STUDIES ON THE DIFFUSION OF PHYSIOLOGICAL FLUID MOLECULES IN POLYURETHANES

A thesis presented

by

SREENIVASAN, K.

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C E R T I F I C A T E

I, Sreenivasan.K., hereby certify that I had personally carried out the work depicted in the thesis entitled "STUDIES ON THE DIFFUSION OF PHYSIOLOGICAL FLUID MOLECULES IN POLYURETHANES" except where external help sought and acknowledged.

Signature:

SREENIVASAN.K

Date: 10.12.1990

Dr.K.V.C.Rao

ABR Organics Ltd.
2-2-3 / B / 7 / 1
Durgabac Deshmukh Colony
Hyderabad - 500 007

DECLARATION

This is to certify that Sri K. Sreenivasan in the division of Technical Evaluation of Biomaterials of the Sree Chitra Tirunal Institute for Medical Sciences and Technology, has fulfilled the requirements of regulations relating to the nature and prescribed period of research for Ph.D degree of that Institute. The work relating to his thesis entitled " STUDIES ON THE DIFFUSION OF PHYSIOLOGICAL FLUID MOLECULES IN POLYURETHANE" was carried out under our joint supervision.

.....
(DR.M.JAYABALAN)

.....
(DR.K.V.C.RAO)

The thesis

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evaluated and approved

by

Dr. K.V.C. Rao	Dr. I. S. Bhardwaj	Prof. S. P. Potnis
(Guide)	I P C L, Vadodara	Bombay University

CONTENTS

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SYNOPSIS

Segmented polyurethane (PU) due to the unique properties arising from the phase segregation, is one of the widely sought material for medical application. Graft copolymers of polyurethanes due to the improved biointeraction have also been used as biomaterials.' The behaviour of these types of materials in bioenvironment has therefore been addressed widely. One aspect which has seldom been studied in this connection, is the absorption and diffusion of small molecules found in body fluids, particularly in blood. The information so far available on the diffusion of blood components through polyurethane and graft copolymers of PU in connection with the structural features is scanty.

The thesis projects the author's effort to understand the diffusional aspects of low molecular weight molecules found in blood, specifically lipids,(i) through polyurethanes as a function of structural aspects,(ii) in drawn polyurethanes to understand the influence of altered morphology on diffusion and (iii) the diffusion in graft copolymers of polyurethanes.

Chapter 1 reviews varied applications of polyurethanes and graft copolymers of polyurethanes, as biomaterials. The chapter also highlights the interaction of the materials with blood and associated interfacial problems. The problem of diffusion of blood lipids in polymers are also surveyed.

Chapter 2 deals the objective and scope of the investigations.

induced ordering in both soft and hard segments at lower elongation and disruption of hard domains at higher elongation resulting in enhanced phase mixing. TGA registered higher thermal stability in stretched materials indicating more ordered structure.

First section of Chapter 4 also deals the characterization of graft copolymers of polyurethane, synthesized with hydrophilic and hydrophobic monomers. Poly(2-hydroxy ethyl methacrylate-g-PU, (PHEMA-g-PU, Poly(N-vinyl pyrrolidone)-g-PU (PVP-g-PU), Poly(methylmethacrylate)-g-PU, (PMMA-g-PU), Poly(methylacrylate)-g-PU (PMA-g-PU), Poly(n-butyl acrylate)-g-PU (PBA-g-PU) and binary polymers, poly(n-butyl acrylate and poly(2-hydroxy ethyl methacrylate)-g-PU (PBA+PHEMA-g-PU), were synthesized by gamma-irradiation method. Using spectroscopic methods, grafting of respective species have been confirmed. Surface morphology of the graft polymers have been studied by scanning electron microscopy. Mechanical testing, gel permeation chromatography, TGA and contact angle measurements were also used for further characterization.

Section 2 discusses the diffusional aspects of cholestrol, cholestryl acetate, triolein, stearic acid, methyl palmitate and butyl oleiate through linear segmented polyurethanes. It has been found that, the diffusion coefficients and equilibrium absorption of the components are governed by soft segment content and morphological aspects like phase mixing. An empirical equation has been proposed to explain the absorption behaviour.

However, deviation in experimental absorption from those provided by the equation, was noted in materials having more hard segment contents which has been tentatively explained as due to more phase mixing resulting in the restriction of soft segment mobility.

Activation energy for the diffusion was found to increase in materials having more hard segments. This is indeed expected in the sense that hard domains acting as physical crosslinks restricts the segment mobility there by increasing the energy for creating adequate space for the diffusion. The section 2 also deals with the diffusion of the components in stretched and relaxed polyurethanes. Both diffusion coefficients and extent of absorption decreased in these polymers. The reduction of these parameters have been visualized in terms of the altered morphology of the polymers induced by stretching.

Section 3 discusses the effect nature and molecular weight of polyols used as soft segment. The absorption of the diffusants was found to be influenced by the molecular weight and nature of the polyol part of polyurethanes. The dependence of these aspects have been explained from thermodynamic aspects.

In addition to the polymer characteristics, the diffusion was also determined by the nature of diffusing species namely geometry, molecular weights etc. The extent of absorption was less for rigid molecules like cholestrol while for linear molecules like stearic acid it was found to be more in all polymers.

The section 4 provides the results and discussion of the diffusion in graft copolymers. The extent of absorption of the diffusants was found to decrease with % grafting of PHEMA, PNVP and PMMA. The theoritical % grafting required to arrest the diffusion obtained from graphical plots of % absorption versus % grafting were comparable with that of the experimental results. These values were found to vary exponentially with hard segment content. A relationship has been proposed which enables the prediction of extent of grafting required to arrest the diffusion. On the other hand in hydrophobic and flexible P(MA) and P(BA) grafted material, absorption reduced initially and then began to increase with the increased % of grafting. The reduced absorption of the diffusants in the graft polymers is attributed to the lessend segment mobility. The enhancement of absorption with increased grafting in P(MA)-g-PU and P(BA)-g-PU can be due to the formation hydrophobic regions with segment mobility at the experimental temperature. The grafting of binary monomers (BA+HEMA), used to study the simultaneous effect of flexible poly(BA) and rigid poly(HEMA) on the diffusion. In this case also the extent of absorption was found to decrease with increase in % of grafting.

