as filler in concrete is the reduction in specific gravity of concrete. This fact has significant effect on reducing freight and on site handling costs of concrete elements. The other important advantage of this study is that recycled plastics does not require the high level of purity, and the colored recycled plastics also can be used as filler without any trouble in its process and application of final product.

1.2 Plastics Recycling System of PET Bottle

The materials in typical 2-L(liter) polyethylene terephthalate(PET) beverage bottle consist of high density polyethylene base cup and adhesive(22g), aluminum cap(1.5g), label and adhesive(3g), and PET(60g) bottle body. The newly designed 2-L PET bottle only contains PET,label and aluminum without HDPE base cup to simplify the material in PET bottle and to reclaim easily.

1.2.1 PET Reclamation System

There are two types of system used to reclaim the PET bottles, 'dry' and 'wet' reclamation systems, by using the difference between their specific gravities(4).

The procedure of PET wet reclamation system is fed the whole bottle into the grinder in one operation, including bottle(PET), cup(Al), label, and base cup(HDPE). After the bottles have ground up, the pieces of the label are removed by air filtration. Since the PET material and aluminum are heavier than water they will sink, while the lighter base cup material floats to the top and can be siphoned off. By the similar process, the chopped aluminum and PET material are separated, see Fig 1-1.

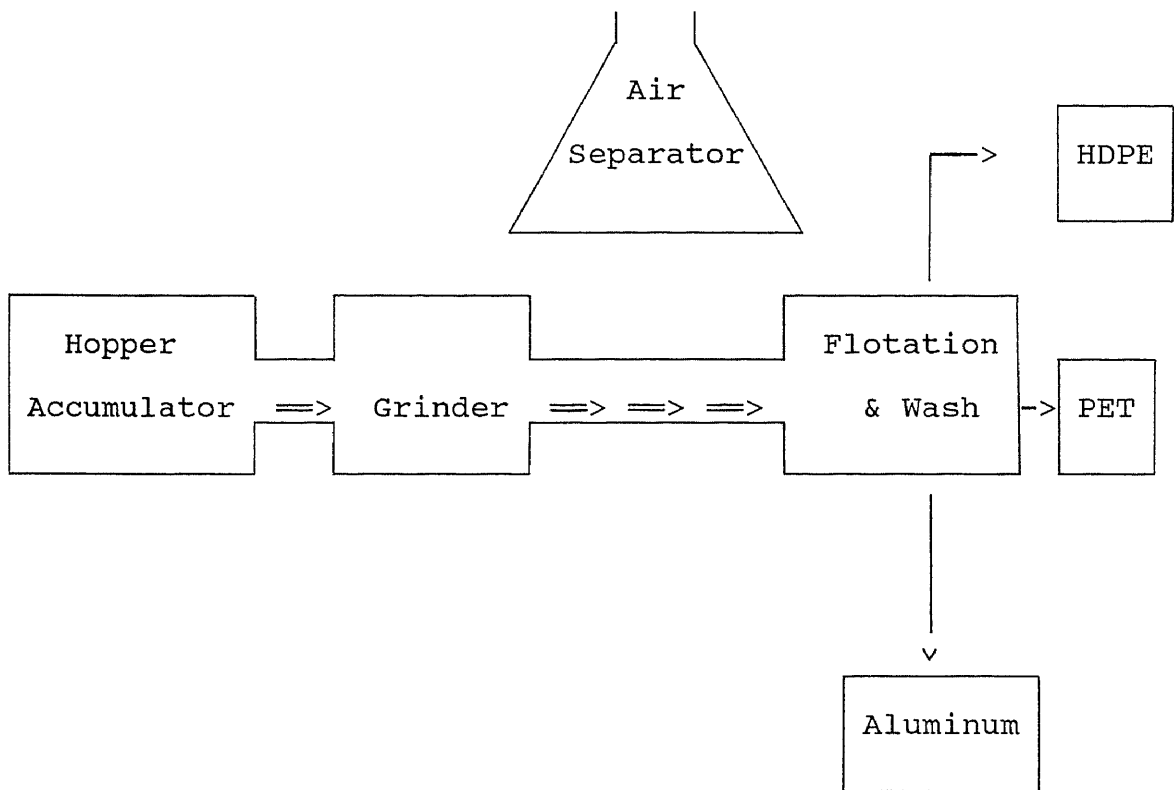


Fig 1-1 PET Wet Reclamation System

In the PET dry reclamation system, the HDPE base cups and aluminum closures are mechanically separated. Air separation may also be used to remove the paper and separate the lighter base cup material and aluminum. The basic PET bottles are separated by color and fed into individual grinders and then on to air separators to remove the labels from the ground up PET material. The base cups and the aluminum caps are ground up separately, collected in separate bins. Washing is still required to assure highest sales values of recycled products.

1.2.2 Examples of Products Made from PET Bottles Recycled

PET soft drink bottles can be used to produce:

Unsaturated polyester(automobile exterior panels)

Polyol(automobile bumpers, water skis)

Thermoformable sheets(beverage bottle carrier)

Fiberfill(stuffing, cushions)

Industrial coatings(component in industrial paint)

Engineering plastics(appliance handles)

Textiles(boat sails)

HDPE base cups can be used to produce:

Beverage bottle carrier for soft drinks and beer

Lumber-like plastic boards

1.3 Types of Concrete

Thousands formulations of the concretes are now widely being used in which consist of the different type of Portland cement, water, sand, aggregate, polymer, filler, and even the mix-proportion, to reach the different requirements about the mechanical properties and practical applications. In general, concretes can be classified into two different types, conventional and polymer concretes, depending on whether is the polymer involved in the composition of the concrete formulation.

1.3.1 Conventional Concrete

Conventional concrete consists of water, cement, sand, and aggregate, sometimes also including the steel or fiber to reinforced. It has various properties due to the type of Portland cement, mix-proportion, and the property of the aggregate or filler. But, it does have weaknesses which may limit its use as a high performance material, since it is a brittle material and has very low impact, flexural and tensile strengths. The major advantages and disadvantages of conventional concrete are summarized in Table 1-2(5).

Table 1-2 Advantages and Disadvantages of Conventional Concrete.

Advantages	Disadvantages
Ability to be cast	Low tensile strength
Low cost	Low ductility
Durability	Volume instability
Fire resistant	Low strength to weight
On-site fabrication	Long curing time
Energy efficient	Sensitive to chemical and salt
Finishability	Brittleness
Non-elasticity	Difficulty to repair

1.3.2 Polymer Concrete

Due to the weaknesses of conventional concrete, a great deal of research have been devoted to ameliorating these problems, and to development of new types of concrete by addition the polymer into concrete, called polymer concrete. Thousands papers concerned with polymer in concrete being published(6), in general, polymer concrete exhibits higher compressive, flexural and tensile strengths and strong corrosive resistance to chemicals than those properties of conventional concrete. The comparative data of typical properties between conventional concrete and polymer concrete are listed in Table 1-3(7).

Table 1-3 Compare the Typical Properties of Conventional Concrete and Polymer Concrete.

Properties	Conv. C.	Polymer C.
Compressive strength(psi)	2000-5000	4000-20000
Flexural strength(psi)	500-800	1000-3000
Tensile strength(psi)	300-500	500-2000
Water absorption(%)	5.0-7.0	0.2-1.0
Density(Kg/M^3)	2000-2400	1900-2400

CHAPTER II

THEORETICAL BACKGROUND

2.1 Literature Review

Cement and concrete are the most important materials for building and construction purposes, because of their comparative cheapness in price, very good workability, fire-proof, and compressive strength. But due to the very low tensile, flexural, and impact strengths, the applications of cement and concrete are restricted to traditional usages.

Since 1950, several kinds of research result, what are now generally called polymer concretes, began to be used in special construction. Polymer concrete(PC) and polymer Portland cement concrete(PPCC, the latter being latex-modified mortar) were in use during the 1950s, and polymer impregnated concrete(PIC) was developed in the middle 1960s. The major driving force was the desire to obtain improved materials for rigorous applications such as bridge decks. Both research and development activities accelerated as the 1970s approached(7).

From the application point of view, polymer concretes are quite good materials because of the excellent mechanical properties. In the past, practice was ahead of scientific finding in this field of many cases. In Europe, Japan, USA, and USSR, precast polymer concrete element production has shown constant growth in comparison to recession conditions in the precast industry.

Today, some polymer concrete materials have already been in use for many years, such as methyl methacrylate(MMA) (8)(9)(10), epoxy(11)(12); some are undergoing their first applications, and some are awaiting for acceptance by a justifiable conservative technological world. After about 10 years of research and development, polymer concrete materials can really meet the requirements in engineering applications for the evaluation between their unique properties and cost effectiveness(7).

2.2 Polymer Concrete

Generally, the polymer concrete materials can be categorized into three types of composites, which depending upon the way of the polymer being introduced into a concrete, the mix components including water(PPCC), the compositions of the concrete mix(PPCC and PC), and the special method directly to let polymer into the hardened concrete(PIC) (6)(7)(13).

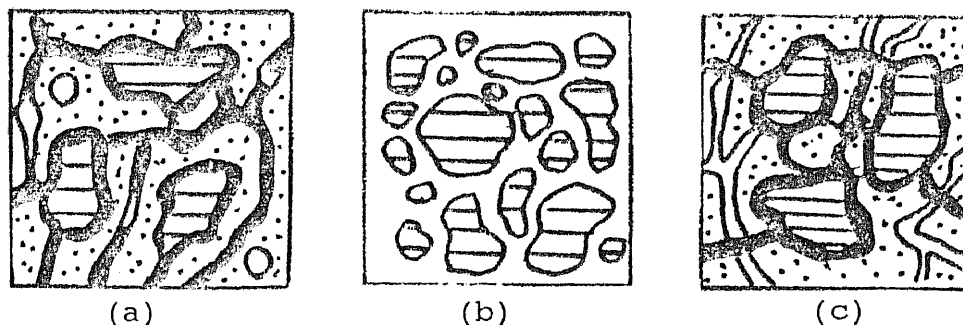


Fig 2-1 (a) Polymer Impregnated Concrete, (b) Polymer Concrete (not to scale), and (c) Polymer Portland Cement Concrete. Crosshatched areas represent aggregate particles. Open and polymer-filled capillary pores are shown in (a) & (c). Dots represent gel pores, some of which are polymer-filled in polymer impregnated concrete(7).

2.2.1 Polymer Impregnated concrete(PIC).

PIC is the previously formed hardened concrete being impregnated with a monomer or prepolymer which is subsequently polymerized in situ. The characteristic of PIC will be gained the properties of the impregnated polymer.

For the PIC process that most of the water (about 90%) in hardened concrete is removed by drying, impregnation to levels of about 15% by volume of a wide variety of liquids (monomers, solutions and even liquid sulfur) has been shown to be feasible(14)(15). The impregnating liquid shall have low viscosity, good wetting property, relatively low cost, and high reactivity; acrylic monomer system has been emphasized, such as MMA or acrylonitrile mixtures.

The general principles of PIC required for impregnation and polymerization of monomer or prepolymer in situ are now reasonable well established(7). Although there is still some disagreement about whether impregnation proceeds by the capillary-rise mechanism or the simple diffusion process, the impregnation does follow the square-root-of-time rate law over most of its course. Consistent with the capillary-rise phenomenon, the rate of impregnation varies with the square-root of the ratio of surface tension to viscosity times the average pore radius, and with the applied pressure.

The principal effect of PIC is the polymer sealing of the continuous capillary pore system, resulting in exceptional decreases(to 99%) in the permeability to water, chemical and salt; the stress-strain behavior can also be modified from brittle to ductile and improved about 2 to 5 times in compressive strength. But, PIC technology is limited due to the complex process, equipment and high monomer cost.

2.2.2 Polymer Concrete (PC)

PC is a thermoplastic or crosslinked polymer used to bind an aggregate together to form a composite material by polymerizing a monomer with aggregate mixture. The polymer acts as the binder to replace the role of Portland cement in the concrete mix.

A wide variety of monomer, prepolymer and aggregate has been used in PC, but the setting shrinkage and stress in PC is a very important factor and must be considerable. The shrinkage forces are generated due to the polymerization and cross-linking of the resin binder when secondary bonds between the monomer or prepolymer molecules are transformed to primary(covalent) bonds, which have smaller interatomic distances. In PC systems where the liquid resin forms a continuous phase, the shrinkage forces are accommodated during the pre-gel part of the curing by a volume reduction in the resin. Right now, research makes every effort to get the zero-shrinkage material in PC field(16).

The epoxy resin are commonly used in PC, but now more attention to the cheaper vinyl monomers, such as polyester-styrene and MMA to cut down the cost. PC does improve the mechanical strengths and physical properties, but it usually has high packing density and monomer ratio.

2.2.3 Polymer Portland Cement Concrete(PPCC or PCC)

PPCC is a monomer, prepolymer, or dispersed polymer latex incorporated into a Portland cement mix, and a polymer network formed in situ during curing of the concrete.

The most attention being focused at the incorporation of a polymeric latex in concrete, the physical process of

film formation is required rather than the chemical process of polymerization. The film formation of some polymer latex requires an elevated temperature to obtain the maximum properties, such as MMA. Since the emulsion lubricates the mix, less water is usually needed for workability, so that the optimum water content in latex is very important. Polymer latex of PPCC includes acrylic, styrene-butadiene copolymer, poly(vinylidene chloride), epoxy, and poly(vinyl ester)(17).

In general, latex-type PPCC exhibits excellent bonding to old concrete, good ductility, resistance to penetration by water, chemical and salt, and excellent durability to freezing and thawing; meanwhile, the flexural and tensile strengths are improved, the process does not complicate(18).

2.3 Unsaturated Polyester Portland Cement Concrete(UP-PPCC)

The impregnation(PIC) method requires a very complex technology which is not only expensive but also difficult for field operation. The polymer concrete(PC) is very expensive due to the high polymer ratio in proportion and high packing density in freight. Only polymer Portland cement concrete (PPCC), the technology is simple and easily suitable for any field applications.

The combination of polyester resin and Portland cement to provide a composite structure, called UP-PPCC, resulted from consideration of the requirements for some applications for which neither individual material was suitable; particularly applications which required adhesive to substrates, e.g., old concrete. Development since 1962 in the U.K., The Cement Marketing Company Limited undertook laboratory and situ evaluation until 1964 and marketing development until 1967(19).

The composition of UP-PPCC comprises a physical mixture of treated Portland cement, polyester resin(or latex) and free radical forming catalyst, which is insoluble in polyester resin but soluble in styrene. This mixture is mixed with aggregate on situ and sufficient water(if necessary) added to enable solution of the catalysts and evolution of calcium hydroxide from the cement to cause the whole mass to set. This structure consists of the coincident polymerization of polyester latex and hydration of Portland cement to form an amorphous polymeric matrix.

2.3.1 Unsaturated Polyester Resin

The polyester resin can be made from a wide variety of polycarboxylic acids with a polyhydric, mainly dihydric alcohol. All the usual conditions applicable to this type of polyester mixture are relevant, but especially the resin

must be selected the low acid value in order to ensure storage stability.

The proportion of unsaturated acid in polyester resin will affect its reactivity and stiffness. A higher proportion of unsaturated acid gives more reactive resin, with improved stiffness at high temperature, while more of the saturated components give less exothermic curing and less stiff resins (20). The unsaturated polyester resin usually consists of phthalic anhydride, maleic anhydride (supplying unsaturated bonding), propylene glycol (dihydroxy component), and styrene (crosslinking component). A typical formula of unsaturated polyester resin contains as following:

Phthalic anhydride	22 - 27% (by weight)
Maleic anhydride	10 - 12%
Propylene glycol	20 - 24%
Styrene	40 - 45%

The acid (anhydride) and glycol components of polyester resin are mixed in a resin kettle and polymerized by step condensation reaction to the molecular weight range about 1000 - 5000, which is highly viscous liquid. Then after cooling, the mixture is thinned down to a pourable liquid by the addition of the monomer, e.g., styrene. An inhibitor such as hydroquinone is added to prevent premature polymerization, so the mixture is stable for months to years at low ambient temperature.

2.3.2 Unsaturated Polyester Latex

Unsaturated polyester latex consists of unsaturated polyester resin, water and emulsifier. This UP-latex is an essentially two-phase system, which consists of a dispersed phase and a dispersive medium; water is the dispersed phase which is discrete and dispersed to the small droplets about 2-5 μm in diameter. This latex is the water in oil(W/O) type, and the polyester resin/styrene is continuous and the aqueous phase is dispersed throughout it. In the PPCC, sufficient water to chemically satisfy cement hydration is required to permit full growth of cement gel; this amounts needs about 15% to 22% water base on cement(21).

2.3.3 Curing of UP-PPCC

The curing takes place when all components are well blended with an initiator, which usually an organic peroxide, such as benzoyl peroxide dissolved in solvent or mixed with aggregate phase. Typically, a promoter or accelerator is added into the admixture to promote the decomposition of the initiator at room temperature, then we can get the rapid low-temperature curing UP-PPCC. Extra water is not necessary for curing because sufficient water in latex can let cement be hydrated. The chemical reactions of curing are happened by two reactions, hydration of cement and polymerization of polymer to form a UP-PPCC.

2.4 Fillers

In composites, filler includes the various organic or inorganic material, in flake, powder, granule or chopped fiber, which can provide enhanced or additional property to a matrix material, or reduced the cost. It can be combined with the matrix by means of mechanical blending, dispersed, mixing and other techniques.

2.4.1 Coarse Aggregate

Coarse aggregate comprises material at least 3/16 inch (4.75 mm) in size. Because the weak aggregate cannot produce strong concrete, coarse aggregate of limestone has the high average compressive strength about 23,000 psi(159 MPa). In fact, the aggregate in concrete is not truly inert and its physical, thermal, and chemical properties influence the performance of concrete(22).

2.4.2 Recycled Plastics

The recycled plastics from the soft drink PET bottle consists of PET and HDPE flakes which now is recycled by research pilot plant and industry. The recycled PET value can be separated to five levels by degree of processing, shown in descending order as following(4):

- a. Pelletized(recycled PET mostly closely approaching
virgin material with minimum impurities)
- b. Clean flake or granulated(value generally determined on
degree of cleanliness)
- c. Uncleaned flake or granulated
- d. Baled bottles
- e. Loose or bagged bottles

The purification of PET bottle recycled:

PET(Polyethylene Terephthalate) .. 99.4% Minimum

HDPE(High Density Polyethylene) .. 0.05% Maximum

(cannot filter out)

Aluminum..... 0.02% Maximum(detrimental to pumps)

Paper..... 0.1% Maximum(can filter out)

Adhesive..... 0.5%(general no problem)

Typically, the melting point of PET is about 260-265°C, for PE about 127-135°C. The reaction heat of hydration and polymerization is not high enough to melt the plastics, even melt still high viscous fluid difficult to spread,generally, this kind filler will not interact with polymer or conventional concrete like inert in the concrete composite.

CHAPTER III

EXPERIMENTAL PROGRAM

3.1 Types of Test

There were a series of conventional and polymer concrete specimens being cast, and five types of tests were conducted to observe the compressive strength, flexural strength, tensile strength, weathering test, and weight reduction effect of each composite. The specimen configurations of tests are listed in Table 3-1(22)(23)(24).

Table 3-1 The configurations of specimen for each test.

Type of Property	Type of Test	Dim. of Specimen
Compressive Strength	Compressive Test	3" x 6", Cylinder
Tensile Strength	Direct Uniaxial Tension	Dog-bone with 1 in ² cross-section
Flexural Strength	Flexural Test	1" x 1" x 12", Beam
Weight Reduction	Specific Gravity	3" x 6", Cylinder
Weathering Test	Compressive Test	3" x 6", Cylinder

3.2 Materials

3.2.1 Materials in Aggregate Phase

a. Cement

Keystone Portland cement, type I. Chemical compositions of it are listed in appendix A, Table I and II.

b. Fly Ash

Fly ash is the ash precipitated electrostatically from the exhaust fumes of coal-fired power stations. The particles of fly ash are spheres. The chemical composition, physical and mechanical characteristics of the fly ash are described in appendix A, Table III.

c. Sand

Silicious sand, passing sieve No.4. Its properties are shown in appendix A, Table IV.

d. Sikatop Series

Sikatop-B(component-B), repair mortar, polymer-modified cementitious powder-mix, containing Portland cement.

3.2.2 Materials in Binder Phase

a. Unsaturated polyester latex

Resin: MR-643, Aristech Chemical Corporation.

Promoter: Dimethyl aniline, $(\text{CH}_3)_2\text{C}_6\text{H}_3\text{NH}_2$,
Eastman Kodak Company.

Emulsifier: Na-Dodecyl sulfate, $\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}$,
Aldrich Chemical Co.

The data of UP-latex is shown in appendix A, Table V.

b. Sikatop Series(Sikatop-111 & Sikatop-122)

Sikatop-A(component-A),factory proportioned,blue-color,
emulsified copolymer latex. The general informations of
Sika series are listed in appendix A, Table VI.

c. Sikabond

Concrete reinforcing agent, factory proportioned,white-
color, emulsified copolymer latex.

3.2.3 Materials in Fillers

a. Recycled PET, PE flakes

The recycled PET and PE flakes are recycled by the
pilot plant of Rutgers' Plastics Recycling Center, and
are used as fillers in this research.

b. Coarse Aggregate

Clean, sound, crushed limestone, size 1/4 to 3/8 inch.

3.3 Experimental Procedure

3.3.1 Preparation of UP-latex

The mixing ratio of resin, water and emulsifier is 7, 3, and 0.06 by weight. Weigh all components accurately. In order to the water in oil(W/O) type emulsion, well mix the water and emulsifier to small microcell, the add the resin into agitating solution to get the stable latex. Water used in making latex should be clean, free from oil, salt, acid, organic matter or other substances injurious to the stability of latex.