Section 5 sketches the absorption behaviour of polyurethanes, and graft copolymers from the mixture of biological components. The results obtained for the absorption of the components, from various media such as silicone oil, phosphate buffer and sheep's blood were presented. The variation in the

absorption profile of the components from medium to medium was explained in terms of interaction of the components with medium as well as with the polymers.

Chapter V draws the conclusion and future prospects. The diffusants were found moving only to the soft segments. However, the extent of absorption was found to vary exponentially with the percentage of soft segment rather than linearily in linear segmented polyurethanes. This behaviour has been traced to the phase mixing in the polymers. The reduction in absorption in drawn polymers has been attributed to the stretch induced changes like the enhanced phase mixing. In graft copolymers having rigid component like poly(HEMA), P(NVP) and PMMA the absorption was found to decrease linearily with increased % of grafting. A non-linear variation in absorption was observed in materials grafted with hydrophobic and flexible P(BA) and PMA. The absorption data, in general, indicate segment mobility is the major factor determining the diffusion.

CHAPTER 1

INTRODUCTION

Man's attempt to repair the human body using implants materials can be traced back to the medieval writings of Hindus, Egyptians and Greek civilzation. Through the middle of the 20th century most of the biomaterials used were of organ and tissue transplants from the same body, from one human to another and one species to a different species. These are still being studied and have experienced varying degree of success and failure. The autograft is a proven procedure, but donor site morbidity has been a problem of concern. Other forms of organ and graft transplantionare still plagued with problems related to the donor availability, immunocompatibility, tissue preservation and functional reconstitution. The use of synthetic materials, as impalants has, therefore, become a logical and promising alternative to modern surgical practice.

1.1. Polymers as biomaterials.

The application of synthetic polymers to medical problems has paralleled the development of synthetic polymers themselves. However serious study of synthetic polymeric materials for medical application did not begin until the early 1950s. During this period, a basic understanding of toxicology and biodegradability was developed and success in applying these to polymeric biomaterials to save lives and to improve the quality of life was increased. Fundamental research on biological reaction to implanted synthetic materials continues with increased interest and effort to the present day. The wide spread use of polymers in

medicine is readily documented(1,2). However,there are still significant problems to overcome before truly functional prosthesis can be developed for all human organs and systems.

Polymers to be qualifying as biomaterials are supposed to possess certain requirements(3). The biomaterial

1. Should be reproducibly produced as pure materials.
2. Should be fabricated into the desired form without being degraded or adversely changed.
3. Should have the required chemical, physical and mechanical properties.
4. Sterilizable without affecting the properties.
5. Should not have their physical, chemical and mechanical properties adversely altered by the biological environment unless purposely designed as degradable materials.
6. Should have no adverse effects upon the receipient of the implant
7. Should not induce thrombosis or intima formation or interfere with the functioning
8. Should not alter configuration or stability of any cellular elements or soluble materials in blood that would lead cell fragility, aging, allergic hypersensitive or toxic reactions.
9. Should not activate the complement system.
10. Should not induce adverse inflammatory and foreign body reaction.
11. Should not be toxic, carcinogenic, or mutagenic .

Though no man-made materials exist at present satisfying all these requirements, polyurethanes, from a broad sense satisfy several of the above mentioned aspects.

1.2. Polyurethanes as biomaterials.

Interest in polyurethanes for medical devices stems largely from their excellent mechanical properties specifically their elastomeric behaviour, high tensile strength, low stress relaxation and resistance to long term cyclic flex failure(4,5). The biomedical applications of polyurethanes have been reviewed extensively(6-11). Biomedical application of polyurethanes go back to the early 60s, when polyester urethane foam was used for in situ bone fixation, while polyester urethane coatings were applied to cardiovascular implants(12-15). In both cases the outcome was, however, poor due to the premature degradation of the polymer. The initial failure, however, did not impede continuous efforts to develop materials with good characteristics including mechanical. Since 1975 pacing leads with polyurethane insulation have been used in humans. In 1982 the Jarvik- 7 total artificial heart with blood sacs from polyurethanes was first implanted in a human(7). The tremendous populairty of polyurethanes as biomaterials can be traced to the specific morphological features leading to unparalleled properties.

1.3.Chemistry of polyurethanes.

World wide interest focussed in polyurethanes since its discovery by Bayer et al in 1937(16). The reaction of aliphatic diisocyanate and glycol led to the formation of polyurethane

suitable for the production of plastics and fibers. Further work using aromatic diisocyanates with high molecular weight glycols resulted in the formation of the first polyurethane elastomer. Chronology of the history of polyurethanes has been documented elsewhere(17,18). The detailed description of chemistry of polyurethanes has been documented widely (19-21).

1.4. Aliphatic polyurethanes.

Polyurethanes are known to suffer from poor stability to uv radiation(22-25). Uv-induced degradation can reduce molecular weight, tensile properties and yellowing all of which can limit potential application(26,27). Polyurethanes based on aromatic hard segments often exhibit Uv-radiation- induced discolouration which has been related to the structure of the aromatic diisocyanate(24). The degradation process has been traced to the photodecomposition of the urethane linkage to give conjugated azo and possibly quinone imide structure(24,28,29). However, replacing the aromatic diisocyanate with hydrogenated analogues like $H_{12}MDI$ removes the potential for conjugated structures and thus the corresponding polyurethanes demonstrate improved light stability(24,26). Polyurethanes based on aliphatic diisocyanates also show better resistance to hydrolysis and thermal degradation(30).

1.5. Properties of polyurethanes: Corelation with the structural features.

All these years have witnessed an exponential growth of literature addressing the chemical structure of the polyurethanes

and resultant properties. The following sections briefly review the physical and morphological characterization of polyurethanes.

1.5.1. Microphase separation.

The thermodynamics of phase separation of block copolymers have been a subject of wide spread attention(31-35). Several theoretical models have been framed to understand the thermodynamic principles governing the phase segregation in polyurethanes(36-39). Krause,Mier,Helfand and Legrand have developed theories based on thermodyanmic and statistical mechanical principles to visualise the phase morphology in polyurethanes(31-39). The two phase structure of polyurethanes basically determines most of the properties though several factors such as segment polarity, block length, concentration of the hard segment etc. have a bearing on realization of such a two phase system(40-43).

1.5.2. Morphological models.

Several morphological models have been proposed to illustrate the domain structure in polyurethane(44,45). Estes et al (46) proposed an early model for schematic representation of domain structure in an undeformed polyurethane. According to this model both phases are continuous or interpenetrating and phase separation is considered to be incomplete. Bonart(47), basically based on the X-ray scattering studies, proposed a morphological model for polyurethane elastomer domain structure. The model was successful in explaining the stress hysteresis phenomenon in polyurethanes. Wilkes,Yusek(48) and Blackwell(49) have proposed models to explain domain shape and chain conformation in poly-

urethanes.

Most of the earlier models are not considering the morphological features of polyurethanes under deformation. Bonart et al(50), Desper et al(51), Ishihara et al (52) and Shibayma et al(53)proposed models capable of explaining the unique behaviour of polyurethanes under deformation.

1.5.3. Hydrogen bonding in polyurethanes.

Hydrogen bonding plays major role in properties of polyurethanes(54,55). H-bonding in polyurethanes results from the -NH groups as donor and the >C=O and the ether oxygen groups as the acceptor. H-bonds may be in the hard segment or in the soft segment. Relative amount of the two types of H-bonds are determined by the extent of microphase separation(56). Increased phase separation favours interurethane H-bonding(57).

1.6.Polyurethanes as implants.

Today polyurethanes are believed to be indispensable and the materials find a variety of medical application. Few of the applications are sketched in Table 1.1. Wide applicability of polyurethanes are believed due to their favourable interaction with biological enviornment.

1.6.1. Blood - polyurethane interaction.

Interaction of polyurethanes with blood has received intensive attention since the recruitment of polyurethanes as biomaterial in the late 60s(58-61). It has been generally accepted that protein adsorption is the first event that occurs after blood contact a polymer surface leading to the formation of

protein layer at the blood polymer interface(62).

TABLE.1.1

LIST OF MEDICAL APPLICATIONS OF POLYURETHANES

Total artificial hearts	Heart valves
Vascular prostheses	Vascular stents
Roller pump tubings in artificial heart	Pericardial patches
Intra aortic baloons	Mammary implants
Oesophageal and tracheal	Ureteral prostheses
Prostheses	Fallopian tubings
Endotracheal tubings	Gastric baloons
Catheters and cannulas	Sutures, ligaments
Wound dressings and draps	Blood Bags
Peripheral nerve repair devices	Adhesives
Orthopaedic Casting tapes	Drug delivery devices
Enveloping membranes for	Dialysis membranes
Soft organ fixation	Pacing leads
Filters in blood oxygenators	insulation
Endovascular embolization	Angioplasty baloons.

Lyman et al and Brash et al(63,64)have shown that the surface, adsorbed more albumin adhere less platelet, and thus passivate the surface. However, fibrinogen has been shown to enhance platelet adsorption and thrombogenicity while gamma globulin activate the reaction(65). Several investigations have shown the dynamic nature of protein adsorption on polyurethane surface

(66,67). Some researchers have studied competitive adsorption from mixed protein solution and have used albumin/fibrinogen or albumin/gamma globulin adsorption ratios as an indication of blood compatibility(68,69). The data, in most of the cases show that these ratios are higher in polyurethanes than in other polymers supporting better performance of polyurethanes in terms of blood compatibility.

The effect of surface characteristics on protein adsorption has figured in several studies. Baszkin and Lyman(70) compared different polymers and found that maximum protein adsorption occured when there was a balance of dispersive and polar forces on the polymer surfaces. Brash et al(71) observed that albumin was adsorbed faster on a hydrophilic PEO based polyurethane than on a more hydrophobic surface. Stupp et al(72) found that fibrinogen adsorption was higher on a high polyether content polyurethane surface. Merrill(73)on the other hand, found thrombin adsorption on polyurethane increased with increased hydrophilicity. The general trend from all these studies indicates that, in vitro protein adsorption and by analysing the adsorbed layer can serve as an index of thromboresistance of polyurethanes though the results vary often widely in experiments to experiments. More recently Lelah et al(74) studied the adsorption of protein on two grades of Biomer. These authors showed using ESCA, a correlation between thrombogenicity and fibrinogen adsorption which in turn depend on the surface soft segment concentration. In general protein adsorption studies indicate better blood compatibility of

polyurethanes.

1.6.2. Polyurethane-Platelet Interaction.

Though protein adsorption studies can serve as an index of thrombogenicity of polyurethanes, more elaborate studies in terms of platelet adhesion, platelet activation etc are necessary to define blood compatibility aspects. Several researchers studied platelets adhesion and activation on polyurethanes resulting in the correlation of several structural parameters of the polymers with platelet interaction(75-79).

The platelet interaction studies in a nutshell, suggest polyurethanes tend to be more blood compatibile. More hydrophilic polyurethanes are more inert to blood components than hydrophobic materials. Again the nature of the surface is specified in several of these studies.

1.6.3. Polyurethane-tissue interactions.

Over the past 2 decades, considerable progress has been made in understanding biocompatibility aspects of a wide variety of polymers including polyurethanes(80,81). Majority of these studies were based on histological observation and morphological evaluation that were directed towards understanding cellular aging action immediately adjacent to the implant. In general the biocompatibility of a given implant has been described in terms of the acute and chronic inflammatory responses and the fibrous capsule formation which is seen over various times following material implantation(82,83).

1.7. Commercial polyurethanes for medical applications.

Polyurethanes have found extensive biomedical uses due to several desirable factors which have been summarized in the preceeding sections. During the last 20 years a number of polyurethanes have been developed and used in various extracorporeal and intracorporeal devices. Table 1.II lists commercial polyurethanes intended for various medical applications.

TABLE.1.II

COMMERCIAL BIOMEDICAL POLYURETHANES

Biomer®	Cardiothane 51
Pellethane 2363 series	Tecloflex-series
Rimplast-PYUA series	Thoratec BPS series
Tynadale plains hunter	Texin AM,DM,M series
Estane®	Biothane
Erythrothane	Toyobo®

1.8. Graft copolmers of polyurethanes.

The introduction of polymeric device into a living system creates an interface between the material and tissue. The surface characteristics like surface tension,surface free energy, surface ionic groups hydrophobicty/hydrophilicty etc of the materials, therefore, will affect tissue-polymer interaction.It has been suggested that polymers with critical surface tension in the range of 20-30 dynes/cm should show minimum adverse biological

reaction (84). A variety polyurethanes have their surface tension in the range of 30-70 dynes/cm and critical surface tension 27-29 dynes/cm (7),favouring good biocompatibility. Several reports have appeared correlating surface morphology of polyurethanes and blood compatibility(85,86). Hydrophilic surfaces are believed to be more blood compatible (87), although it has also been suggested that a good hydrophilic/hydrophobic balance is required for optimal blood compatibility(88). Anionically charged surfaces show a good blood compatibility, since repulsive interactions are operative between the surface and the platlets, which also possess an anionic charge(89).