3.3.2 Mixing Proportion

The different mixing proportion was done individual in this research to get the optimum quality which based on strengths, durability, specific gravity, and workability. The optimum mixing proportion of each specimen is listed in Table 3-2.

Table 3-2 Mixing Proportion.

Type	U-L	S-A	B-L	WTR	S-B	CMT	SND	ASH	BPO	Filler
CC	-	-	-	1.5	-	3	2	1	-	*
UP-PPCC	2	-	-	-	-	3	2	1	0.04	*
Sika111	-	2	-	-	15	-	-	-	-	*
Sika122	-	2	-	-	15	-	-	-	-	*
Sikabond	-	-	2	-	-	3	2	1	-	*

Type: type of concrete

CC: Conventional Concrete

Sika111: Sikatop-111

Sika122: Sikatop-122

U-L: Unsaturated Polyester Latex

S-A: Sikatop-A(component A, latex)

S-B: Sikatop-B(component B, aggregate phase)

B-L: Sikabond(concrete reinforcing agent, latex)

WTR: Water

CMT: Portland Cement, type I

SND: Sand

ASH: Fly Ash

BPO: Benzoyl Peroxide, catalyst

*: It is arranged that every dosage of plastics used in the concrete will be in the range of 0 - 20 percent by weight depending on the wetting ability of water or each latex; for coarse aggregate, 0 - 45 %.

3.3.3 Preparation of Test Specimen

The procedure of making each composite is much similar to the traditional way of making conventional concrete. Measure each amount for all components to be used in each experiment. First, pour all powdery components (aggregate phase, component-B) into a mixing pail except filler (coarse aggregate, PET, PE), and mix thoroughly to make it uniform. Depending on each formulation, water or certain type of latex (component-A) will be added into the premixed powdery mix. Thorough continuous mixing, the component-B (aggregate phase) shall be completely wet by component-A (binder phase); then, the certain type and amount of filler is added into the admixture with continuous mixing, so that the final mixture becomes uniform in its composition. This mixture can be cast in the molds for mechanical and weathering tests.

The working time is dependent on temperature, humidity, and can be shorter for hot, windy, dry weather. The time in mixing should be as short as possible. The total mix time should not exceed 5 minutes to make the specimen of UP-PPCC type; for Sika series, fifteen minutes is limited. After that certain time, the admixture will lose adhesive ability very quickly, and the mechanical properties of polymer concrete will be decreased sharply if the specimen can not be cast within the specific time. The reason is that all monomers or prepolymer (including crosslinking agent) will be

polymerized within a short period after adding of the catalyst, which usually mixed within aggregate phase. Such as benzoyl peroxide, 2% to latex, is used as catalyst for UP-PPCC type.

All specimens would be polymerized, if PPCC, and cured at room temperature and humidity(45-70%). The different configurations of specimens were made under standard process for different types of mechanical test. After aging for 28 days, the specimens were tested for the certain kinds of mechanical property.

3.4 Test Procedure

3.4.1 Compressive Strength and Weight Reduction Tests

Three types of compression test specimen are used: cubes, cylinders, and prisms. Cylinder specimen is the standard configuration in the United States. So, the well mixed composite was discharged to the standard cylinder (diameter: 3 inch and height: 6 inch). Until the cylinder being near one third full, a stirring rod was used to swirl out and entrap air from the sides of the cylinder. One or two motions were generally be given. When the cylinder was filled, the concrete surface was flattened by using screed or similar device.

After 28-day aging in room temperature and humidity, the specimens were weighed to get their specific gravity, and then tested the compressive strength by the help of the instrument(Material Test System 810). The end surfaces of the concrete cylinders were capped by sulfur so that the end planes will be parallel to one another. The stress-strain relationship for concrete in compression was recorded during the test.

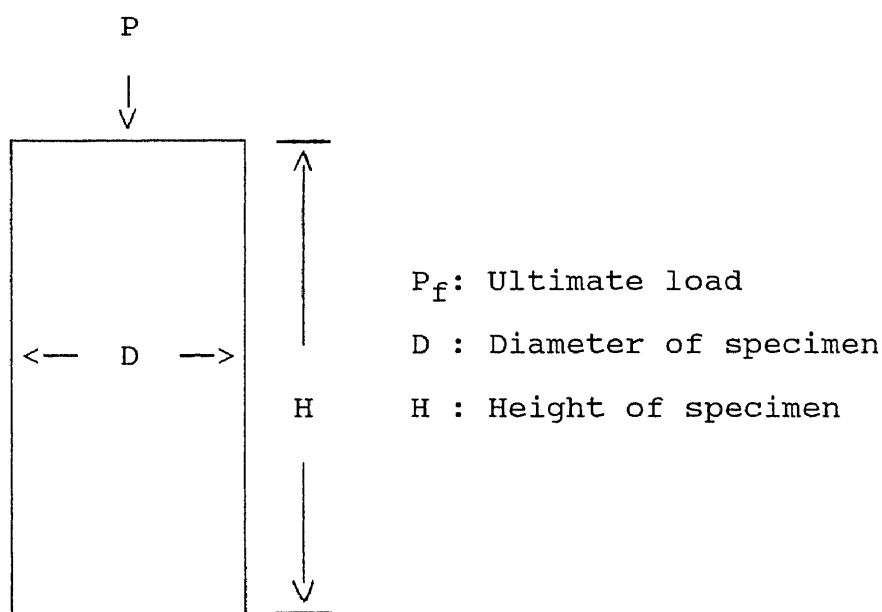


Fig 3-1 Compressive Strength Test.

$$\text{Compressive Strength} = P_f / A = P_f / [3.14 \cdot (D/2)^2]$$

For Diameter = 3.0 inch, the unit of load is "lb_f",

$$\text{The Compressive Strength(PSI)} = P_f / 7.0686 \text{ lb}_f/\text{inch}^2$$

3.4.2 Flexural Strength Test

After the admixture thorough mixing, the beams were cast in 12 inch x 1 inch x 1 inch mold. Aged for 28 days, each specimen was tested with the help of the instrument (Instron) to get the data for calculation of each flexural strength.

The specimen is supported by two standings and loaded with a concentrated load P in the middle of span L . The flexural strength can be calculated with the data of the ultimate load P_f at which the specimen failed.

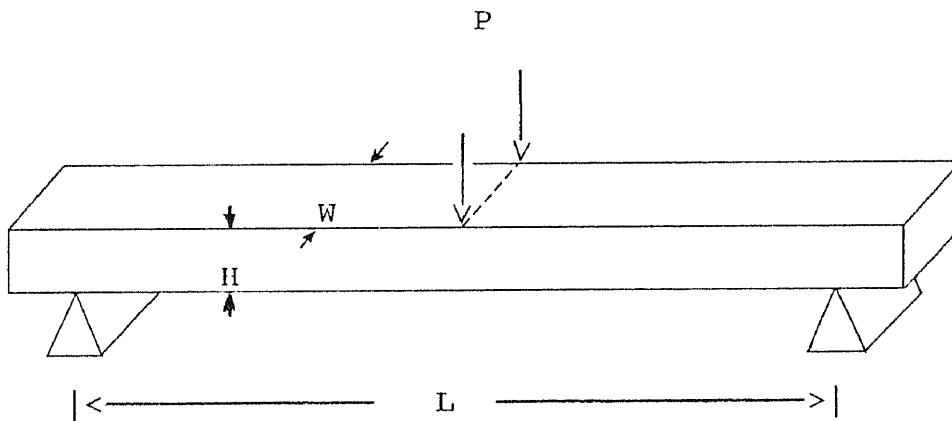


Fig 3-2 Flexural Strength Test

P_f : Ultimate load

L : Distance between two standings

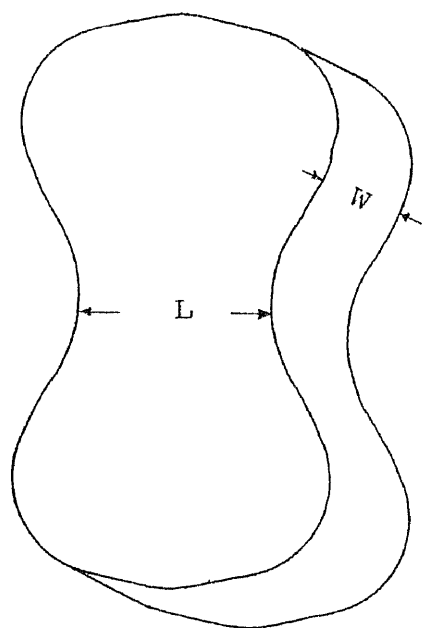
W : Width of specimen

H : Height of specimen

$$\text{Flexural Strength} = \sigma = \frac{3 \cdot P_f \cdot L}{2 \cdot W \cdot H^2}$$

3.4.3 Tensile Strength Test

The same procedure was adopted as was used in beam casting, the dog-bones with 1 inch square cross-section were cast in the mode. Each specimen was tested with the help of the instrument (Instron) and the data was obtained on each tensile strength after aging for 28 days.



P_f : Ultimate load

L : Length of cross-section

W : Width of cross-section

Fig 3-3 Tensile Strength Test

$$\text{Tensile Strength} = P_f / A = P_f / (L \cdot W)$$

3.4.4 Weathering Test.

Cement reacts with water to form a cement hydrate, which, as cures, coalesces, shrinks, and hardens to become the matrix for the entire mixture. As water leaves the mix, however, voids and microscopic cracks are left behind. Normally, these voids and cracks are not a problem. But in concrete subjected to more demanding conditions, these 'openings' in the concrete are literally a door to serious trouble. Corrosive chemicals penetrate to deteriorate the concrete itself. Moisture penetration in extreme weather cycles can quickly cause severe freeze-thaw damage. Polymer Portland cement concrete can much improve this property.

All specimens for weathering test were made in same way as for compressive strength tests and stored outdoor for six and nine months under natural weathering conditions during September 1986 to June 1987 in New Jersey. Specimens had been tested by the instrument(MTS 810) and compared with regular data(indoor, 28 days) of compressive strength(25).

CHAPTER IV

RESULTS AND DISCUSSIONS

Over four hundred specimens had been mixed, cast and tested. All formulations of the composites can be reacted and hydrated in room temperature. Meanwhile, coarse aggregate as filler was involved in this study as reference.

The heat generated by the polymerization of polymer and hydration of cement matrix will rise the system temperature. Some experiments conducted about the temperature rising curves, by using the mold of cylinder, were done and shown in appendix B(Fig 1, 2 and 3). For UP-PPCC system, the temperature of the cylinder will begin to rise about five minutes after mixing. About thirty-five minutes later, the temperature of the system will reach the ultimate value about 50°C. The composite will harden at this moment, then, the temperature will go down to ambient temperature within a couple hours. For Sika series, Sikabond and conventional concrete, the ultimate temperature will be around 37°C, 31°C and 27°C.

From the preceding data, the temperature of each system would not reach high enough to melt the plastic filler in this study. But for large mass of concrete, the center of concrete may rise to a very high temperature because the heat conductivity of concrete is comparatively low like the insulator, a little higher for all types of polymer concrete.

The results of all tests are shown in serial figures for different formulations, fillers and mix proportions. Some strain-stress curves are figured in appendix C.

The data of **compressive strength** are shown in Fig 4-1, 4-2 and 4-3 for PET, PE and coarse aggregate as filler, respectively. As expected, the incorporations of recycled PET and PE flakes in concrete matrix result a decrement in compressive strength for all types of concrete, because the plastic flakes will block the bond formation between polymer and concrete matrix. During the all composite systems, the UP-PPCC shows the smallest reduction trend in compressive strength, because it has better adhesive ability to bond the PET or PE with polymer-concrete matrix; meanwhile, the compressive strengths of Sikatop-111 and Sikatop-122 are both decreased rather sharply.

When the coarse aggregate incorporated with concrete, it results an increment in compressive strength for all kinds of concrete, both conventional and polymer cement concretes. It means that incorporation of coarse aggregate within a certain level of filling in concrete matrix will get higher compressive strength due to the formation of the stronger binding force between coarse aggregate and concrete matrix, and the high compressive strength of coarse aggregate.

Fig 4-1 Compressive Strengths of Conc.

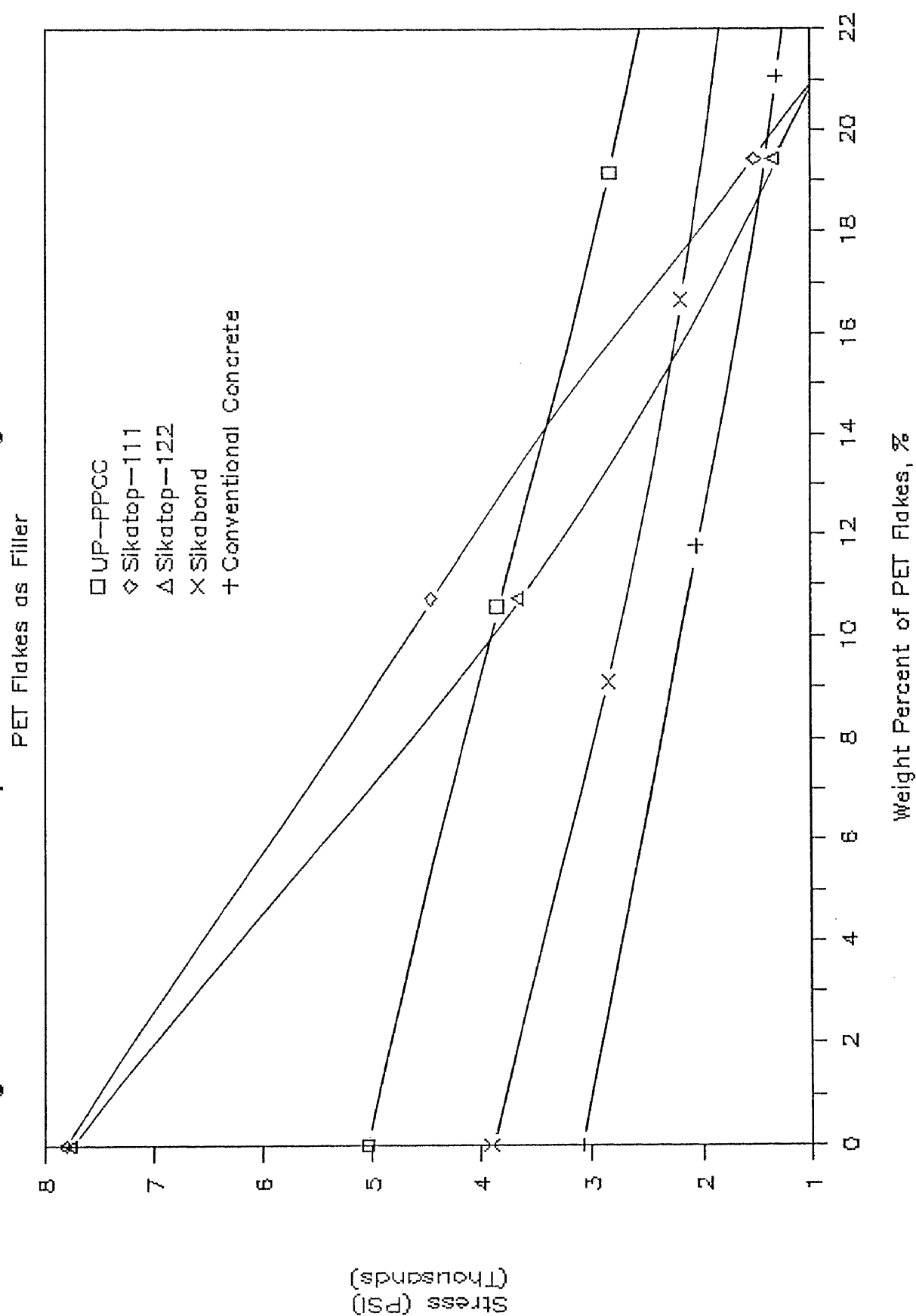


Fig 4-2 Compressive Strengths of Conc.

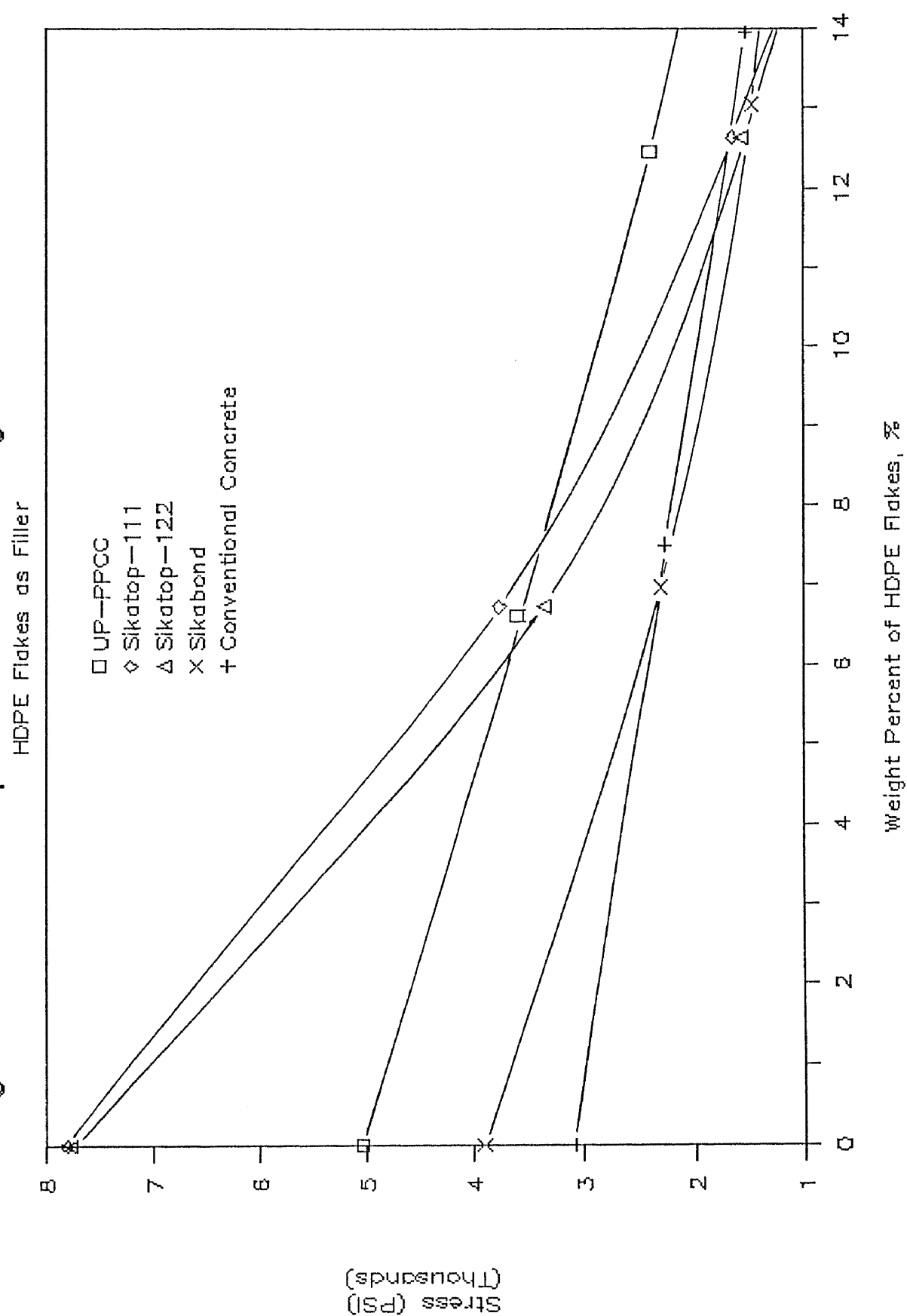
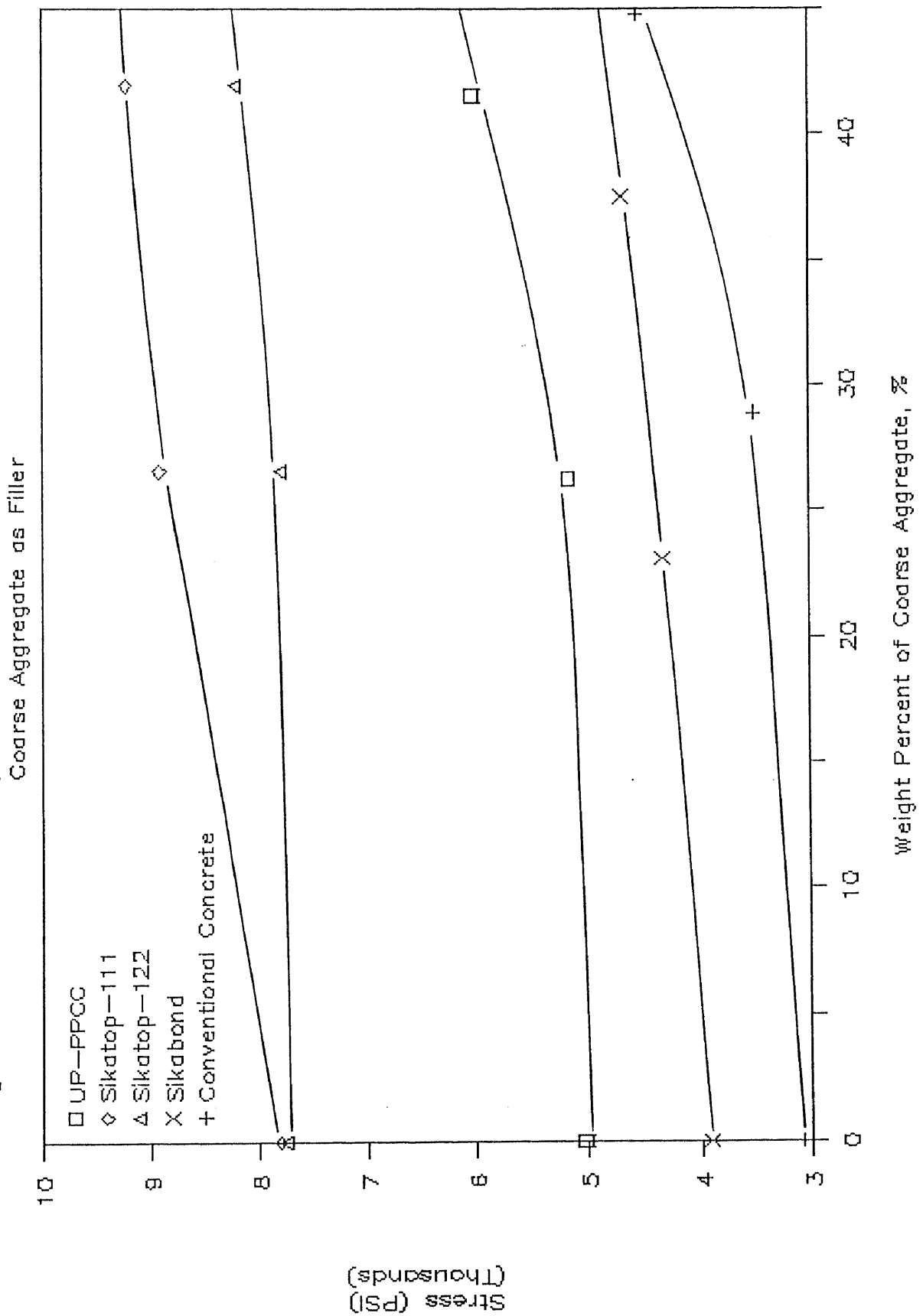


Fig 4-3 Compressive Strengths of Conc.



For the flexural strength, Fig 4-4, 4-5 and 4-6 show the results of PET, PE and coarse aggregate as filler in concrete, respectively. In general, all types of filler will decrease the behavior of flexural strength, except fiberglass or reinforcing material.

The decrement in flexural strength with 10% PET incorporation is about -10%, -60%, -50%, -35% and -30% for UP-PPCC, Sikatop-111, Sikatop-122, Sikabond and conventional concrete, respectively. Similarly, the decrement in flexural strength with 10% PE incorporation is about -20%, -65%, -70%, -40% and -25% for UP-PPCC, Sikatop-111, Sikatop-122, Sikabond and conventional concrete, respectively.

On contrary to compressive strength, the flexural strengths of all types of concrete are decreased as coarse aggregate as filler. With 10% coarse aggregate incorporation, the decrement of flexural strength is about -4.5%, -7.0%, -7.5%, -8.5% and -5% for UP-PPCC, Sikatop-111, Sikatop-122, Sikabond and conventional concrete, respectively.

Among of these results, the UP-PPCC system shows the best behavior to flexural strength when PET, PE, coarse aggregate is incorporated as filler, the smallest reduction trend of strength for UP-PPCC due to its high reactivity easily to form a film.

Fig 4-4 Flexural Strengths of Conc.

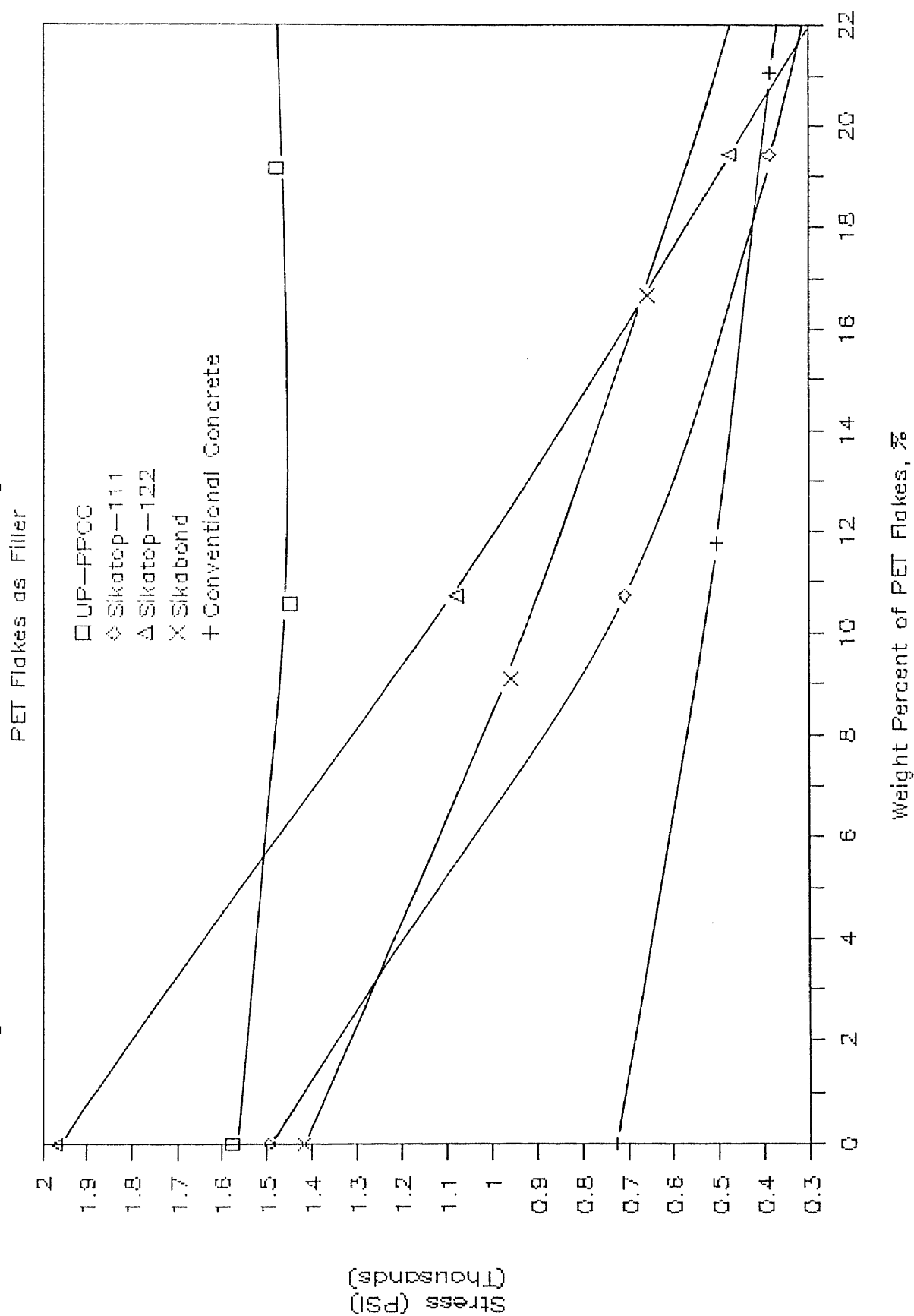


Fig 4-5 Flexural Strengths of Conc.

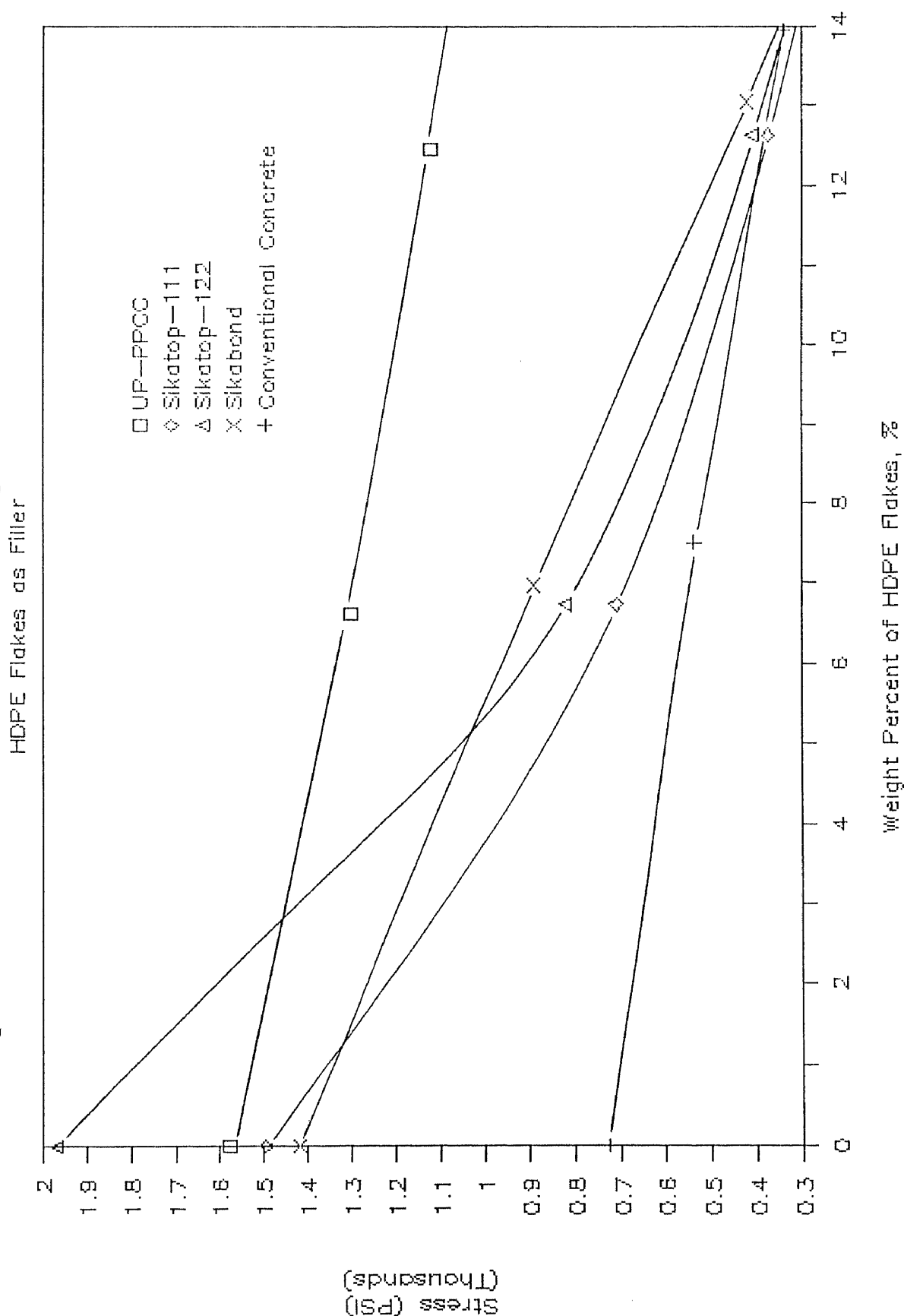
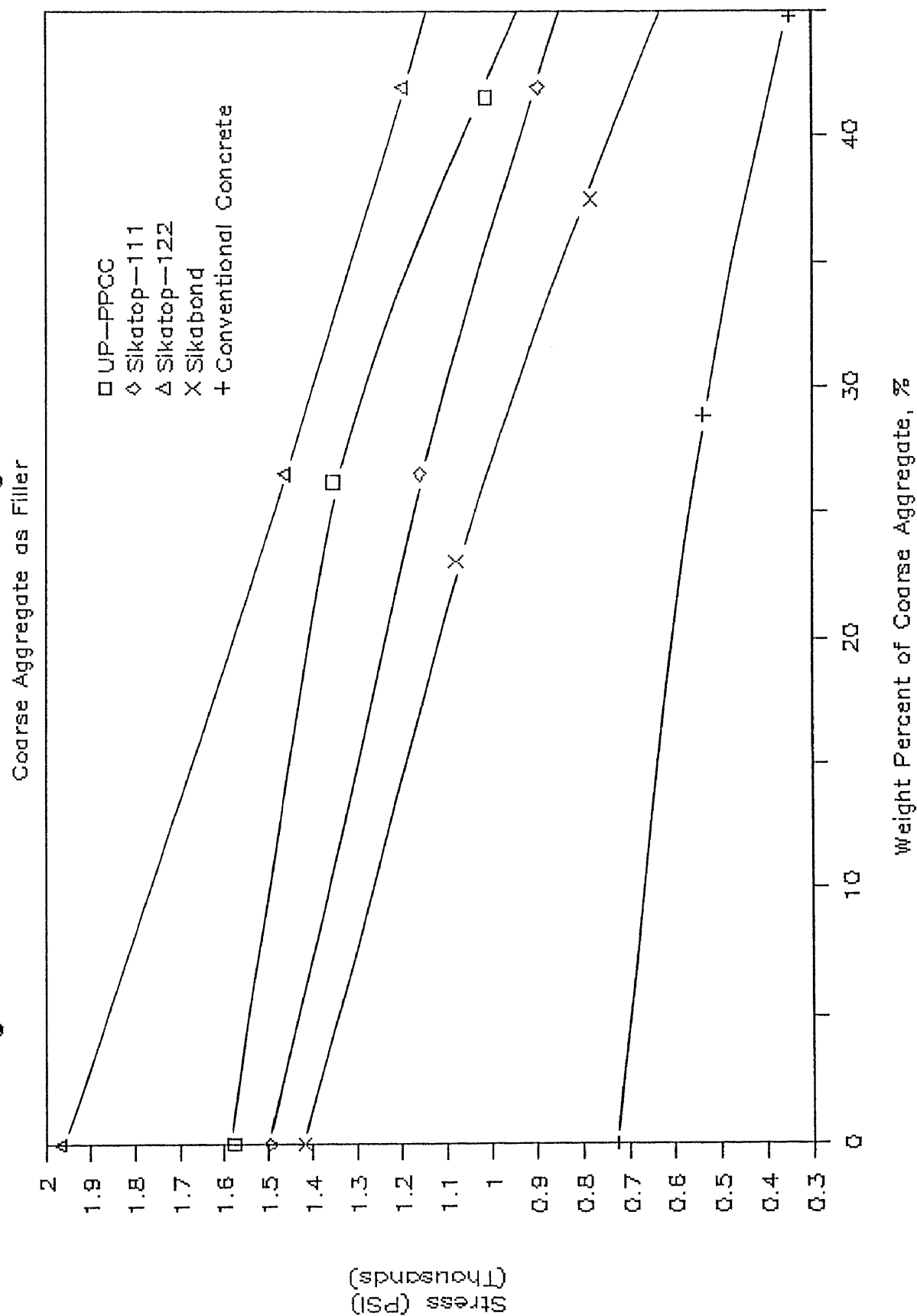


Fig 4-6 Flexural Strengths of Conc.



As shown in Fig 4-7,4-8 and 4-9, the results of **tensile strength** are complicated for PET, PE and coarse aggregate as filler, respectively.

In case of PET or PE used as filler, the UP-PPCC still is the smallest reduction trend among all types of concrete. For example, the decrement in tensile strength with 10% PET incorporation is about -4%, -38%, -54%, -25% and -50% for UP-PPCC, Sikatop-111, Sikatop-122 and Sikabond, respectively.

As coarse aggregate used as filler, the curves of tensile strength show rather complex behaviors. In general, the strength obtained from UP-PPCC shows slight increase or no change within 30% of gravel by weight, but they decrease beyond 30%, by weight. Conversely, both Sika series and conventional concrete show the reduction in strength monotonously by the incorporations of gravel.

Fig 4-7 Tensile Strengths of Conc.

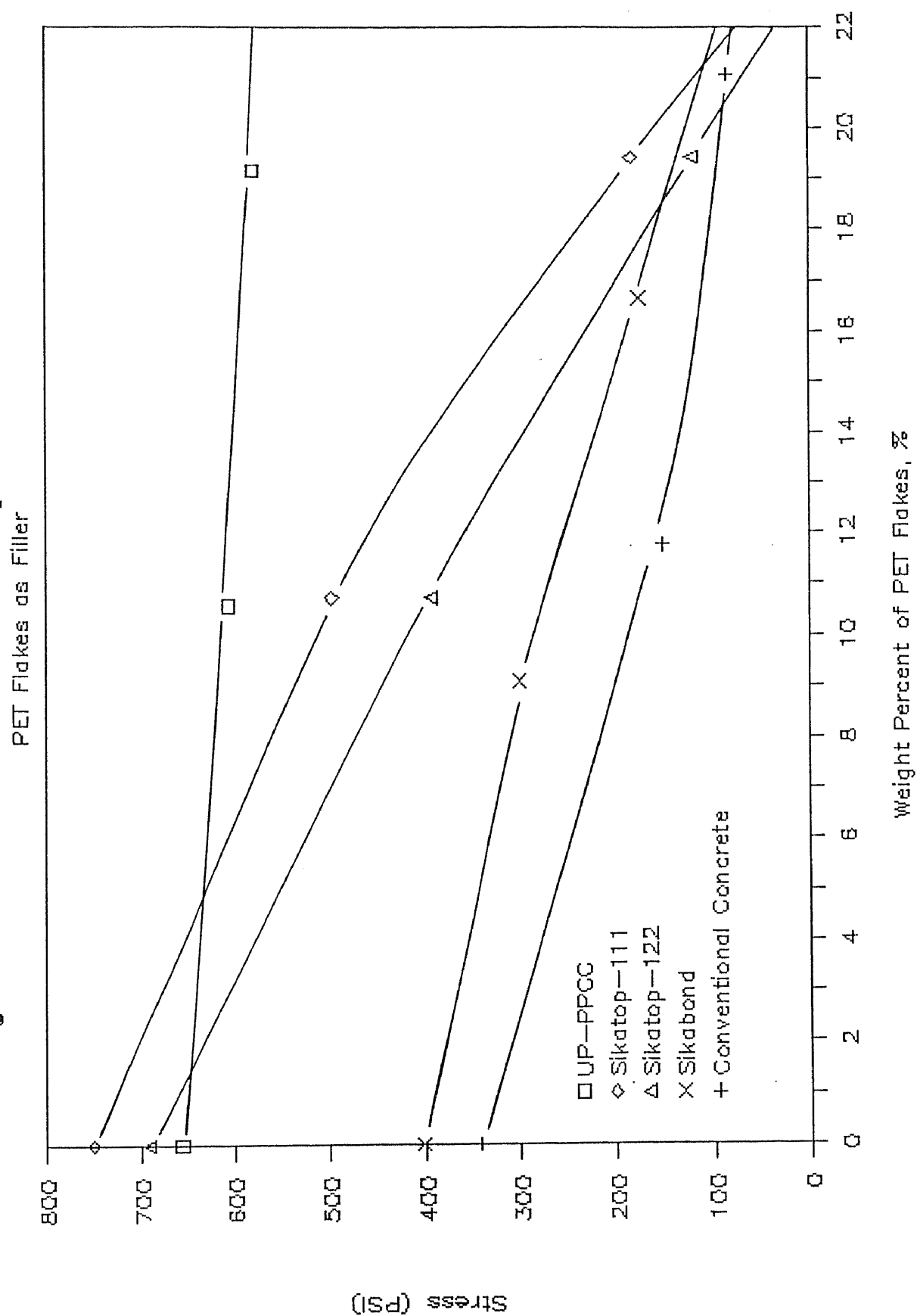


Fig 4-8 Tensile Strengths of Conc.