Various approaches have been applied to produce a surface with antithrobogenic properties(90-92). Among these covalent grafting of vinyl monomers has been vastly practiced (93,94) and perhaps the simplest way to tailor the surface to modulate biological responces. Surface modified polymers by grafting different entities mainly hydrophilic are increasingly being studied for their improved blood contacting properties (95-97). Chemical modification is an effective means to alter biological interaction to particular material and offers a number of advantages in biomedical fabrication. By varying only the outermost composition at the surface of the material, the mechanical and related properties as well as the fabrication methods of an impalant can remain unaffected while modulating the chemistry and properties that direct biological reaction. Some of the benificial aspects resulted by chemical modification on existing bioma-

terials are listed in Table.1-III

TABLE.1.III

EFFECT OF CHEMICAL MODIFICATION ON THE PERFORMANCE OF A BIOMATERIAL

Improve blood compatibility
Reduce (or increase) Tissue adhesion
Improve lubricating
Increase or decrease wettability of surfaces
Add biologically active substances to the surface layers.
Alter the protein adsorption characteristics
Protect the device from the body or vice versa
Act as a rate limiting membrane.

Graft polymers have a number of important and unique advantages for use in application involving the interfacing of the synthetic materials and living systems. By optimizing the graft methodologies the mechanical properties of the grafts can made to closely resemble those of the unreacted trunk polymer orginally selected to have the appropriate modulus and durability for the proposed application. The surface properties of the graft polymer, on the other hand, influenced by the graft and can be engineered to produce the desired response in contact with the biological environment.

Hydrogels have physical properties similar to those of

human tissues and possess excellent tissue compatibility. Wichterle and Lim (98) as early as in 1960, demonstrated the immense potential of hydrogels, particularly the one based on poly HEMA as biomaterials. In subsequent years, the biomedical applications of hydrogels has been explored extensively(99,100). The interest in hydrogels as implant devices stem from a number of advantages, mainly the possibility of realizing very low or zero interfacial tension with the surrounding biological fluids and tissue there in by minimizing the driving force for protein adsorption and cell adhesion(101-103). The serious drawback of hydrogels is their poor mechanical properties which substantially limits their applications. Grafting of hydrogels to mechanically superior polymer is an attractive alternative. By optimizing the grafting technique, it could be possible to tailor the surface for modulating the desired bioreaction, simultaneously preserving the mechanical properties of the systems. This possibility has been explored widely(104,105).

Though polyurethanes scores over other polymers in several aspects, a variety of biomechanical drawbacks are associated with the hydrophobic nature of most of the polyurethanes(106-108). Altering the surface of polyurethanes by grafting other chemical entities is often sought as an alternative to minimize the adverse reaction. Hydrophilic vinyl monomers, due to their highly desirable factors, have been grafted to the backbone of polyurethanes using methods involving free radical initiation(109,110), Gamma irradiation(111,96) and anionic techniques

(112,113). One of the most widely used method for chemical modification of polyurethanes is grafting vinyl monomers by gamma irradiation(114-116).

Jansen and Ellinghorst(97,117) grafted series of hydrophilic monomers like HEMA, AM etc. onto polyurethane and studied for their mechanical characteristics and blood compatibility. They demonstrated very low interfacial tension in the modified materials which is hypothesized as a prime requisite for improved blood compatibility. These authors are successful in showing increased albumin adsorption with the extent of grafting, a sign of better blood compatibility.

P(VP) is another hydrophilic polymer used for grafting polyurethane surfaces. The polymer has a long history of use as blood extender. Boffa et al(118) and Hunter et al(119) have shown improved compatibility by grafting NVP. Egboh et al(120,121) have studied the grafting of NVP onto polyurethane, in a view to widen the applicability of polyurethanes.

1.9. Biostability.

The stability of a medical device in the biological enviornment is equally important as that of the other aspects like blood compatibility. The subject of biostability of polyurethanes has been addressed widely. Hydrolysis is an important degradation mechanism in the biological environment. Schollenberger and Stewart(122) have studied the hydrolytic stability of different polyurethanes.They found that polyether polyurethane is considerably stable.

Another route to biodegradation is associated with enzymes. Liptova et al(123) have investigated the influence of enzymes in destablizing polyurethanes. Hung et al(124)studied the enzymatic degradation of Biomer. Phua et al(125) examined the in-vitro degradation of Biomer in presence of various enzymes and they observed sufficient loss of fatigue resistance. Smith et al(126) prepared a series radiolabelled polyurethanes and studied the effect of hydrolytic and oxidative enzymes on the stability of these systems. The polyurethanes with a polyether molecular weight 1000 was affected by estearse, papain,trypsin etc. Ratner et al(127) have studied enzymatic and oxidative degradition of polyurethanes. Varying degree of both modes of degradation were seen.

Coury et al (128) investigated the degradation of polyurethanes in presence of metal ions which may be present in the environment of a device like pacemaker leads. They have shown that the cause of degradation is oxidative occuring in the polyether segment of the polymer. Polyurethanes are also shown to be succeptible to degradation by fungi(129). Darby and Kaplan (130) studied several polyurethanes for their succeptibility to degradation by fungi. The polyether urethanes were comparatively high resistant to the attack.

In vivo stability of polyurethanes have also been subjected to several studies. Boretos et al (131) investigated the stability of commercial polyurethanes by implanting sub-cutaneously in mongral dogs. Hunter et al and Stokes et al (132,

133) have also studied in vivo stability of several polyurethanes.

In general most of the studies indicate that susceptibility to degradation depends on the structural features of the materials. It seems that by optimizing structural parameters and processing variables long term biostability could be realized.