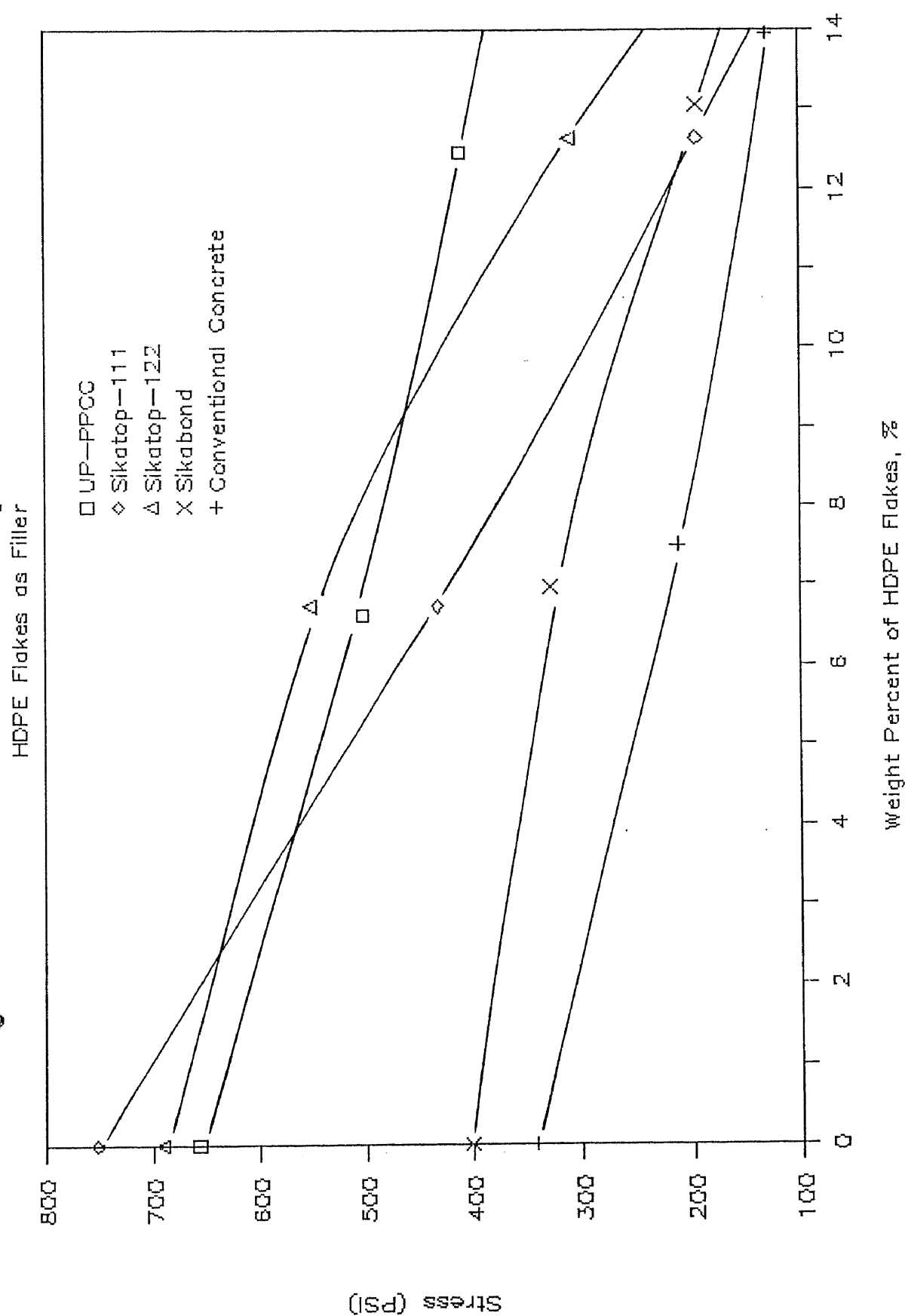
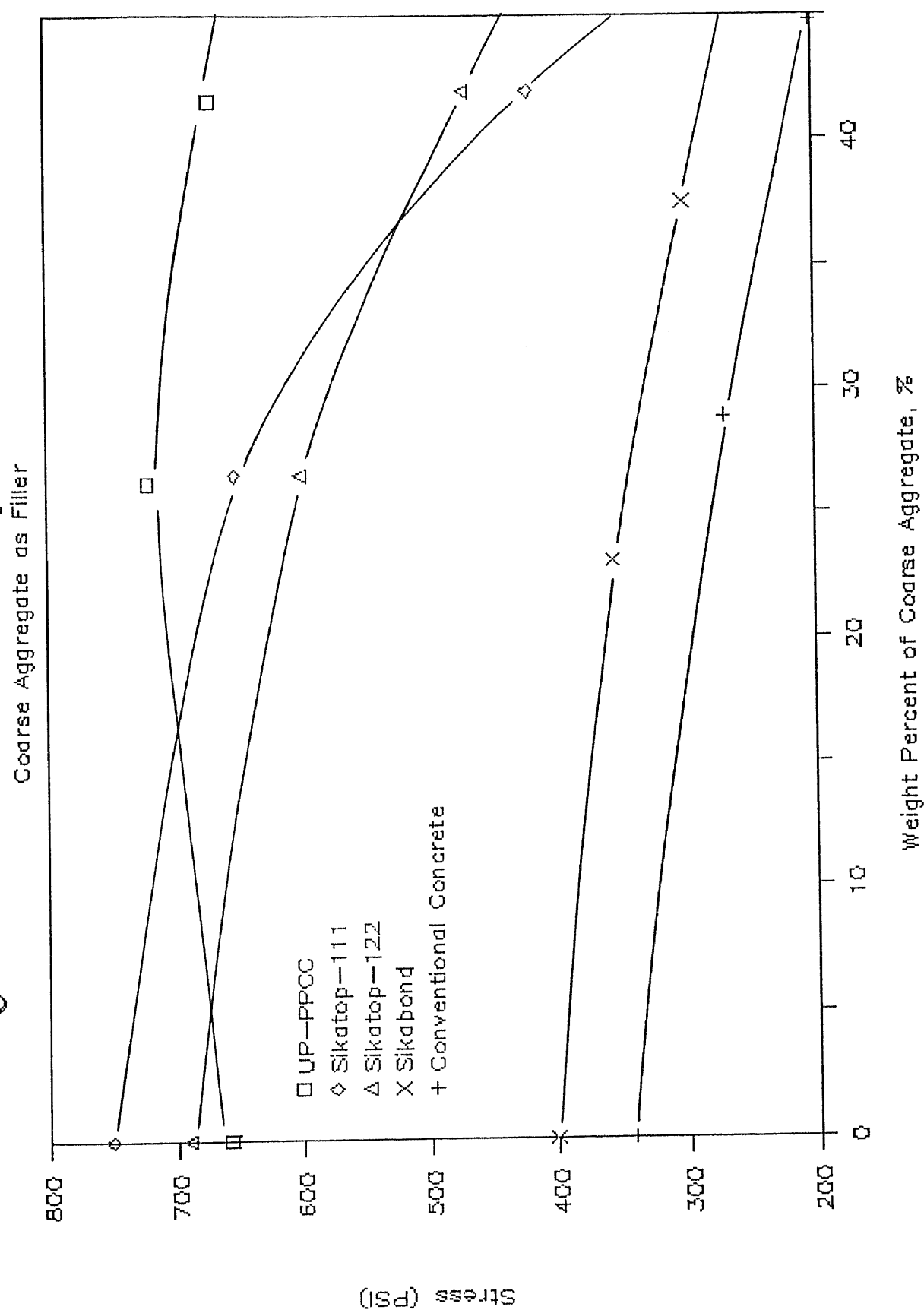


Fig 4-9 Tensile Strengths of Conc.



The results of **weight reduction** are figured in Fig 4-10 4-11 and 4-12; and the derivative data of **weight reduction effectiveness** are shown in Fig 4-13, 4-14 and 4-15 for PET, PE and coarse aggregate as filler, respectively.

From the first two figures, PET and PE as filler, the decreased slopes are little high than those of expectation; for the surfaces of the plastic flakes are not easy to be wet, and the UP-latex is high viscous fluid, so that is not easy to get rid of bubbles. If the voids can be totally entrapped, the all kind strengths will improve about 20-50%. Conversely, the specific gravity of products is increased by filling coarse aggregate.

In the Fig 4-13, 4-14 and 4-15, the weight reductions are effected by filling recycled plastics, about 15% reduction for 20% PET or 13% PE in concrete. Conversely, it shows the increase in specific gravity by filling of coarse aggregate.

Fig 4-10 Specific Gravities of Conc.

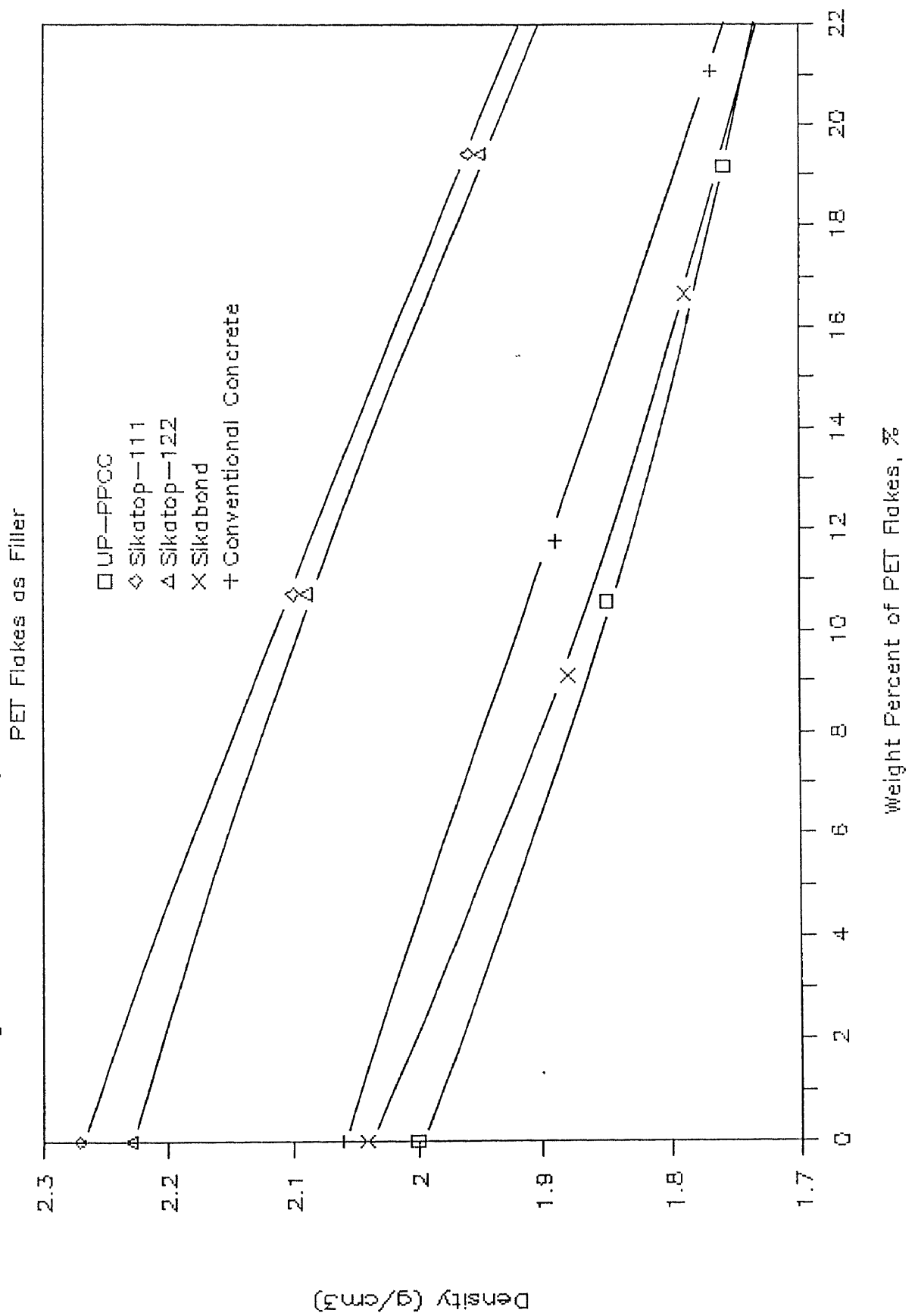


Fig 4-11 Specific Gravities of Conc.

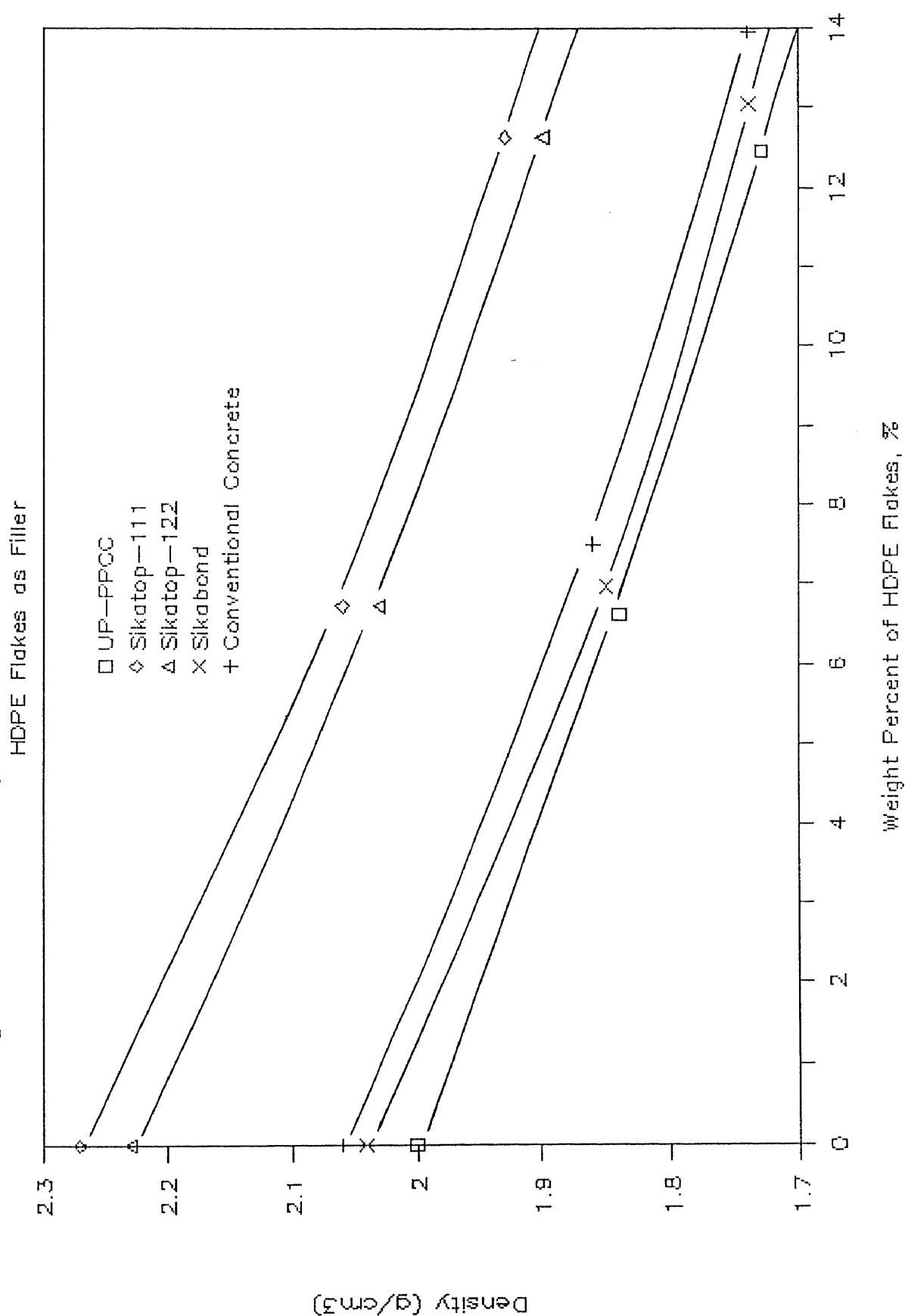


Fig 4-12 Specific Gravities of Conc.

Coarse Aggregate as Filler

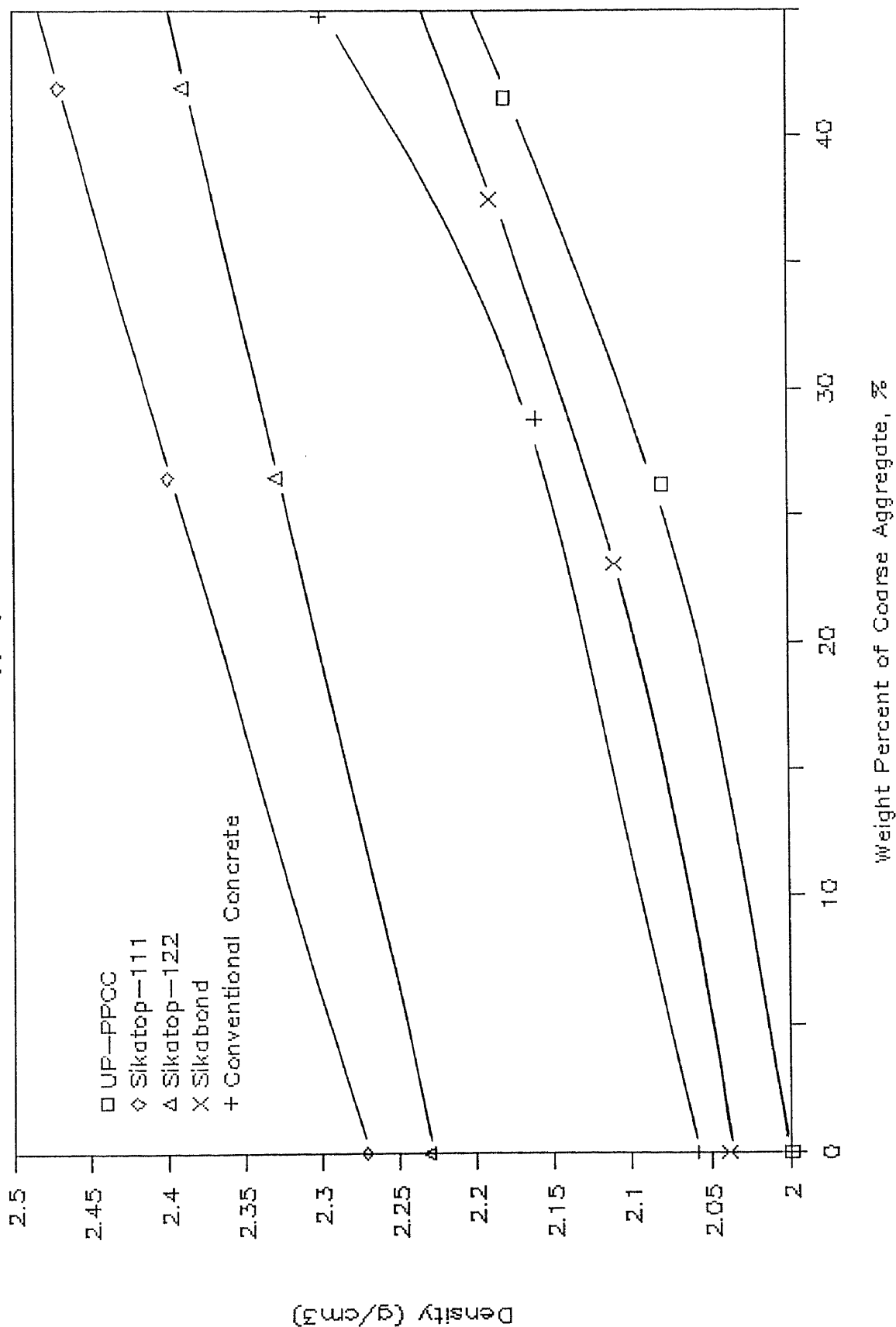


Fig 4-13 Weight Reduction Effect.

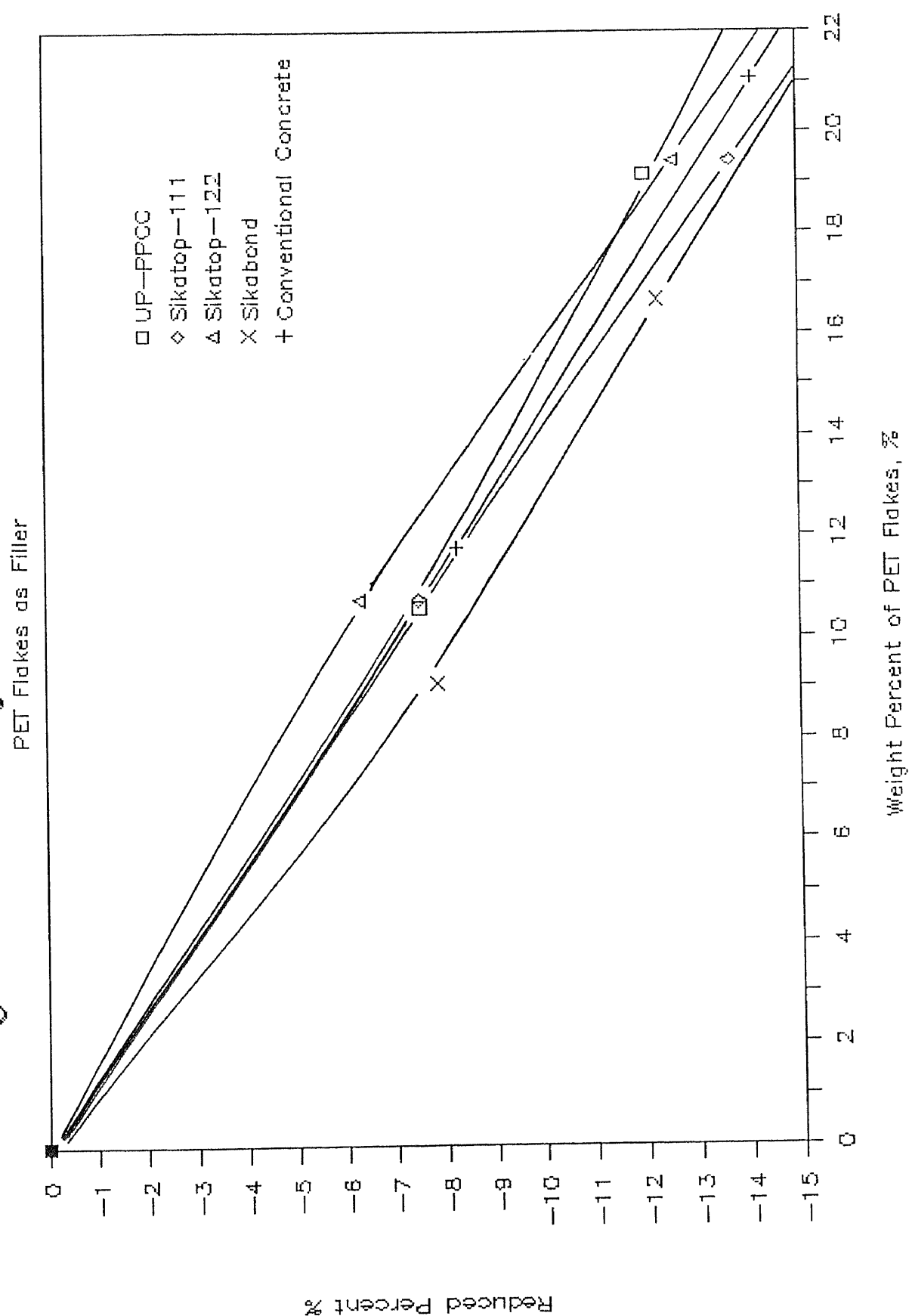


Fig 4-14 Weight Reduction Effect.

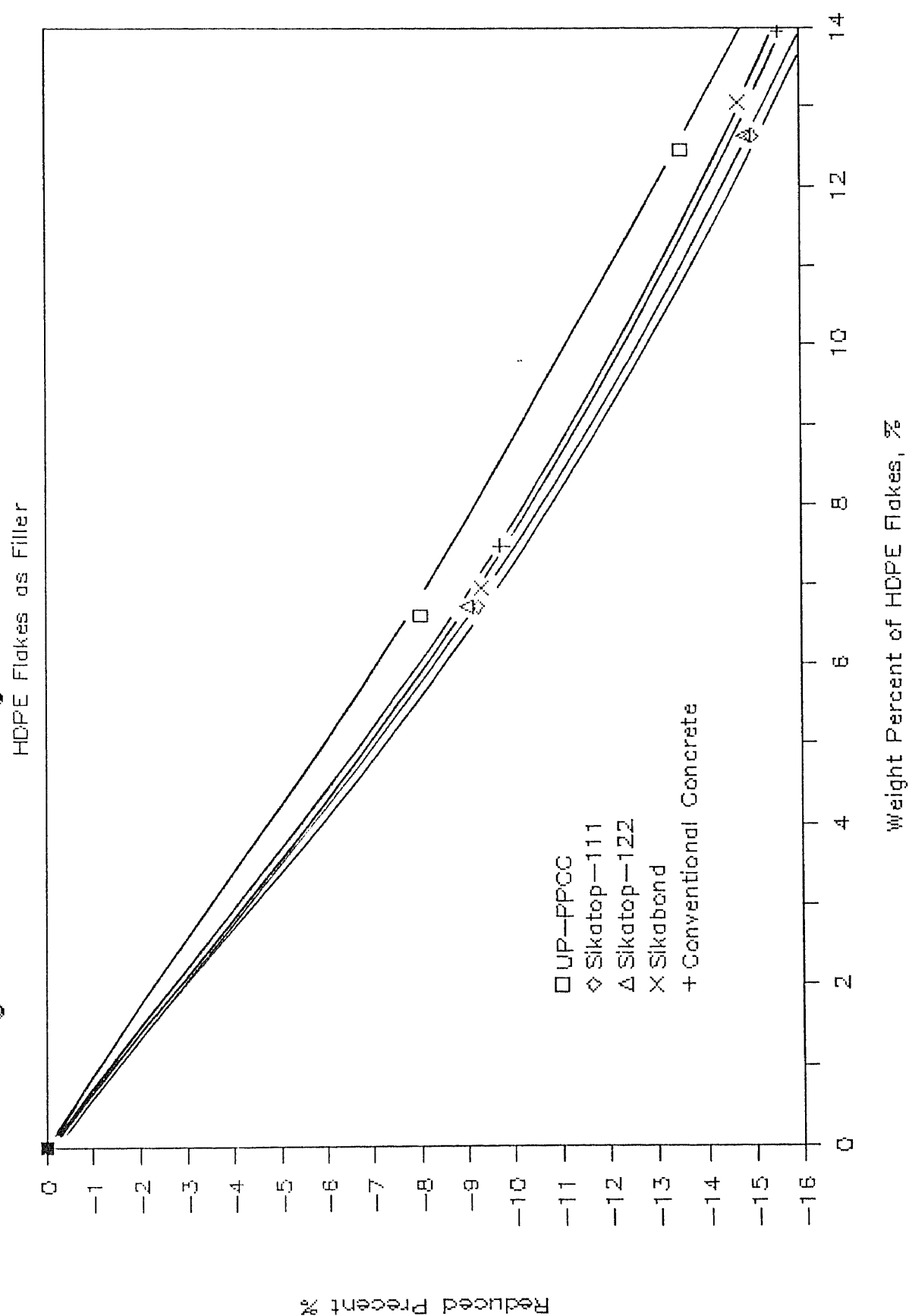
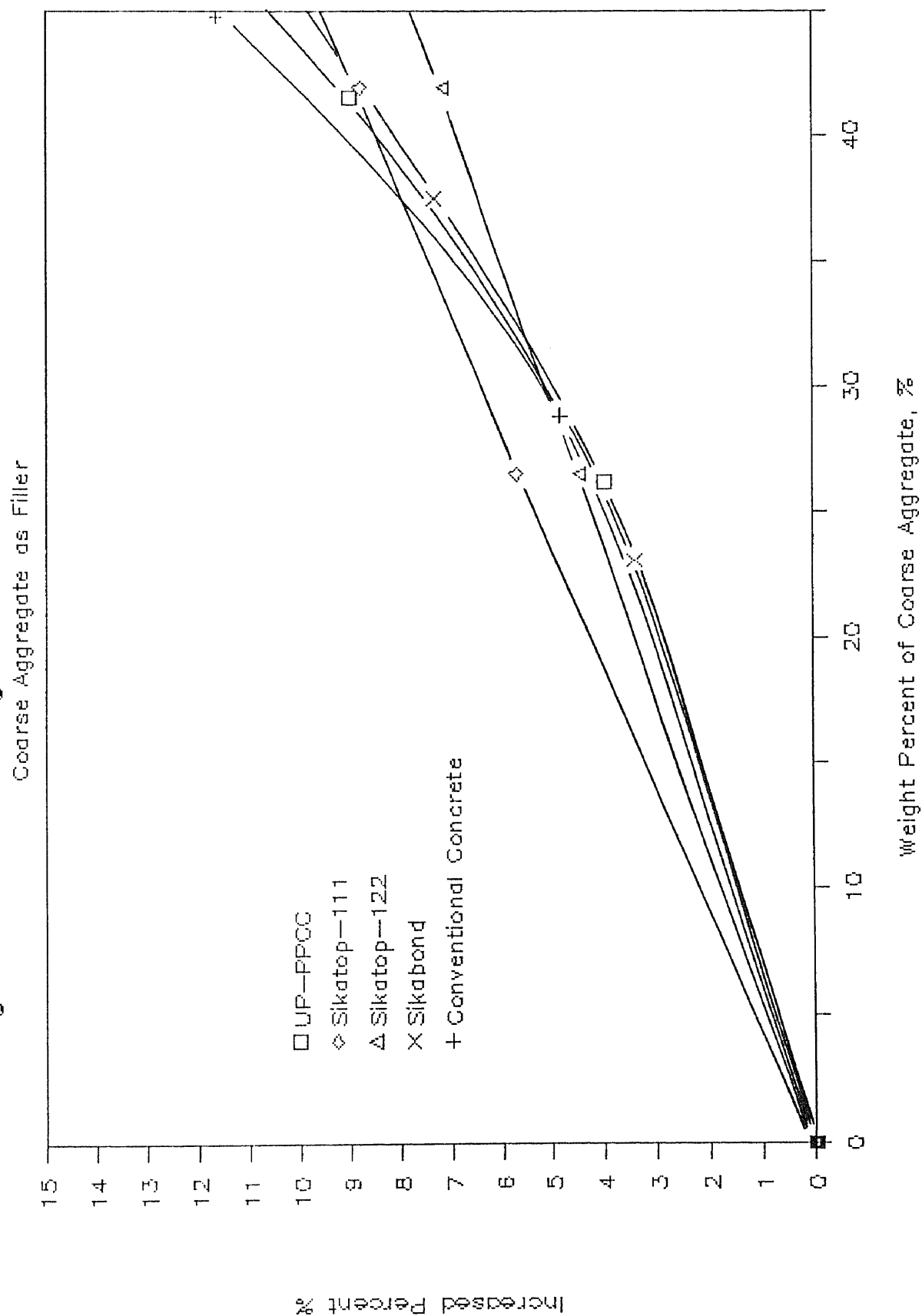


Fig 4-15 Weight Increment Effect.



The specimens, which had been exposed outdoor for six and nine months of natural **weathering tests**, were measured for their compressive strengths, and were compared with the data of controlled specimens(same compositions aged for 28 days, in the laboratory without weathering test).

No significant change, in compressive strength of the concrete composites filled by PET, PE or coarse aggregate, is observed in outdoor weathering tests. The weathering data for six and nine months long are almost same as controlled data of all types of concrete, because nine months is too short for natural weathering test.

CHAPTER V

CONCLUSIONS

Recycled plastics blended into concretes gives the following results, and these polymer concrete composites may offer some advantages over conventional concrete.

- a. Energy effectiveness in the application of these polymer concrete composites as concrete elements or structures, the products can be processed at ambient temperature and can be simply formed by the similar manner as conventional concrete mixture.
- b. The purity and color of the recycled plastics are not so critical for the quality of products in this kind of application.
- c. For UP-PPCC, no significant reduction in the flexural and tensile strengths can be observed which is more ductile than unfilled polymer concrete and conventional concrete on an equal weight basis.

- d. Weight reduction of concrete material by filling waste plastics is advantageous in material handling, transportation, and in other applications.
- e. The quality deterioration of filled plastics in concrete will be minor in the weathering test. The latex can seal off the voids and cracks, and reduce the penetration of moisture or corrosive chemicals. Concrete matrix was found to be effective to prevent such deterioration under the outdoor exposure.
- f. The addition of plastics as filler in PPCC does not like the behavior of plastics blending or alloying.
- g. From the stress-strain curves, the waste plastics filling in concrete show much improvement in energy absorbing capacity than unfilled concrete(see appendix C).
- h. The resultant composites offer unprecedented end-uses. The potential applications include pier decking, truck paneling, farm fencing, and even molding parts for automobiles and appliances.

The further research can be concerned with following directions.

- a. Some coupling agent may greatly improve the bonding force between plastics filler and cement matrix and resin, such as 3-methacryloxypropyltrimethoxy silane coupling agent.
- b. The new process, to get rid of void and to entrap the bubble, will improve 20-50% of all type strengths.

APPENDIX A

TABLES

TABLE I Main Compounds of Portland Cement

Name of Compound	Oxide Composition	Abbreviation
Tricalcium Silicate	$3\text{CaO} \cdot \text{SiO}_2$	C_3S
Dicalcium Silicate	$2\text{CaO} \cdot \text{SiO}_2$	C_2S
Tricalcium Aluminate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	C_3A
Tetracalcium Aluminoferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C_4AF

$\text{CaO}=\text{C}$	$\text{SiO}_2=\text{S}$	$\text{Al}_2\text{O}_3=\text{A}$	$\text{Fe}_2\text{O}_3=\text{F}$
-----------------------	-------------------------	----------------------------------	----------------------------------

TABLE II Typical Values of Compound Composition of Portland Cements, Type I

Compound Composition	Percent	Mean Value
C_3S	42-67	49
C_2S	8-31	25
C_3A	5-14	12
C_4AF	6-12	8
CaSO_4	2.6-3.4	2.9
Free CaO	0.0-1.5	0.8
MgO	0.7-3.8	2.4
Loss of Ignition(LOI)	0.6-2.3	1.2

TABLE III Chemical Composition, Physical and Mechanical Characteristics of Fly Ash (ASTM C618, Class C)

Constituents	Weight Percent
SiO_2	48.9
Al_2O_3	23.9
Fe_2O_3	3.4
CaO	15.3
MgO	0.5
SO_3	0.3
Na_2O	2.9
K_2O	0.7
TiO_2	< 1.0
Free Ca(OH)_2	8.1
Loss of Ignition (950°C)	0.6

Optimum moisture content at 25 blows	= 19.6 %
Maximum dry density at 25 blows	= 1280 Kg/M^3 (2160 lb/yd^3)
28 days compressive strength at 28 blows	= 870 KN/M^2 (2100 lb/ft^2)
Specific gravity	= 1.97 g/cm^3
Specific surface	= 314 M^2/Kg (1530 ft^2/lb)

TABLE IV Properties of Sand

Maximum Size, inch(mm)	0.05(1.2)
Fineness Modulus	2.48
Specific Gravity	2.65
Water Absorption Percent	2.71
Unit Weight, Pound/Liter(Kg/Lt)	3.59(1.63)

TABLE V Properties of Unsaturated Polyester Latex

Composition	Parts by Weight
Unsaturated Polyester Resin	70
Water	30
Peroxide	0.02
surfactant	0.06
Promoter	0.001
PH value	3.0-4.5
Weight per Gallon(U.S.)	8.6-9.0 Lb/G
Color	White

TABLE VI The General Informations about Sika Series

Maker: Sika Corporation

Construction Products Division, Lyndhurst, NJ.

a. Sikatop Series(111 & 122): polymer Portland cement concretes, the commercial products of two components.

Component-A: Sikatop-A, factory proportioned, blue-color, emulsified copolymer latex.

Component-B: Sikatop-B, repair mortar, polymer-modified cementitious powder-mix, containing Portland cement.

b. Sikabond: Concrete reinforcing agent, factory proportioned, white-color, emulsified copolymer latex.

Shelf Life: 1 year

Storage Condition: 65°F - 80°F

Application Time(working time): Approximately 15 minutes after adding bagged dry component to liquid component. Mortar remains plastic for longer period, but will have less adhesion after that time. Application time is dependent on temperature; shorter when hot, longer when cold.

Finishing time: 20 to 60 minutes, after combining components, depends on temperature, relative humidity, and type finish desired.

Limitations: Siaktop111 for minimum thickness is 1/2 inch, Sikatop122 minimum thickness 1/8 inch. Minimum ambient and substrate temperature is 45°F(7°C) and properly prepared substrate.

APPENDIX B

TEMPERATURE RISING CURVES

Fig 1 UP-PPCC Temperature Rising Curve

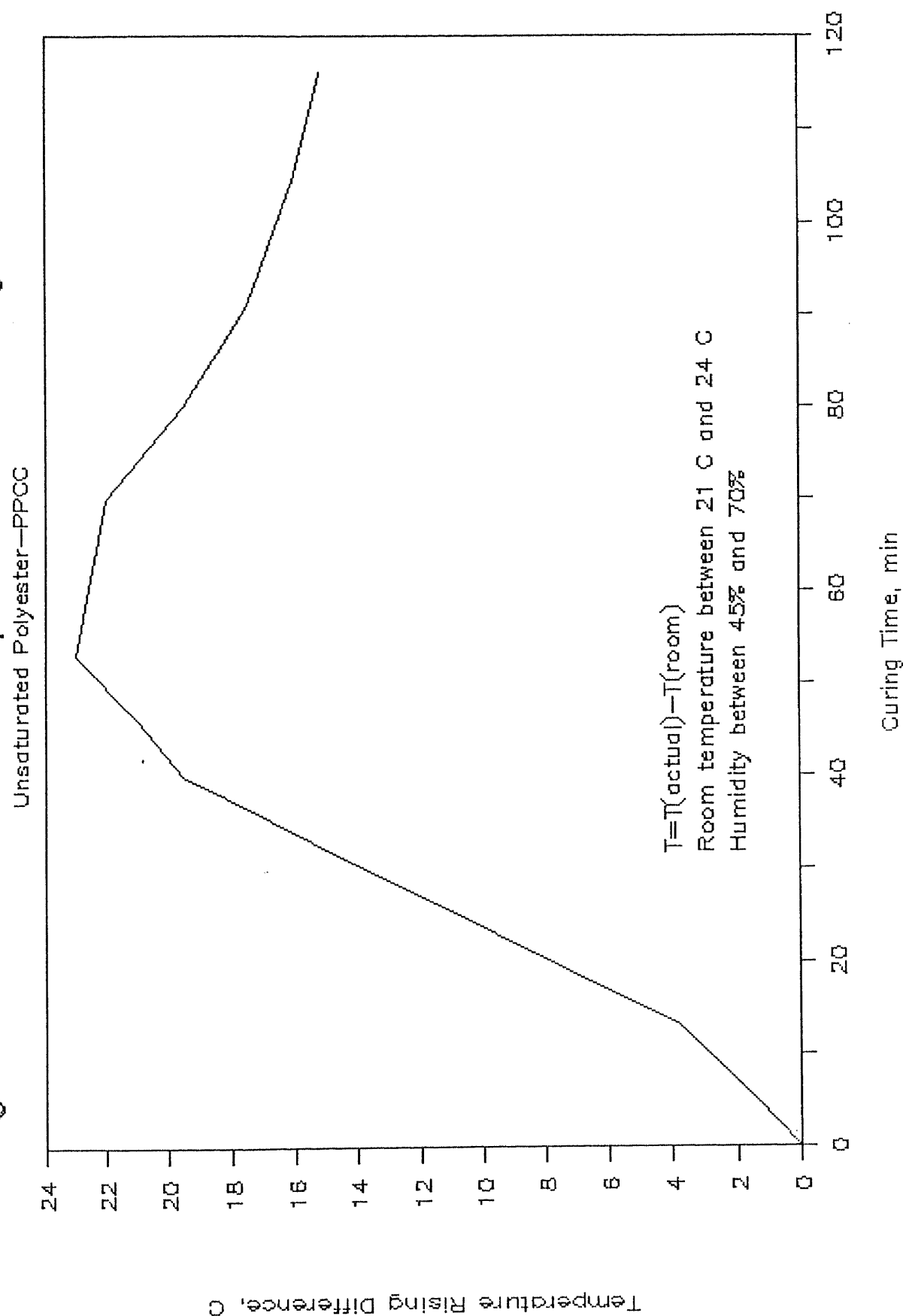


Fig 2 Sika111 Temperature Rising Curve

Sikatop 111

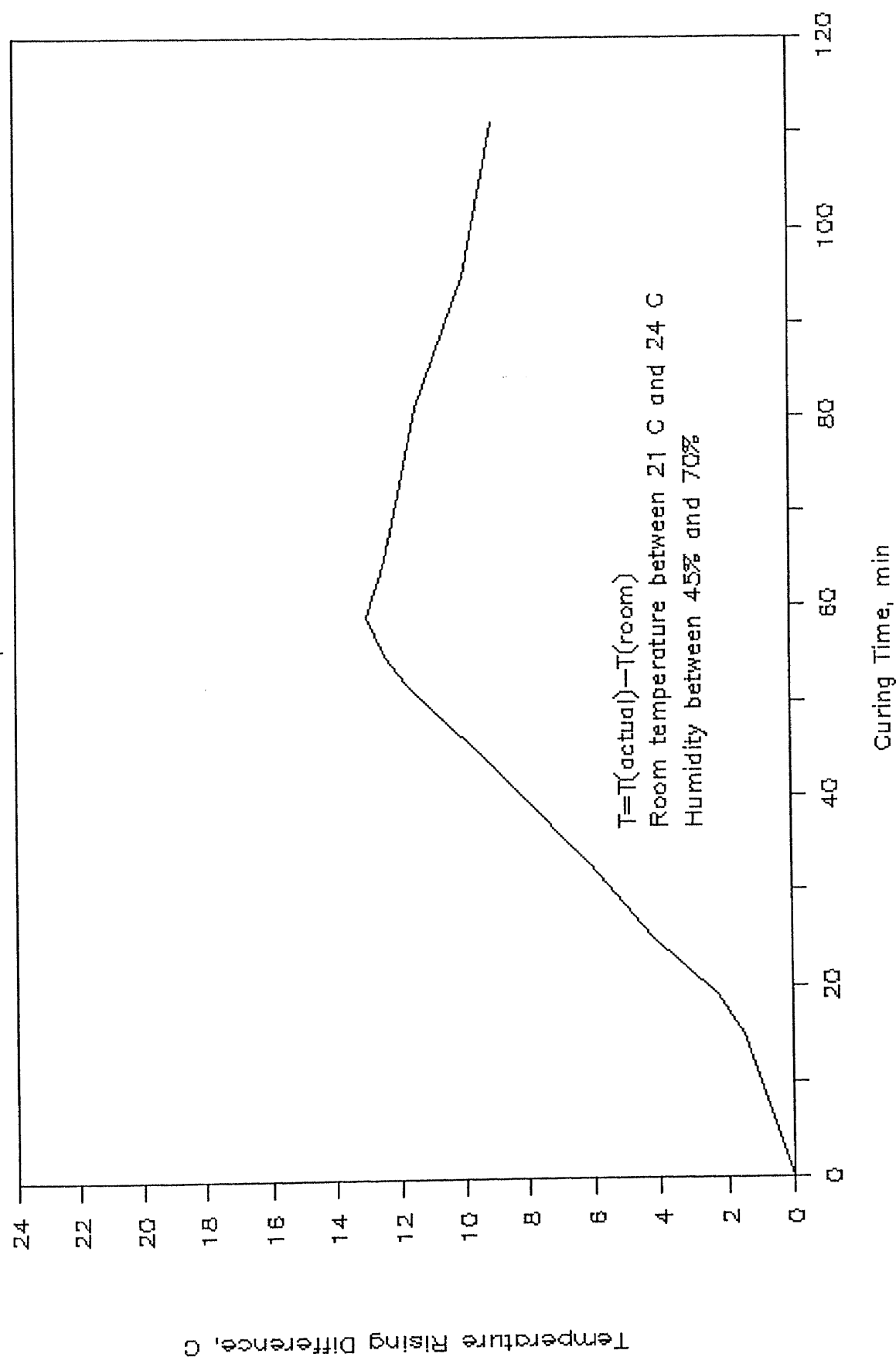
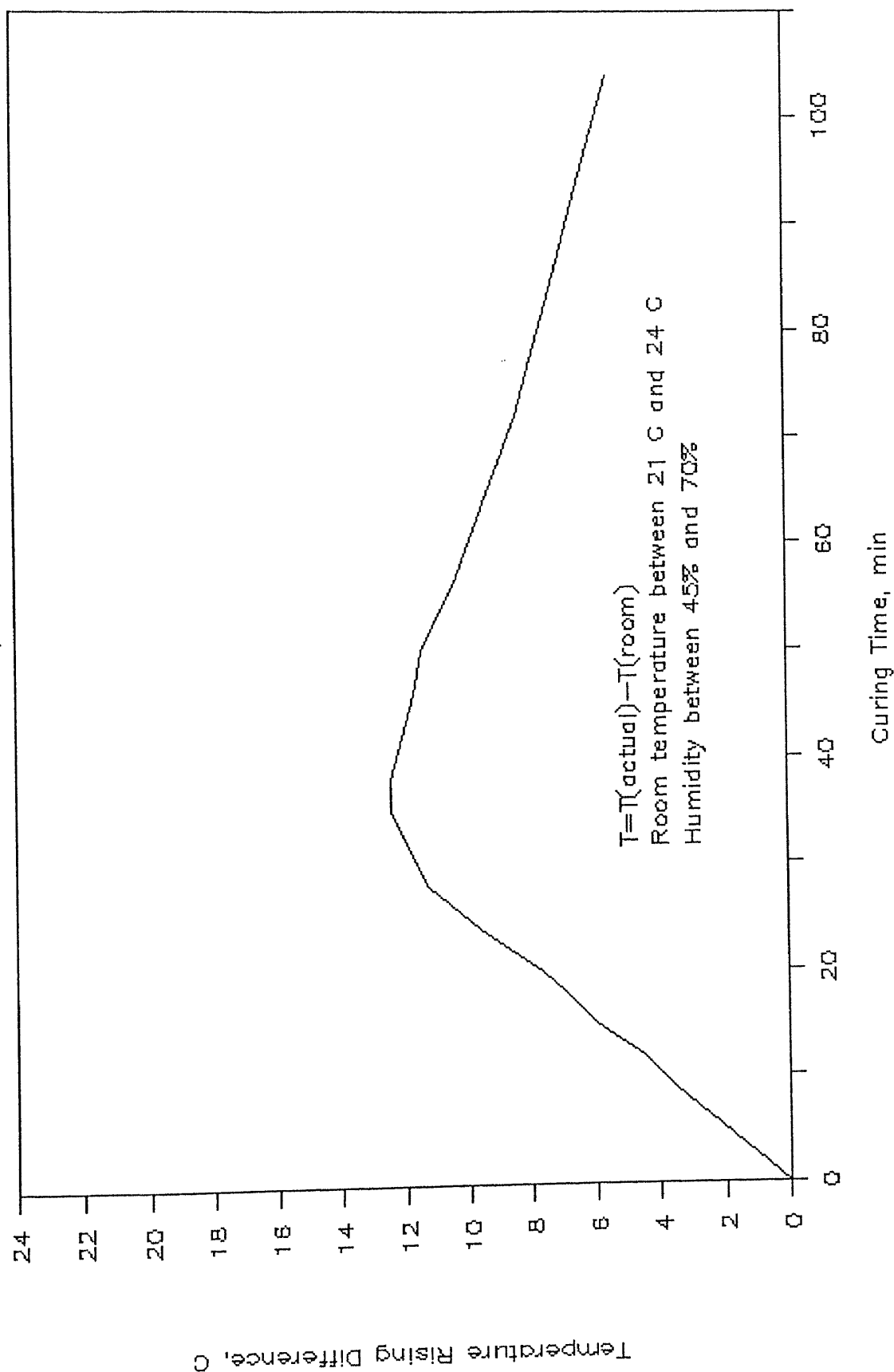