1.10. Lipid absorption in polyurethanes.

Lipids have shown to be quite active in the surrounding of polymeric implant(134,135). In searching the failure of silicone rubber heart valves first demonstrated lipid absorption in an elastomer in contact with blood (136). While probing the reasons for calcification on the surface of artifical devices, Coleman et al(137) showed the lipid absorption by polyurethane elastomer. Their results indicated the presence of cholesterol, cholesteryl acetate and free fatty acids in deposits extracted from the polyurethane sample. Owen and Hughes (138, 139) also detected lipids in AHD bladder fabricated using Biomer. Biomer film has been shown to sorb > 10 weight percent of lipids from a synthetic plasma solution(140). This study indicated a diffusion limited sorption of lipids at the surface. Hayashi et al(141) noted a reduction in mechanical characteristics of polyurethanes exposed to aqueous dispersion of lipid mixture and they presumed this variation as due to the absorption of lipids. More recently Takahara et al (142) observed a reduction in fatigue strength in polyurethane samples exposed to lipids. They attributed the decrease in terms of the plastisizing effect and the formation of

micro cracks resulted from the lipid absorption.

The cause of calcification, one of the most serious problem encountered in polyurethane blood contacting devices has been investigated through the years (137,143-147). Lipid absorption has been hypothesized as one of the factor initiating the mineralization process (139), though validity of this hypothesis was questioned considering the fact that silicone rubber is free from calcification in spite of the lipid absorption(148). Several of these studies undoubtedly confirm the absorption of lipids by polyurethane. An indepth study of this problem connecting the structural parameters of polyurethanes has, however, yet to be addressed.

CHAPTER 2

AIM AND SCOPE OF INVESTIGATION

CHAPTER 2

AIM AND SCOPE OF INVESTIGATION

CHAPTER -2

Since the demonstration of polyurethane as a suitable material for blood contact application, extensive research has been carried out to study various aspects of its compatibility with biological environment. In spite of such an explosive growth of literature on polyurethane as a biomaterial and its interaction with biological interface, least efforts have been expended to understand the diffusion and absorption of relatively smaller biological molecules in polyurethanes. Though much emphasis was given on the study of material-biological interface, diffusion of molecules into the material has not attracted widespread attention. In spite of extensive failure of implants due to the absorption and diffusion of biological molecules, to our knowledge, not much work has been carried out to study various parameters which influence or control the absorption of biological molecules. Though biological fluids, such as blood, contain innumerous components of varied types, the relatively hydrophobic nature of polyurethane specifically favour the diffusion of hydrophobic molecules like lipids.

The objectives of the investigation was therefore to understand the factors which influence the diffusion and absorption of a few representative lipids in polyurethanes with different morphological features. To understand the diffusion in connection with morphological parameters, it was proposed to use linear segmenteded polyurethanes, stretched polyurethanes and grafted polyurethanes. It was planned to synthesise linear segmented poly-

urethanes with varied hard segment content and different polyols as soft segment to know the influence of both hard and soft segment domains on diffusion. Linear segmented polyurethanes when subjected to stretching were expected to have an altered morphology. The diffusion studies in these materials may provide interesting correlation between physically induced structural changes and absorption. Another interesting altered morphology could be observed in graft copolymers of polyurethanes. The diffusion study has to be carried out in graft copolymers due to the application of such polymers in blood contacting devices. Extensive physico-chemical studies were planned to understand the morphology of these materials.

It was planned to synthesise polyurethanes based on different polyols (PTMG, PPG, PEG) having varied molecular weights, $H_{12}MDI$ and 1,4-butanediol with altered hard/soft contents. Elaborate efforts were expended to understand structural aspects like extent of phase mixing, presence of crystallinity, the nature of the continuous phase etc. The diffusion and absorption studies of representative lipids were aimed to provide basic understanding of this aspect in linear segmented polyurethanes. The data would provide whether the diffusion is Fickian or non-Fickian and influence of hard/soft segment content, nature of polyol, polyol molecular weight etc on the absorption.

It was proposed to use polyurethanes uniaxially stretched to different elongation and to study the effect of stretch-induced morphology on the diffusion of lipids.The aim of the study was to

know about the feasibility of arresting the diffusion in the polymers by mechanically stretching to certain degree of elongation. The aim of the present investigation was also to find the effect of the altered morphology of polyurethanes grafted with hydrophilic species like HEMA,NVP and hydrophobic entities such as MA,MMA and BA. Itwas also planned to use polyurethane grafted with both hydrophobic and hydrophilic species to know how functionally different systems influence the absorption of diffusants.

Though the proposed studies with individual lipids could help to define some of the basic aspects of absorption of lipids in polyurethanes, particularly in terms of the characteristics of the polymers, it appears that, to get a more realistic picture in connection with the in vivo situation, the studies have to be performed using mixture of the lipids. With this aim, it was planned to conduct the studies using the mixture of the lipids dissolved in a suitable medium. To get a specific understanding, it was also planned to persue further the absorption studies using aqueous dispersion of lipids and blood (of suitable species).

It was expected that, the proposed study would provide a deeper understanding on the phenomenon of lipids absorption in polyurethanes of various morphology.

CHAPTER 3

EXPERIMENTAL

CHAPTER-3

3.1.CHEMICALS

3.1.1.Constituents of the polyurethanes

The diisocyanate used in the synthesis of the polyurethanes was Methylene bis(p-Cyclohexyl diisocyanate),(H12MDI),which was obtained from Bayer's chemicals,Germany. Polytetramethylene glycol(PTMG)1000,2000(QO,chemicals,USA),Polypropylene glycol(PPG) 1000,2000(Aldrich,USA)and Polyethylene glycol(PEG),1000,2000 (Aldrich,USA) were used as soft segment. 1,4-Butanediol(Merck) was used as chain extender. Dibutyl tin dilaurate(Fluka) was used as catalyst.

Diisocyanate was used as recieved. However,all the polyols and chain extender were vacuum dried prior to use.

3.1.2.Solvents

Dimethyl acetamide(DMAC) was HPLC grade and procurred from SD chemicals, Bombay. Carbontetrachloride, Ethylalchol, Acetone and Tetrahydrofuran (THF) were analytical grade reagents and obtained from BDH India. Methyl alcohol(BDH,India) and n-Hexane(Merck,Germany) were spectroscopic grade.

The HPLC and Spectroscopic grade solvents were used as received. The analytical grade solvents were distilled prior to use.

3.1.3.Monomers.