Fig 3 Temperature Rising Curve

Sikatop 122



APPENDIX C

STRESS-STRAIN CURVES

Fig 1 Compressive Strength, UP-PPCC

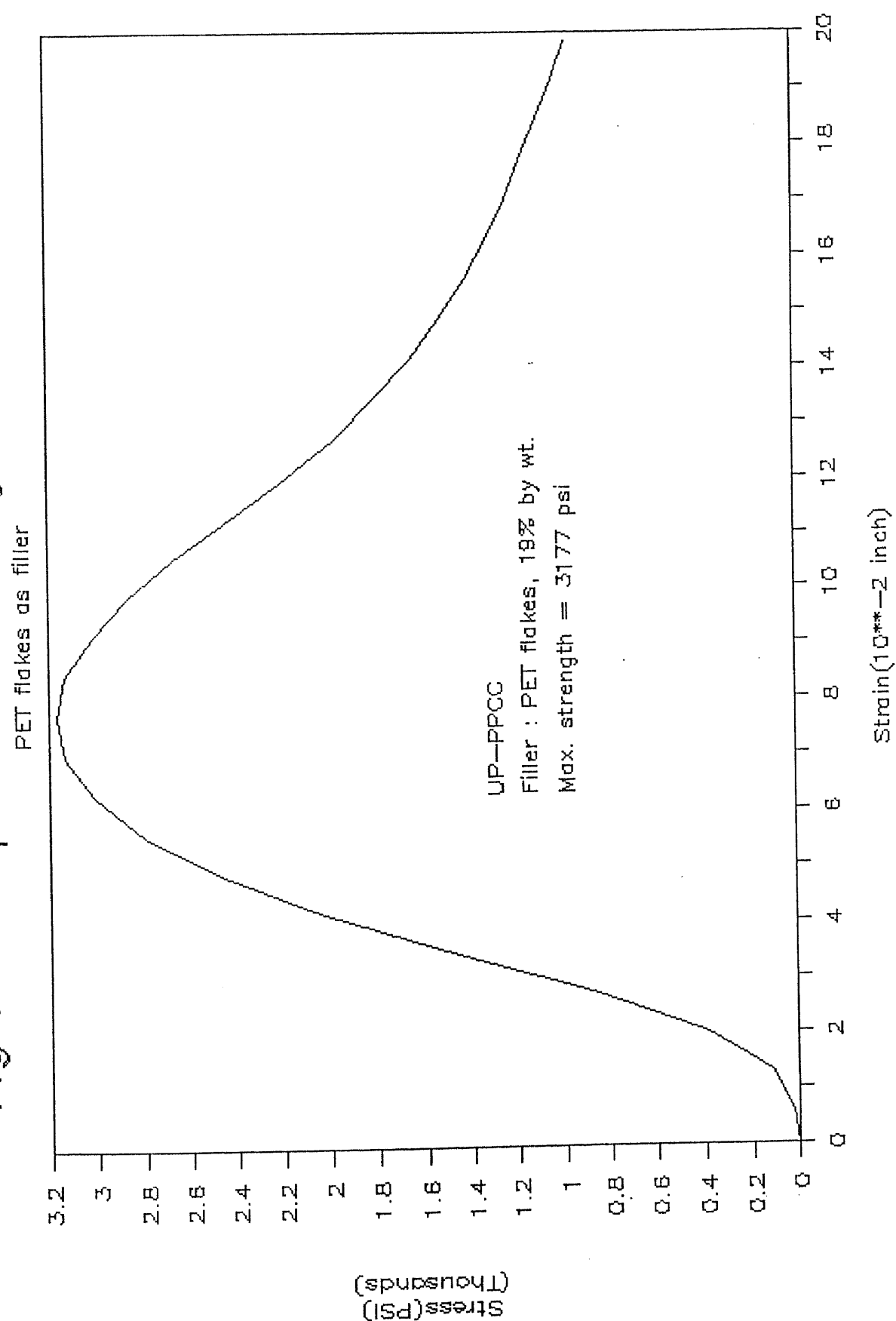


Fig II Compressive Strength, UP-PPCC

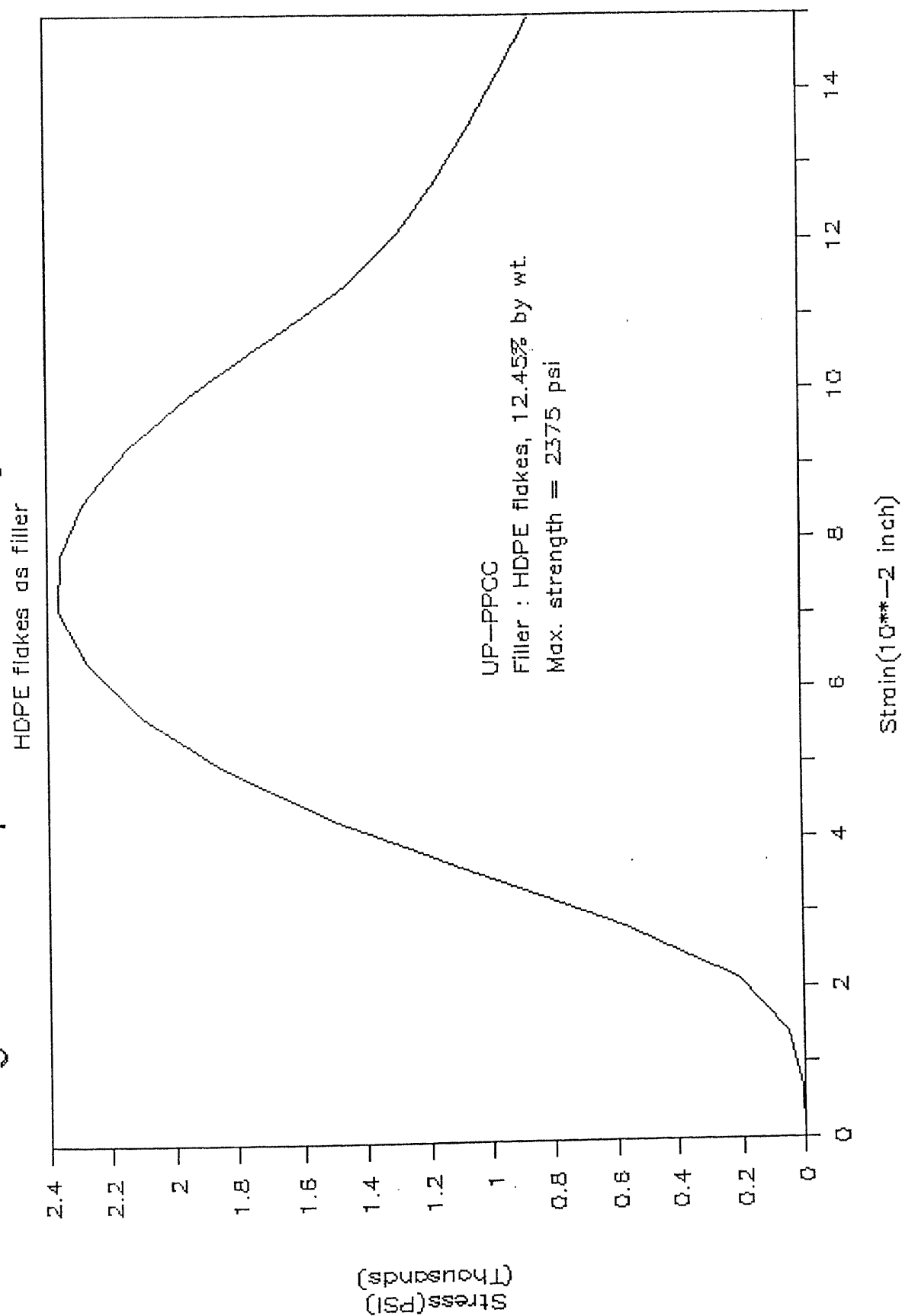


Fig III Compressive Strength, Sika-111

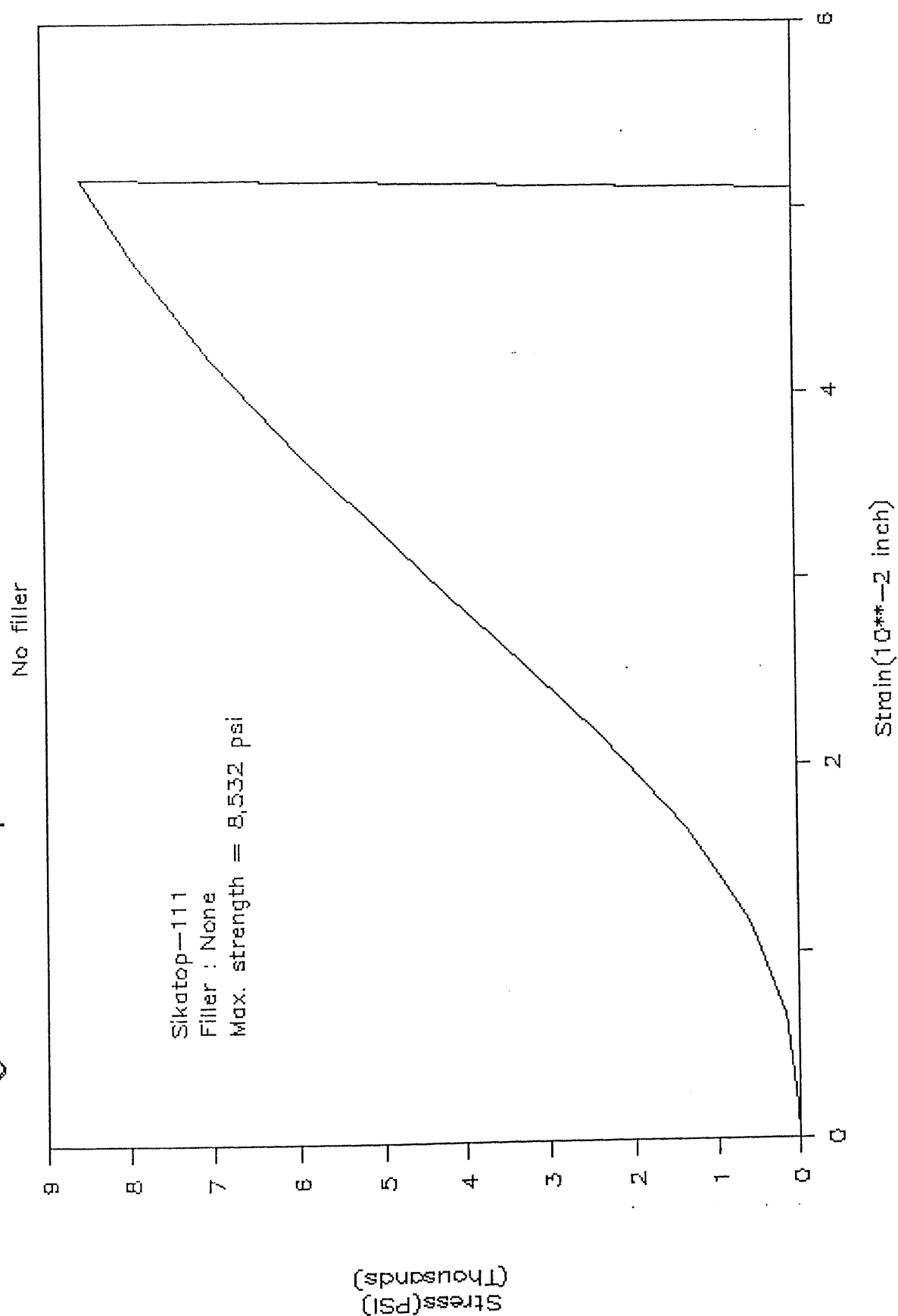


Fig IV Compressive Strength, Sika-111

PET flakes as filler

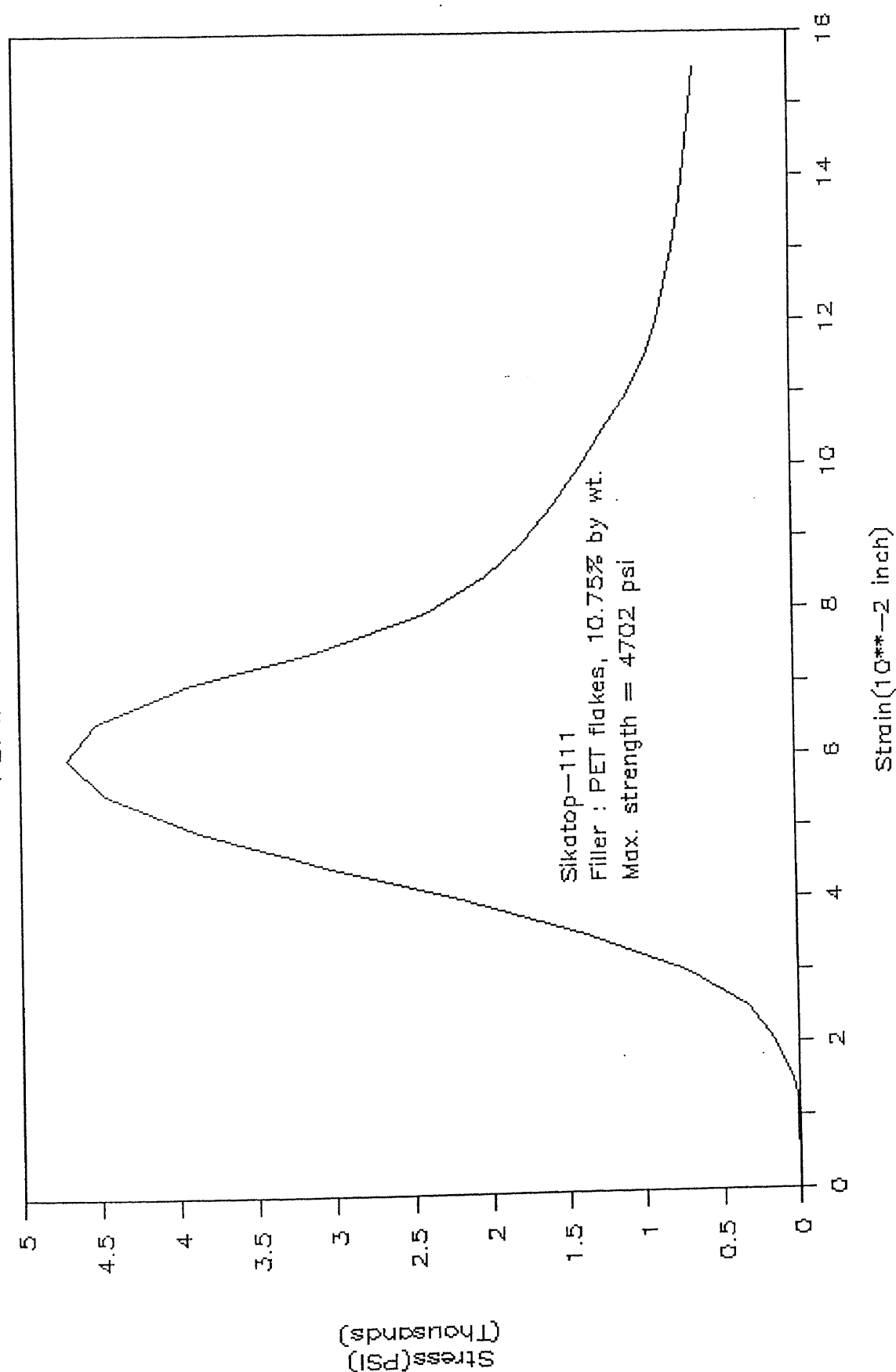