2-hydroxy ethyl methacrylate, HEMA (Fluka),N-Vinyl pyrrolid-done, NVP,(Rika), Methyl methacrylate,MAA, Methyl acrylate,MA and n-Butyl acrylate, BA, all from Merck, Germany, were used for

grafting onto the polyurethanes.

All these monomers were purified by vacuum distillation in presence of cuprous chloride. The middle portion of the distillates was collected and stored at 4°C.

3.1.4.Lipids used as diffusants.

Stearic acid, Cholesterol, Cholestryl acteate, Triolein, Methyl palmitate and Butyl oleiate were used as diffusants. All these chemicals were procured from Sigma Chemicals, USA and used without further purification.

3.1.5.Reagents.

ACD solution(PH-5) was used as an anticoagulant. The reagent was prepared by dissolving 2.2 g of trisodium citirate2H2O, 0.8 gm of citric acid and 2.5 g of dextrose in 100 ml distilled water.

Phosphate buffer (0.15M, PH 7.4) was used for making the aqueous dispersion of the lipids. The reagent was prepared by dissolving 21.42 gm of disodium hydrogen phosphate and 4.689 gm of monosodium hydrogen phosphate in 1 litre of double distilled water.

3.2.SYNTHESIS OF POLYURETHANES.

The polyurethanes were synthesised by the prepolymer method In this method,the polymer was formed in two stages.

To the required quantity of H_{12}MDI,taken in a resin kettle, polyol was added slowly under stirring followed by the addition of DMAC. Dibutyl tin dilaurate(0.2%) was added as a catalyst and the temperature was raised to 60oC. The reaction was

carried out under nitrogen atmosphere with constant stirring. The reaction was continued to nearly 3 hrs. After cooling the mixture to about 40°C, 1,4-butanediol was added and stirred for 1 h simultaneously raising the the temerature to 60°C. The contents were then cured at 65°C for 48 hrs after transfering to a glass plate. By changing the molar ratios of the H_{12}MDI/polyol/chain extender, polyurethanes with varied compositions were prepared.

3.2.1.Cleaning of the polymers.

The polymer cured at 65°C was then dissolved in DMAC, casted into a film and dried at 60°C in a vacuum oven. The strips of the polymer film were then extracted with ethyl alcohol and then with hexane to remove residual DMAC and other impurities. The vacuum dried strips were then used for further studies.

3.3. INSTRUMENTAL.

1.Gel Permeation Chromatography (GPC). Molecular weight parameters of the polymers were estimated using a Waters Assoc Inc GPC system consisting of solvent delivery pump, model 6000A, U6K injector and 730 data module. Another HPLC system without a data module was also employed for the analysis. A set of 3 micro-styragel columns(Waters) of nominal pore size 10^5, 10^4 and 10^3 A were used with THF or DMAC as eluent at a flowrate of 1 ml min^{-1}.

The columns effluents were monitored by a R-401 differential refractometer. The columns were calibrated using poly styrene standards(Waters) as reported elsewhere(149).

2. IR spectroscopy. A Perkin-Elmer model 597 IR spectro-photometer was used for recording the IR spectra of the materials

The polymer as thin film was sandwiched between sodium chloride windows and scanned from 4000 cm^{-1} to 400 cm^{-1}.

3.Stress-Strain analysis. For getting the stress-strain behaviour of the polymers, a model 1193 Instron Universal Testing machine was used. The testing was carried out as per ASTM 638.

4.Differential Scanning Calorimetry. To get the glass transistion tenperature and other transistions, a DuPont's model 1090 thermal analsyer with a 910 DSC cell was used. To obtain subambient temperature range, liquid nitrogen was used as coolant. 10-15 mg of the sample was encapsulated non-hermitically and heated from -120°C to 280°C at the heating rate of 10°C/min.

4.Thermogravimetric analysis. For assessing the thermal stability of the polymers, a DuPont's 990 Thermal analyser in conjuction with a 951 TGA module was used. 10-20 mg Of the samples were heated from 30°C to 600°C at a heating rate of 10°C/min under a dynamic nitrogen atmosphere.

5.Optical microscopy. A Nikon model 35A optical microscope was used for viewing the samples.For getting the birefringence pattern of the polymers crossed polarizers were incorporated.

6. Wide angle X-ray diffraction (WAXD)studies. WAXD studies were performed on a Philips PW-1710 Diffractometer employing Nickel filtered CuKα radiation. 2θ scan rate was 1°/min.

6.Scanning electron microscopy(SEM). For obtaining the surface morphology of polymeric materials, a Jeol 35C SEM was used. Prior to observation, the samples were coated with an

evaporated layer of gold. The accelerating voltage was 10Kv and the magnification in all the observation was 1000X.

7.Contact angle measurement. To understand the relative hydrophilic or hydrophobic nature of the materials,a captive bubble technique was used as described by Hamilton(150). In this method the sample, in the form of a film,was placed face down in glass cell containing water after conditioning. Air bubbles were released from the tip of a syringe beneath the sample.The contact angle was measured using a Rame-Hart goniometer.

3.4.UNIDIRECTIONAL STRETCHING OF POLYMERS.

To understand the effect of room temperature stretching on the structural features of polyurethanes and the subsequent effect on the diffusion and absorption of lipids, polyurethanes with varied hard/soft segment contents were subjected to stretching. Three polyurethanes samples with 23%, 33% and 47% hard segment content were used for the stretching studies.Polymer strips(2x7 cm^2) were stretched to varied degree of elongations using an Instron Universal Testing Machine(model1193) at a cross head speed of 100 mm/min. The materials after drawing to the desired elongations were allowed to remain in the stretched state for 15 min. After removing the applied stress, the polymers were allowed to relax at room temperature for 72 h. These materials were used for further studies.

3.5.SYNTHESIS OF GRAFT COPOLMERS OF POLYURETHANES.

Radiation grafting method was used for preparing the grafts of polyurethane with different entities. Gamma irradiation has

been used extensively to create free radical sites on polymer chains. These radicals can either initiate the polymerization of a second monomer or recombine with growing radicals, yielding the expected grafts. Several specific procedures have been discussed by Chapiro(151,152).

The direct radiation grafting which has been followed widely, (153-155) was used to prepare the grafts. In this procedure, the polymer strips were swelled in the monomer followed by gamma-irradiation. As radicals were formed on the polymer, they initate the polymerization of the monomer. Grafts were grown from these sites with the simultaneous formation of the homopolymer.

Three polyurethane samples having a hard segment content of23%, 33% and 47% were used for grafting. 2x8 cm^2 strips of the polymers were immersed in the vinyl monomers;HEMA,NVP,MMA,MA and BA to varied peroid of time. After exposing to the monomers, the strips were slightly pressed between filter paper to remove the superficial monomers and immediately subjected to gamma-irradiation from a Co^{60} source (Panoramic batch irradiator, BARC, Bombay) under a blanket of nitrogen. The total dose was 0.5 Mrad at dose rate of 0.23Mrad/hr. Increased grafting yield was achieved by increasing the swelling time rather than increasing the total dose.

The binary grafts were prepared by grafting BA and HEMA simultaneously from the mixture of these two. The polymer strips were swelled in 1:1 mixture of these two monomers and subjected

to gamma-irradiation.

3.5.1. Isolation of the grafts.

1. poly(urethane-g-HEMA). The polymer strips after irradiation, were extracted with hot water(50°C) for three days for removing ungrafted polyHEMA and unreacted monomer. The dried polymer strips were then extracted with THF for removing homo polyurethane. The graft found as an insolouble residue was washed several times with methanol and then vacuum dried.

2. Poly(urethane-g-N-Vinylpyrrolidone). The NVP grafted polyurethane strips were extracted with water continously for 4 days. The dried polymer strips were then extracted with hot dichloromethane to remove homo polyurethane. The poly(urethane-g-NVP) found, as a residue was isolated and vacuum dried.

3. Poly(urethane-g-MMA). The MMA grafted polyurethane was isolated by a two stage dissolution process. Ungrafted PMMA chains were removed by extracting the graft with toluene. The residual strips were then extracted with DMAC to remove homo polyurethane. The highly swelled residue, the graft copolymer, was washed with methanol and vacuum dried.

Poly(urethane-g-MA) and Poly(urethane-g-BA) were also cleaned adopting the same procedure used for the cleaning of MMA grafts.

4. Binary grafts. Poly(urethane-g-HEMA/BA). The polymer strips after irradiation were extracted with water as in the case of Poly(urethane-g-HEMA) to remove ungrafted polyHEMA chains. The strips after this treatment were dried and then extracted with

dichloromethane to remove homo polyBA and homo polyurethane. The binary graft was isolated as insoluble residue and dried.

3.5.2.Estimation of graft yield(% grafting).

% grafting was determined using the relationship

$$\%grafting=(W-W_o/W_o)X100 \text{ ----------1}$$

where W is the weight of the graft polymer and W_o is the initial weight.

3.5.3.Characterization of the grafts.

The instrumental techniques(IR,SEM,Contact angle and Stress-Strain analysis) mentioned earlier were employed for analysising the grafts. The GPC method was also used to confirm the grafting. The GPC system already mentioned was used for this purpose.

HEMA grafts and binary grafts(HEMA/BA) were found to be insoluble in common GPC solvents. Poly(urethane-g-NVP) was found to be soluble in THF and the GPC analysis was carried out using THF solution of the grafts employing THF as the mobile phase. Poly(urethane-g-MMA), Poly(urethane-g-MA) and Poly(urethane-g-BA)were found to be soluble in chloroform and these grafts were analysed using chloroform as mobile phase. In all the analysis the flow rate was $2ml min^{-1}$ and the eluted peaks were monitored by RI detector.

3.6.DIFFUSION STUDIES.

Silicone oil(MS200/200,GLC grade,BDH,Poole,England)was used as a medium for dissolving the lipids as well as for performing the diffusion studies. The diffusion of the lipids through the

polyurethanes was a very slow process and therefore ,immersion and weighing method was adopted as suggested in the literature(156). Rectangular polymer strips having an area of 2 cm^2 and 0.5 to 0.51 mm thickness were conditioned in silicone oil for several days at the experimental temperature of 37°C. These strips after pressing between filter paper,for removing the adhered silicone oil,were weighed and then placed in the silicone oil solution of(3mg/ml)of the respective lipids. At definite time intervals, the polymer strips were taken out,pressed between filter paper and weighed. The experiments were continued until constant weight gain or equlibrium % absorption was attained. All these studies were performed at static conditions. Alternatively IR spectral analysis was used to estimate the amount of lipids diffused.

3.6.1.Estimation of diffused lipids using IR spectroscopic method.

The polymer strips recovered from the respective lipid solutions were extracted with 3 ml of CCl_4 for half an hour which was fixed by performing extraction efficency experiments as discussed in section 3.6.2. The solution was concentrated to 0.5ml. Control polymer strips(polymer kept in silicone oil for the same peroid) were also extracted in a simillar fashion. A matched pair of 0.2mm sodium chloride cells(Perkin-Elmer) were used for recording the spectra. In the reference beam the CCl_4 extract of control polymer strips was kept to balance the absorption of the silicone oil in the sample solution to avoid

the interference. By comparing the spectra of the lipids with spectra recorded using known concentration, the quantification of the diffused lipids was achieved.

3.6.2.Extraction efficency.

The extraction efficency of each of the lipids was determined. For this purpose, both polymer and lipid were mixed in a known proprotion and dissolved in dichloromethane. The solution was then poured into a watch glass to cast a film. The solvent was evaporated in an vacuum oven. The lipid from the polymer film was extracted with CCl_4. A 10 minutes peroid was found to be sufficient to extract over 98% of the lipid.

3.6.3.Estimation of diffusion coefficients.

Diffusion process is quantitatively expressed by Fick's law(156).

$$d_c/d_t = div(DgradC) \text{--------} 2$$

where c is the local concentration of the diffusant, t is the time and D is diffusion coefficient. Assuming D is a constant, independent of the diffusant concentration, a solution to equation(2) in terms of M_t (mass uptake at time t) is

$$M_t = 2M_\infty (Dt/L^2)^{1/2} \{1/II^{1/2} + 2\sum_{n=0}^{\infty}(-1)^n \text{erfc}[nL/(Dt)^{1/2}]\} \text{------} 3$$

where M_∞ is the amount of diffusant absorbed as $t \to \infty$. The form of this equation suggests that a plot of fractional equlibrium mass uptake M_t/M_∞ versus $t^{1/2}$ should be linear at small times and the diffusion coefficient can be calcuated from the initial slope. At longer time intervals another solution to equation-2 is proposed(156).

$$Mt=1-(8/\Pi^2)\sum_{m=0}^{\infty}([1/(2m+1)^2]\exp[-D(2m+1)^2\Pi^2 t/4L^2])\text{---------}4$$

which reduces to $\ln[1-Mt]=\ln(8/\Pi^2)+(-D\Pi^2+t/4L^2)$ as t- . Thus a plot of ln[1-Mt] versus t should be linear and the slope is proprotional to the diffusion coefficient.Through out this study, however, equation(3) was used for estimating D since both equations provided identical values for D.