Fig V Compressive Strength, Sika-111

HDPE flakes as filler

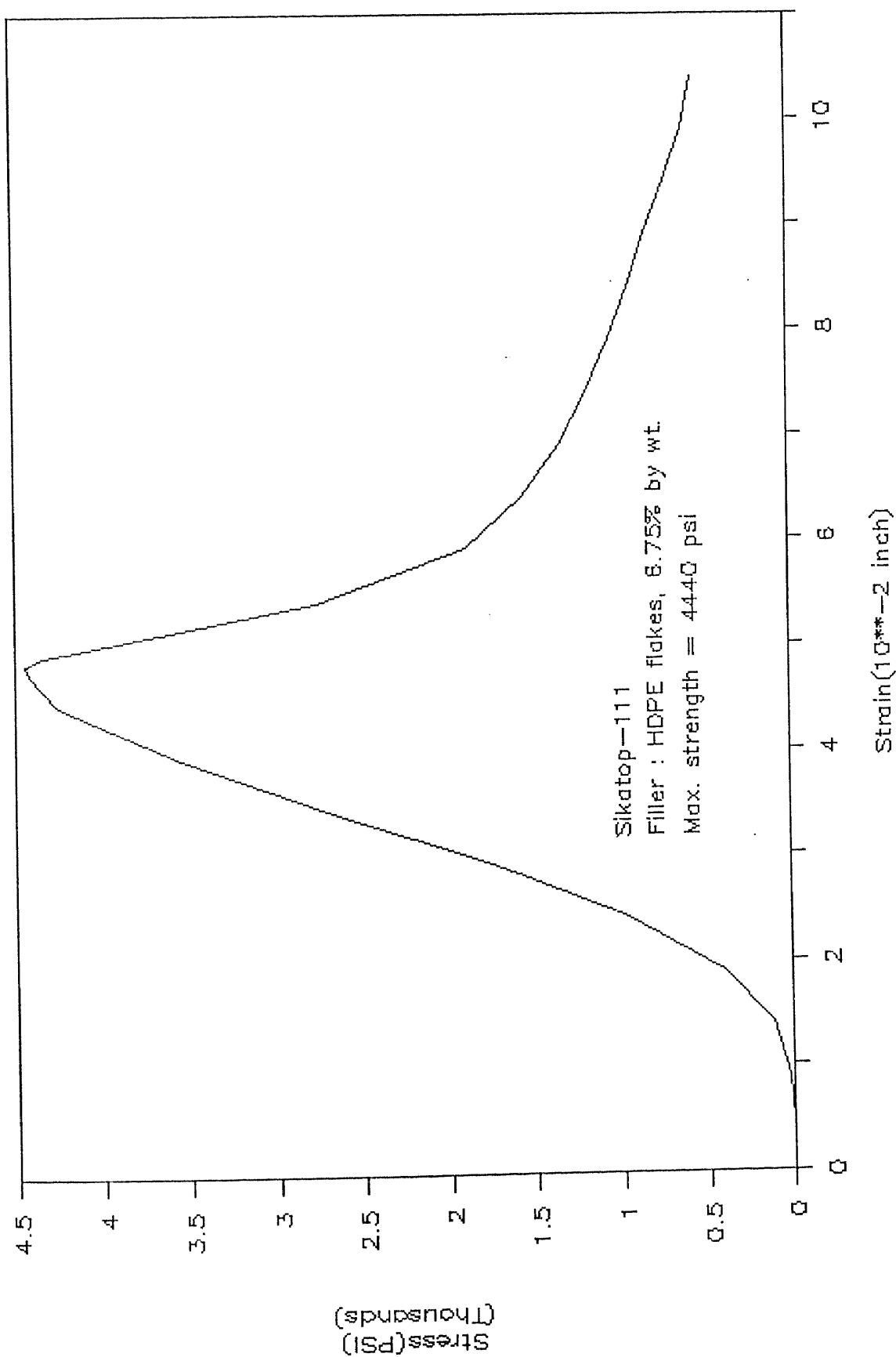


Fig VI Flexural Strength, UP-PPCC

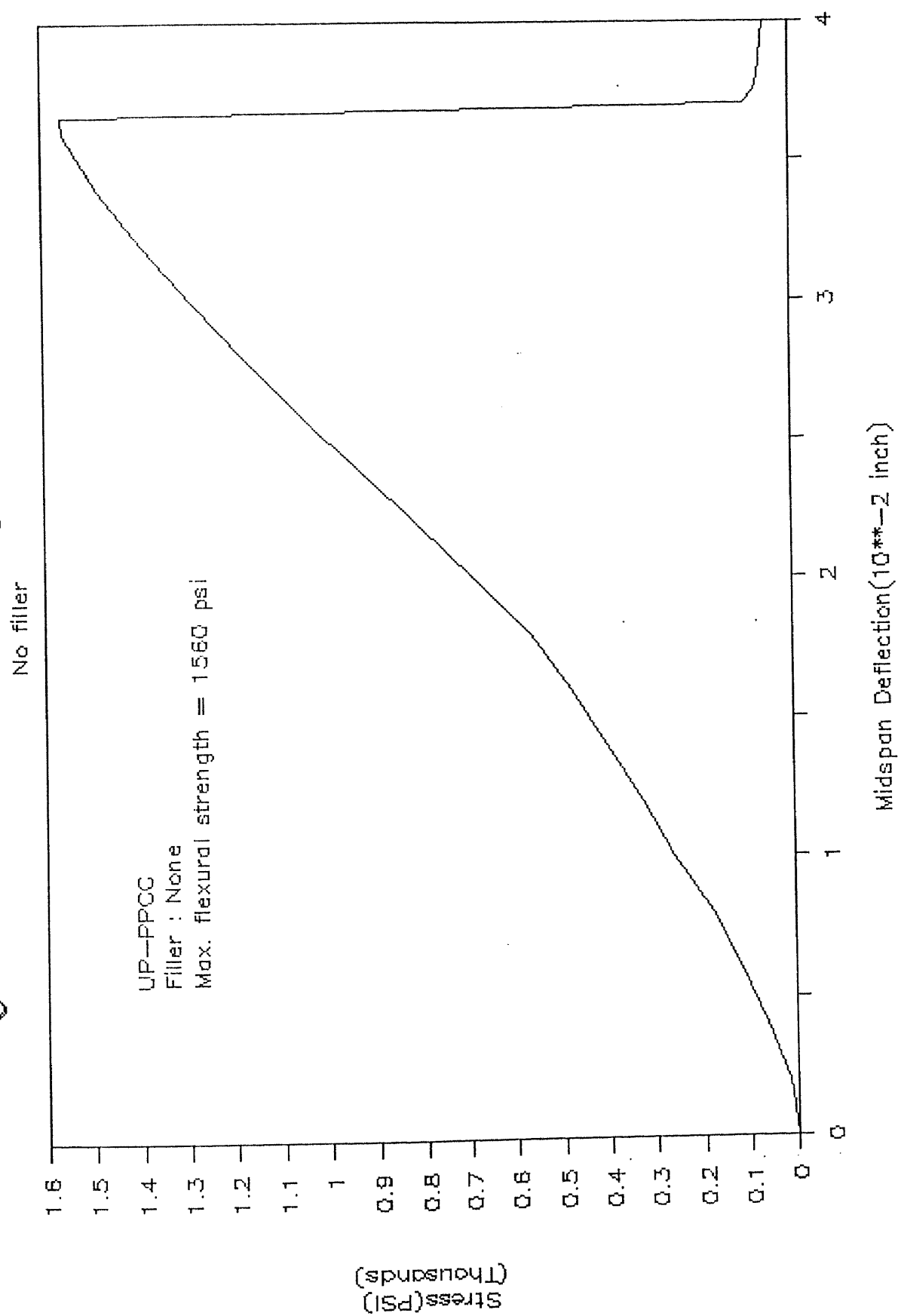


Fig VII Flexural Strength, UP-PPCC

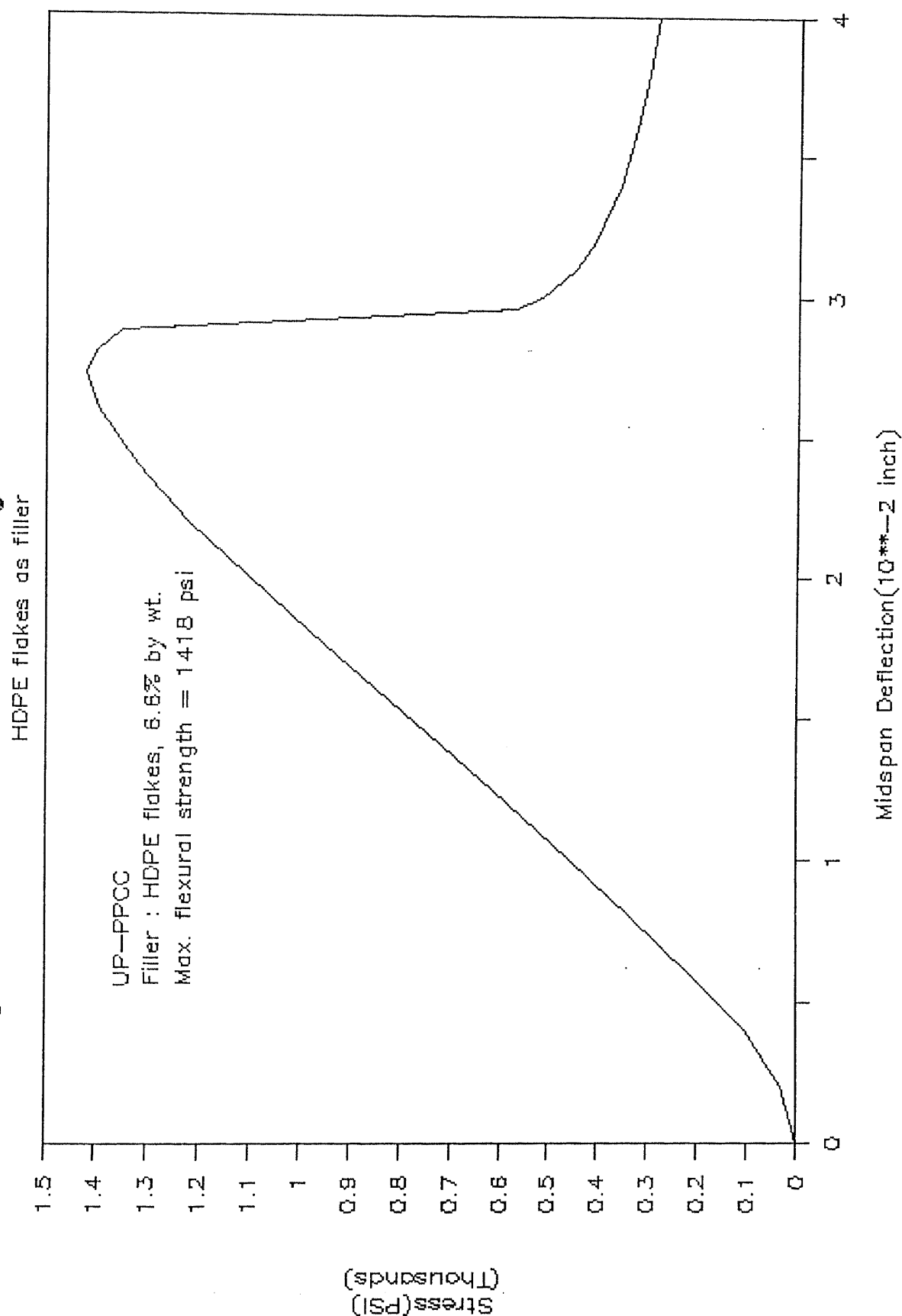


Fig VIII Flexural Strength, Sikatop122

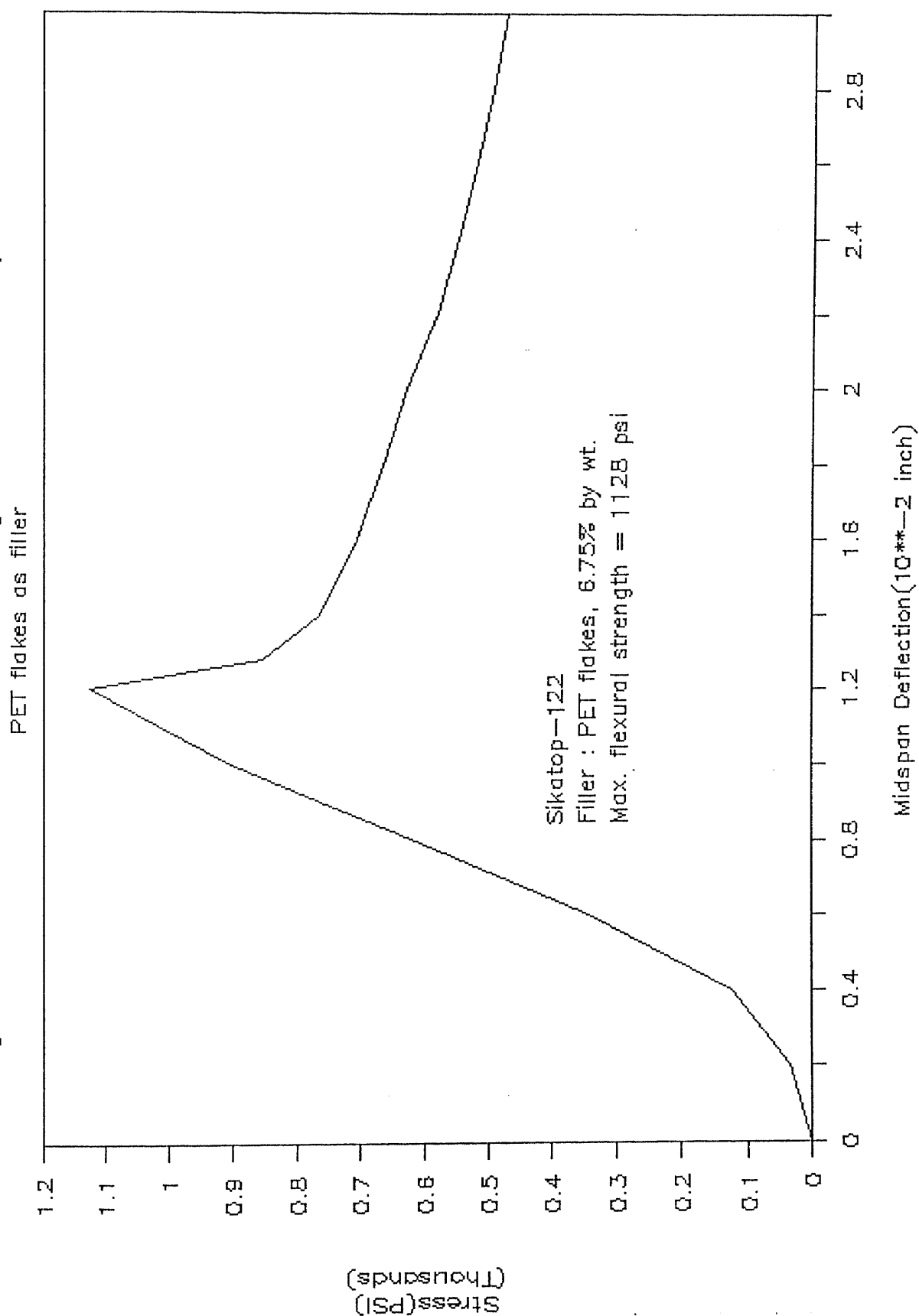


Fig IX Flexural Strength, Sikabond

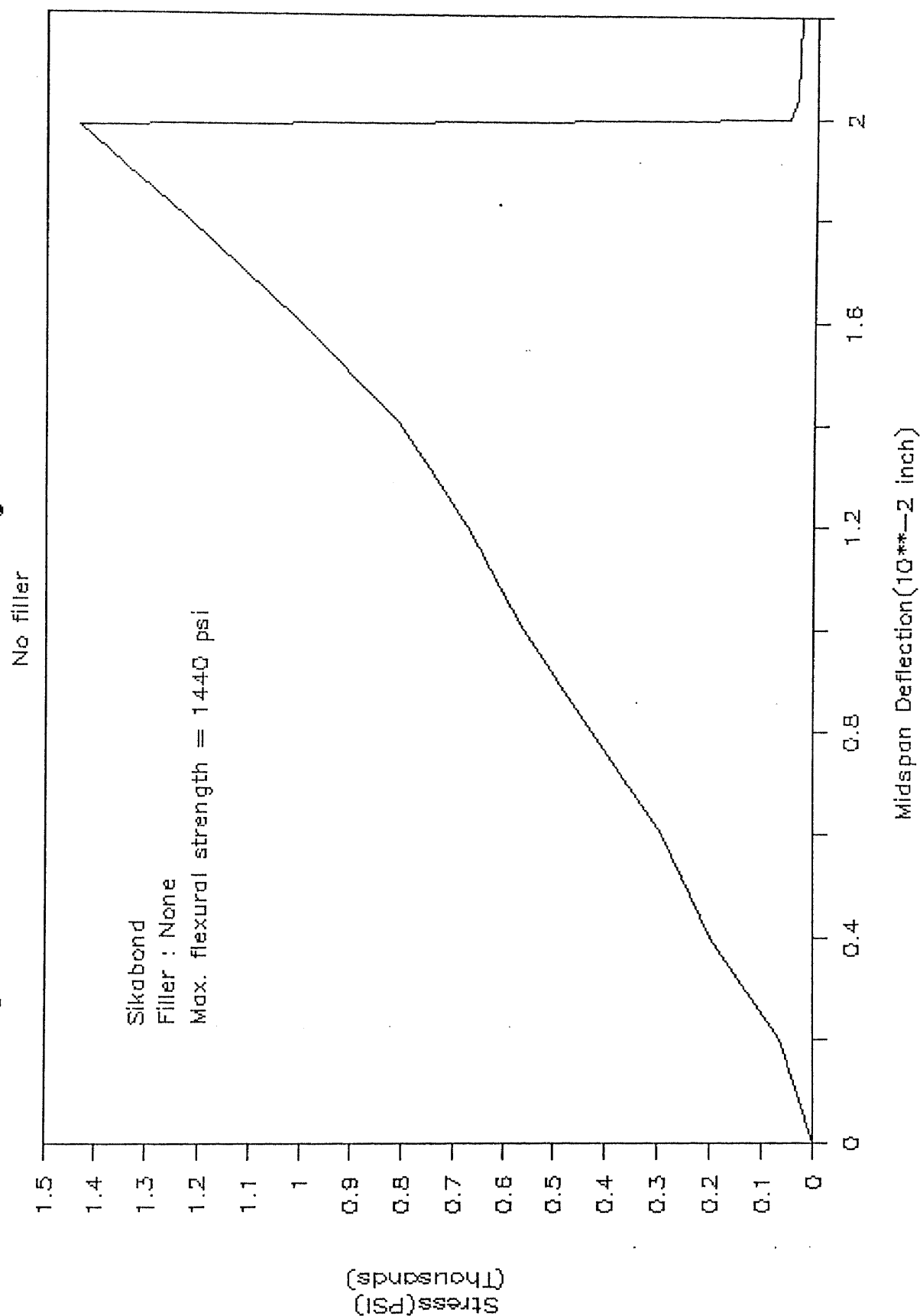


Fig X Flexural Strength, Conven. Conc.

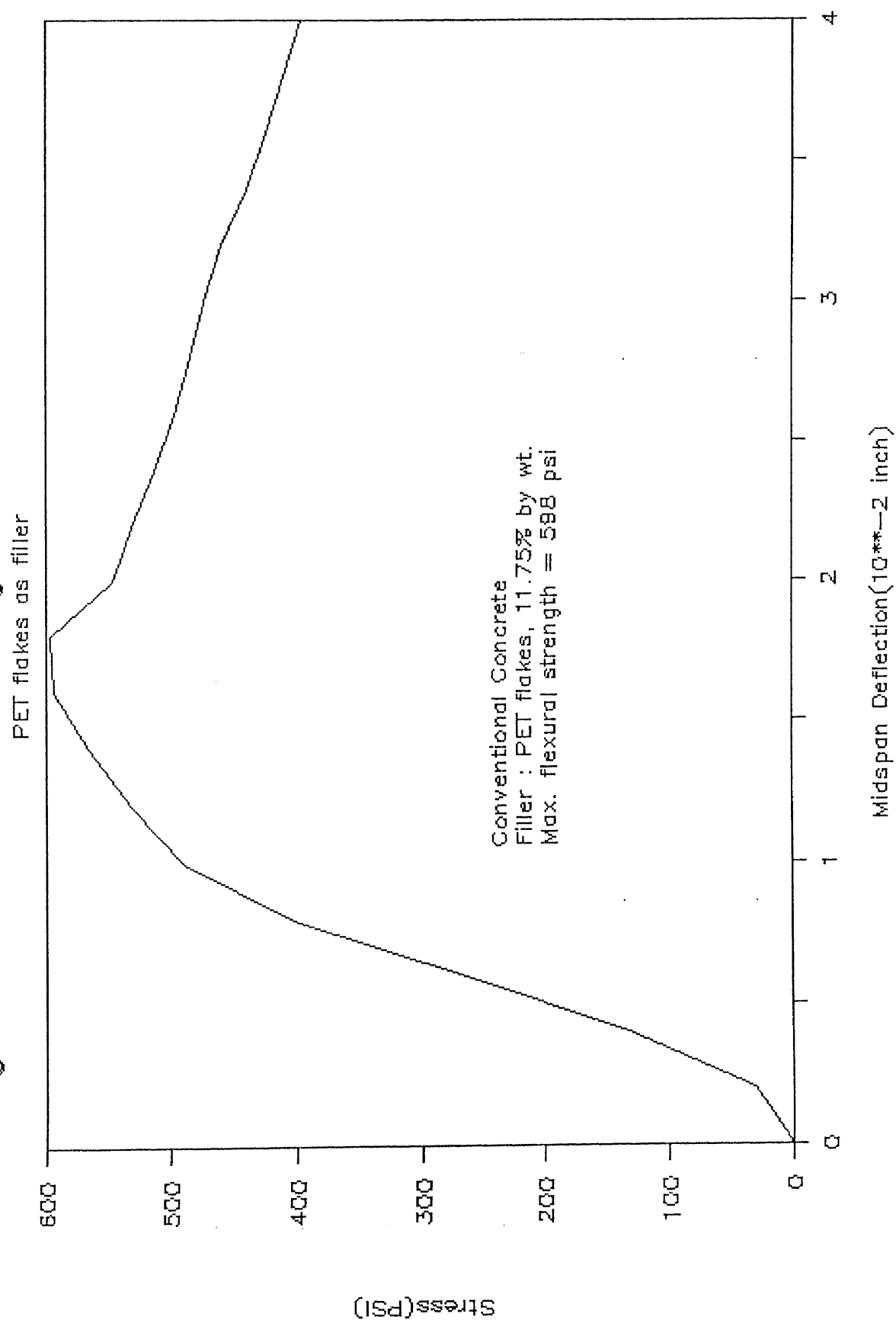


Fig XI Tensile Strength, UP-PPCC

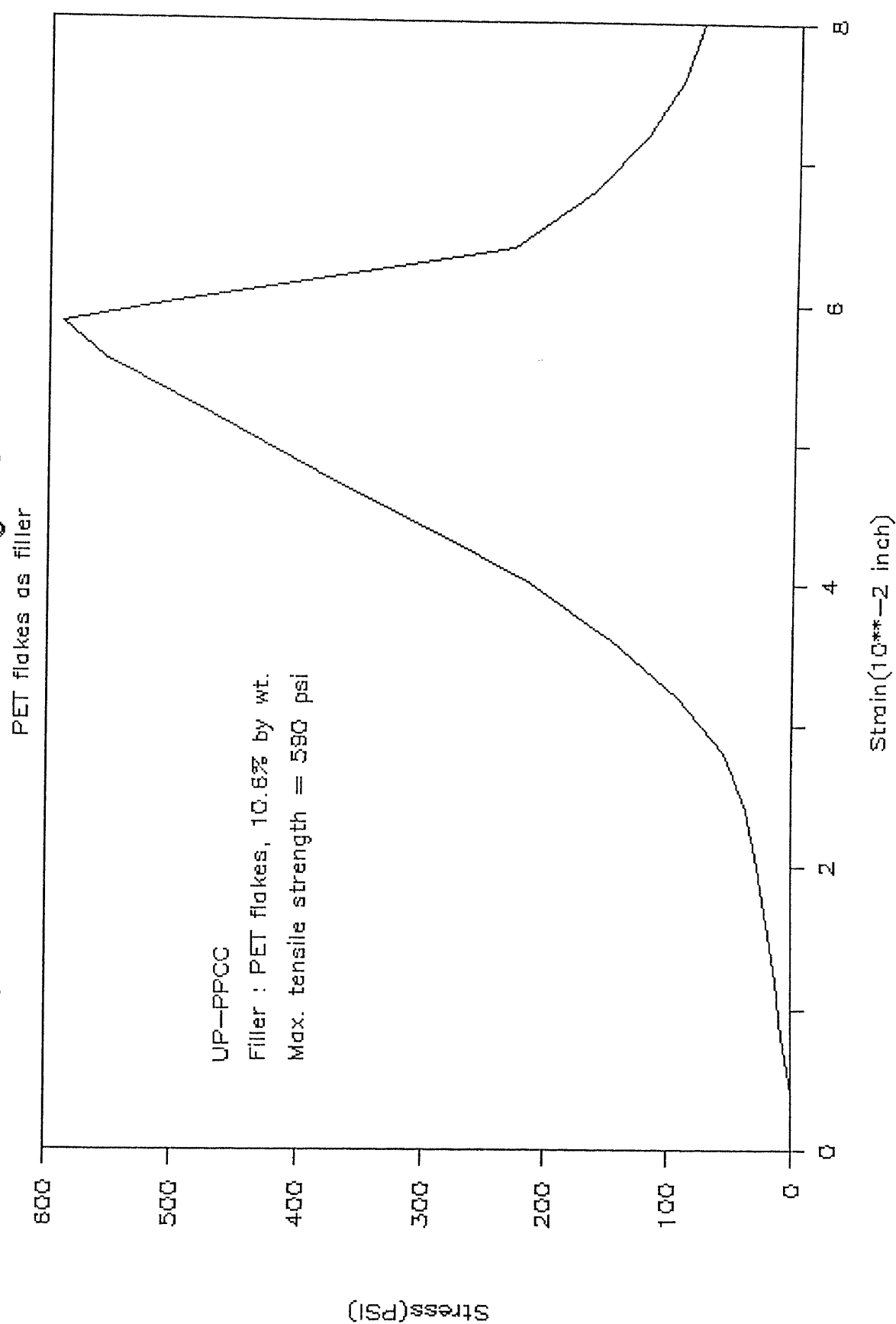


Fig XII Tensile Strength, UP-PPCC

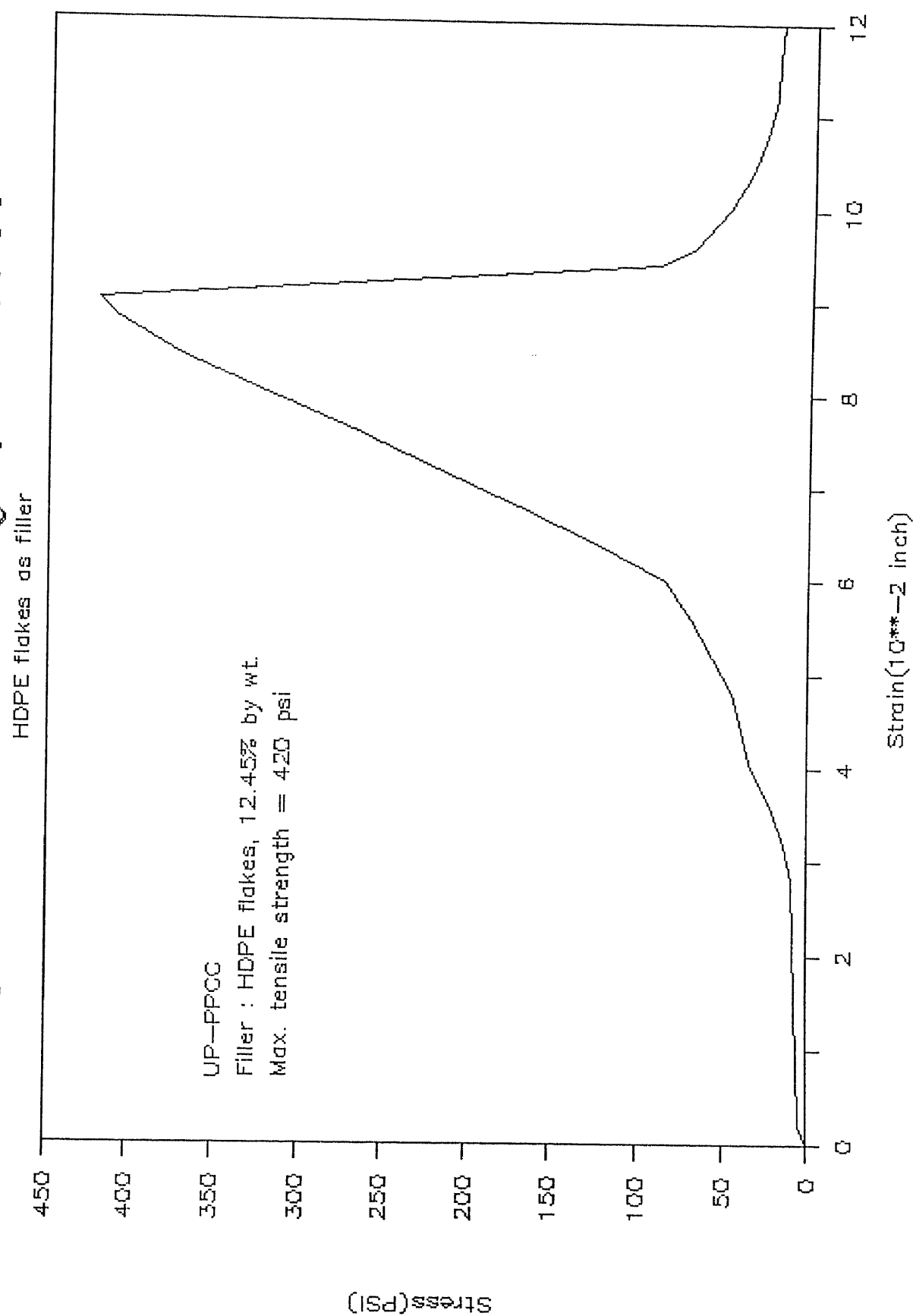


Fig XIII Tensile Strength, Sikatop-111

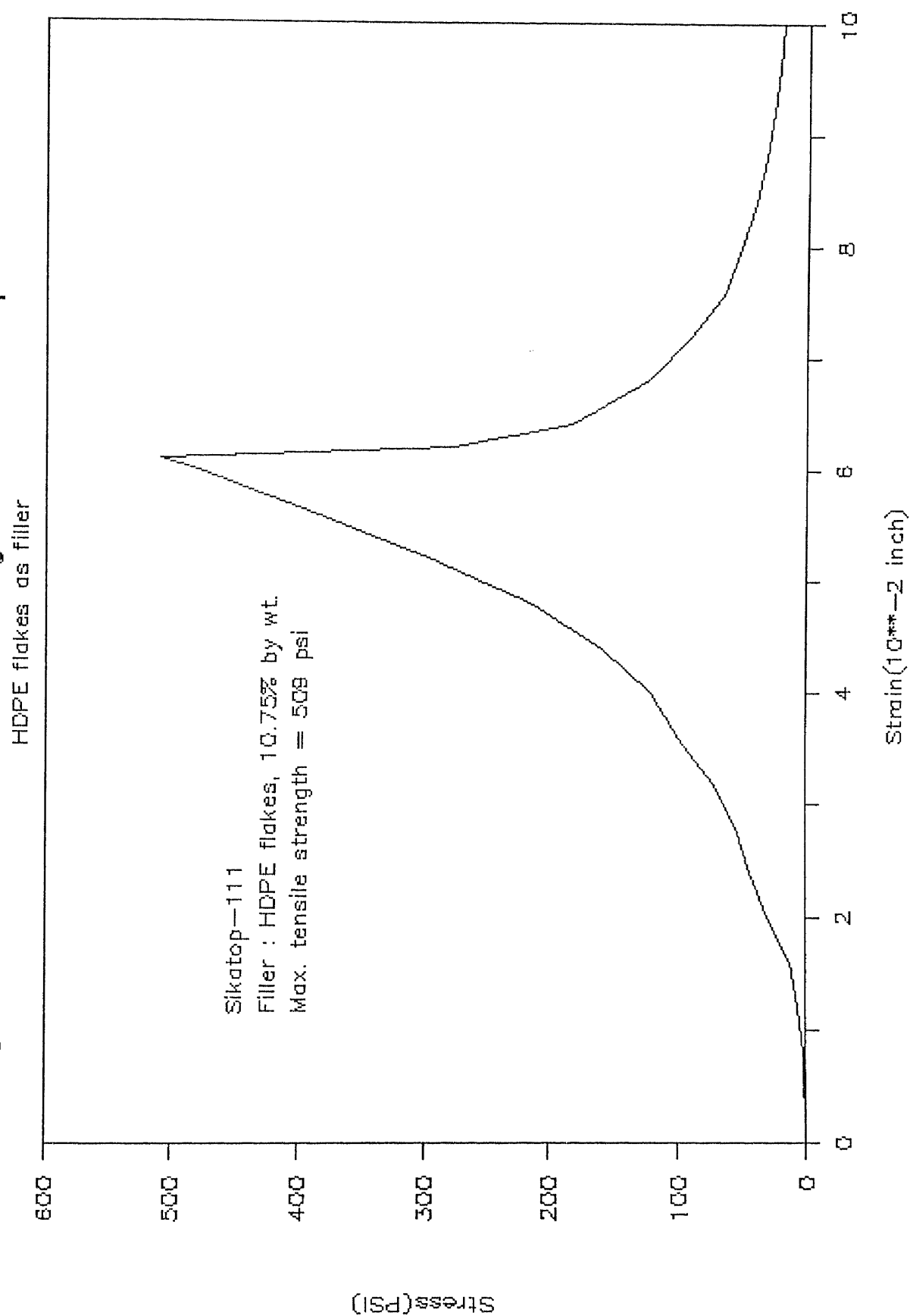


Fig XIV Tensile Strength, Sikatop-122

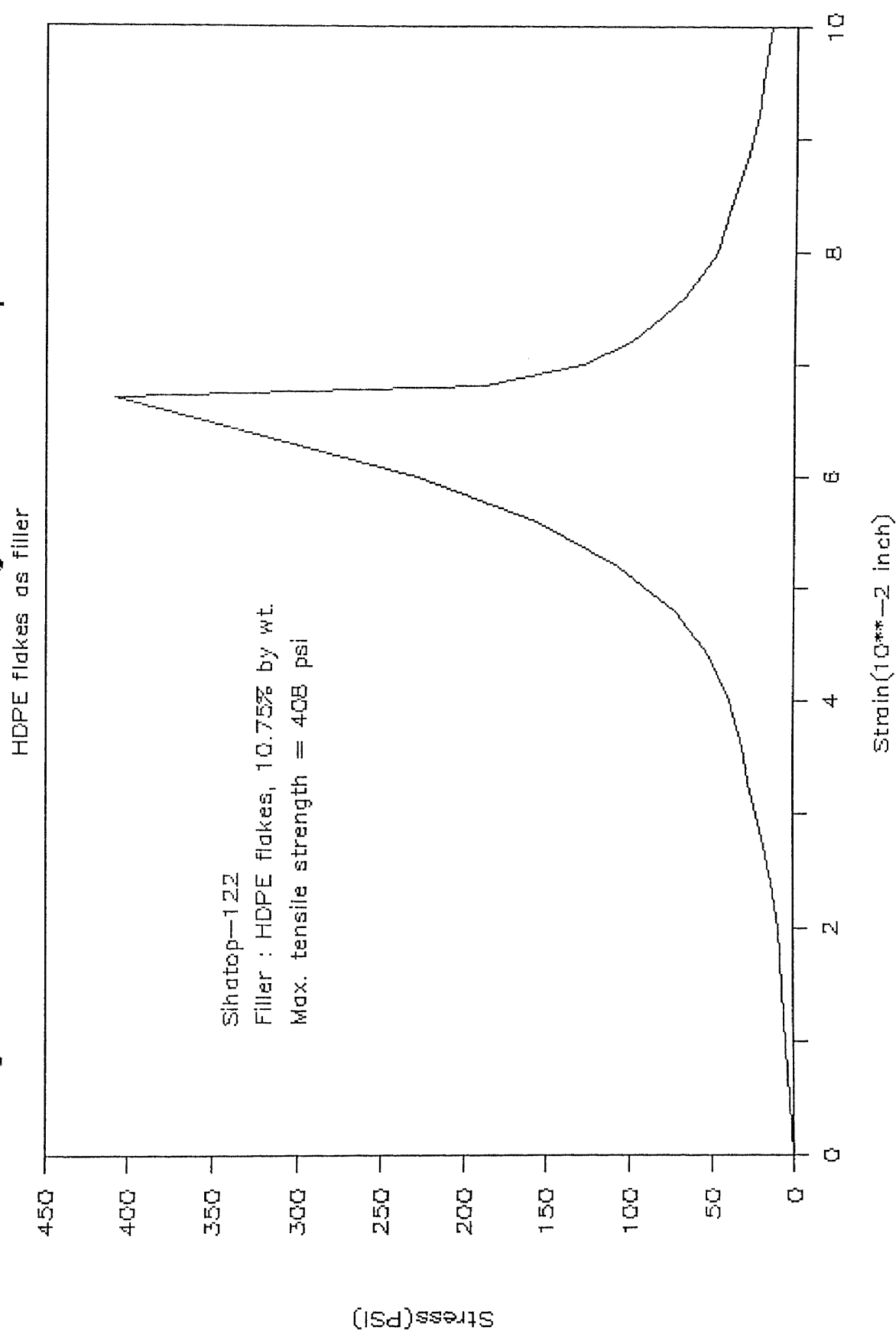
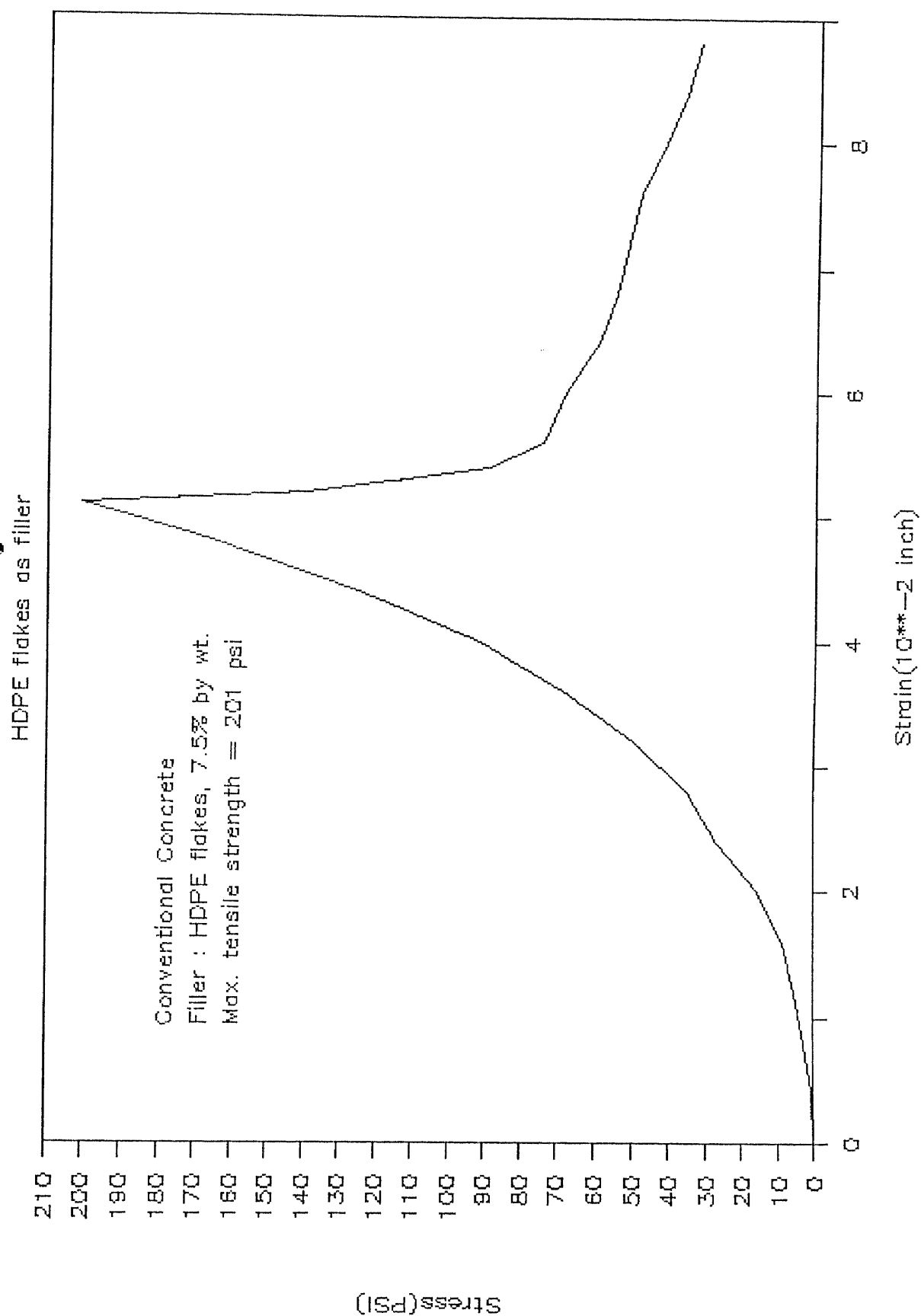


Fig XV Tensile Strength, Conv. Conc.



SELECTED BIBLIOGRAPHY

1. Gordon Bishop, "Recycling", a special report on the Star-Ledge, from Sept. 20 to Sept. 27, 1987.
2. Robert D. Leaversuch, "Industry Begins to Face up to the Crisis of Recycling", Modern Plastics, March 1987, pp. 44-47.
3. Andrea Vittone, "Fibrillated Polypropylene Reinforced Cement-Based Products", Concrete International: Design & Construction, September 1987, pp. 43-45.
4. "Plastic Bottle Recycling Directory and Reference Guide, 1985", compiled by The Plastic Bottle Institute, Division of The Society of The Plastics Industry, Inc., pp. 25-35.
5. Adam M. Neville, "Properties of Concrete - An Overview", Concrete International: Design & Construction, three-part article, part I: February 1986, pp. 20-23, part II March 1986, pp. 60-63, part III: April 1986, pp. 53-57, Vol. 8 No. 2, No. 3, No. 4.

6. Lech Czarnecki, "The Status of Polymer Concrete", Concrete International: Design & Construction, Vol 7 No 7, July 1985, pp. 47-53.
7. John A. Manson, "Overview of Current Research on Polymer Concrete: Materials and Future Needs", American Concrete Institute(ACI), SP-69-1, Applications of Polymer Concrete, 1981, pp. 1-19.
8. Jack J. Fontana and John Bartholomew, "Use of Concrete Polymer Materials in the Transportation Industry", ACI SP-69-2, Applications of Polymer Concrete, 1981, pp. 21-43.
9. Danny Marsh, W. J. Simonsen, and D. W. Fowler, "Machine Application of Polymer Concrete for Highway Repairs", ACI SP-89-1, Polymer Concrete: Uses, Materials, and Properties, 1985, pp. 1-17.
10. Authur M. Dinitz and Russ Ferri, "Polymer Concrete (MMA) for Bridge Rehabilitation Applications", ACI SP-89-8, Polymer Concrete: Uses, Materials, and Properties, 1985, pp. 141-159.
11. Peter Mendis, "Commercial Applications and Property Requirements for Epoxies Construction", ACI SP-89-7, Polymer Concrete: Uses, Materials, and Properties, pp.

127-140.

12. Sandor Popovics, "Modification of Portland Cement Concrete with Epoxy as Admixture", ACI SP-89-11, Polymer Concrete: Uses, Materials, and Properties, pp. 207-229.
13. "Improving Concrete with Polymers", An abstract of the ACI Committee 548 report, "Guide for the Use of Polymers in Concrete(548.1 R-86)", Concrete International: Design & Construction, Vol. 9 No. 12, December 1987, pp. 61-66.
14. James R. Clifton, James E. Fearn and Eric D. Anderson, "Polymer Impregnated Hardened Cement Pastes and Mortars" U.S. Department of Commerce/ National Bureau of Standards, Building Science Series 83, 1976.
15. Yu Feixiong and Huang Yiun-yuan, "Mechanical Properties of PIC Impregnated and Polymerized Under High Pressure", ACI SP-89-9, Polymer Concrete: Uses, Materials, and Properties, pp. 161-176.
16. E. Haque and C. D. Armeniades, "Montmorillonite Polymer Concrete: Zero-Shrinkage and Expanding Polymer Concrete with Enhanced Strength", Polymer Engineering and Science, Nov. 1986, Vol. 26, No. 21, pp. 1524-1529.

17. R. D. Eash and H. H. Shafer, "Reactions of Polymer Latexes with Portland Cement Concrete", Polymers in Concrete: Transportation Research Record No. 542, 1975, pp. 1-8.
18. Ohama, Y., "Strength of Polymer-Modified Mortars using Super High Early Strength Cement", Proc. First International Congress on Polymer Concretes, the Construction Press, London, 1976, pp. 151-156.
19. W. O. Nutt, "An evaluation of a polymer cement composite"
20. Fred W. Billmeyer, Jr., "Textbook of Polymer Science", third ed., John Wiley & Sons, Inc., 1984, pp. 361-368, 413-416, 442-445.
21. D. Gerry Walters, "What Are Latexes?", Concrete International: Design & Construction, Vol. 9, No. 12, December 1987, pp. 44-47.
22. Adam M. Neville, "Properties of concrete", Pitman Publishing Inc., third ed. 1981, pp. 8-17, 63-81, 118-133, 529-548.
23. Yu. M. Tarnopol'skii T. Kincis, George Lubin, "Static test methods for composites", Van Nostrand Reinhold company, 1985, pp. 237-239.

24. Lawrence E. Nielsen, "Mechanical Properties of Polymers and Composites", Marcel Dekker Inc, 1974, pp. 3-31, 52-54, 174-181, 257-265.
25. Anthony Davis and David Sims, " Weathering of Polymers", Applied Science Publishers Ltd, 1983, pp. 268-273.