3.6.4.Effect of concentration and thickness on the diffusion coefficient.

Separate experiments were performed to know the influence of concentration of the diffusant and thickness of the polymer film on 'D'. Solutions of lipids with three different concentrations, 1mg/ml, 3mg/ml and 6mg/ml were prepared. Polymer strips having a thickness of 0.5,1.0 and 1.5mm were also used.

3.6.5.Estimation of Activation energy.

The diffusion studies were carried out at 37°C,45°C and 55°C respectively. The diffusion coefficients at these temeratures were determined. Diffusion coefficient-Temperature relationship is given by Arhenious equation, $D=D_0 e^{-E/RT}$, where D_0 is the preexponential factor, E is the activation energy, T is the temerature in Kelvin and R is the molar gas constant. Activation energy was determined from the slope of the lnD versus 1/T plot.

3.7.LIPID ABSORPTION FROM MIXTURE.

3.7.1.Silicone oil solution. All the six diffusants, stearic acid, cholestrol, cholestrylaceate, triolein, methylpalmitate and butyloleiate were dissolved in silicone oil to give a concentrat-

ion of 2mg/ml. The polymer strips kept in the the solution were weighed at definite time interval as mentioned in section.3.6.

3.7.2.Phosphate buffer dispersion of lipids. The six lipids were dissolved in hexane and evaporated the solvent by a stream of nitrogen. To this phosphate buffer was added to give a concentration of 2mg/ml and sonicated using a Sonipred 150 ultrasonic disintegrator(MSE Scientific Instruments,UK)to get a fine dispersion. 0.2% sodium azide was added to this to retard the growth of bioorganisms. The polymer strips kept in the buffer disperson at 37°C were taken out at a definite time interval, vacuum dried and weighed. The polymers were kept in the dispersion for a total period of 30 days.

3.7.3.Absorption from blood. Sheep's blood was collected using a syringe into glass bottles containing ACD solution as anticoagulant (1ml to 10 ml of blood). Polymer strips sterilized by gamma irradiation(2.5Mrad) were placed in the bottles containing the blood and kept at 4°C for 30 days. The polymer strips were taken out, cleaned with water and then kept in 1% Trition X-100 solution to remove the adsorbed proteins.The vacuum dried strips were then weighed to obtain the % absorption of the lipids.

3.8.CHROMATOGRAPHIC SEPARATION OF LIPIDS.

To know the absorption profile of the lipids absorbed from different media, a chromatgraphic separation is necessary.The chromatography of lipids has been widely documented(157,158).Most

of these papers are, however, dealing with the strategies of methodlogy development and optimization of separation of a given class of components(steoriods,phospholipids etc). The lipids used in the present investigation consisted members belonging to different classes namely free fatty acids,fatty acid esters and steorids. Adopting any of the existing procedure may not provide a satisfactory separation particularly in the isocratic mode which is essentially needed if refractive index detector is used. To address the separation, an effective chromatographic procedure involving an non-aqueous solvent system was developed. For seperating the lipids a micro-bondapakC18 column(Waters Assoc Inc,USA) was used. The mobile phase was prepared by mixing methanol and acetone(60:40V/V). A standard solution(1mg/ml)of the lipids was prepared by dissolving all the six components in the same solvent mixture used as the mobile phase. The separation was effected at a flow rate of 1ml/ min and the column effluents were monitored using a Differential Refractometer detector. Silicone oil was found to be insoluble in solvent mixture used as the mobile phase. This avoided the interference of the oil in the analysis.

The polymer strips from the mixture of the components (Silicone oil,Phosphate buffer disperson and Blood) were extracted with 2ml each of the solvent mixture (mobile phase) and concentrated to 500 microlitre. 100 microlitre of these solutions was used for the analysis.

Control polymers were also extracted similarly and ana-

lysed under the same chromatographic conditions

CHAPTER 4

RESULTS AND DISCUSSION

SECTION 4.1

CHARACTERIZATION

4.1.1
CHARACTERISATION OF LINEAR SEGMENTED POLYURETHANES

CHAPTER 4

The observation of high plateau modulus in linear segmented polyurethane in the absence of crosslinking or crystallinity led Cooper and Tobolsky to assign a microphase separated structure to linear polyurethane(159). Clustering of hard and soft segments into separate entities, arising from the thermodynamic incompatibility, has been traced to the realization of such a morphology. In later years, several investigators using independent techniques including electron microscopy have arrived at similar conclusion (42,49,160-162). The morphology, however, to a large extent, is governed by several factors like synthetic conditions, molecular weight and nature of both hard and soft segments, interaction between the segments, crystallinity, molecular orientation,casting solvents, temperature etc. Probing of molecular architecture of segmented linear polyurethane, has always been a challenge and in spite of the existence of substantial literature, the exact nature of the microphase structure of this class of polymers has yet to be elucidated(7). This is particularly true in the case of PU based on H_{12}MDI which is picturised as a polymer containing phase mixed state in comparison to the aromatic counterpart (MDI) and as relatively less phase separated entity according to several other investigators(163-167).

The following sections deal with various parameters obtained using different techniques in order to elucidate the structural features of the synthesized polymers.

4.1.1.1. Infrared spectral studies:

The relevant parameters of the synthesized polyurethanes are shown in Table 4.1. The molecular weight averages of the polymers slightly vary from sample to sample. However, the dispersity of the materials is close to 2 indicating the molecular wight distribution is nearly identical irrespective of the variation of the hard and soft segment content.

Infrared spectroscopic method is one of the widely employed techniques to understand the morphological features of polyurethanes particularly in terms of hydrogen bonding(168,169) It has also been used as an effective method to determine the extent of phase separation in polyurethanes(74). Earlier studies showed that nearly all -NH groups in polyether polyurethanes are hydrogen bonded(169). However, in actual practice, only a portion of the urethane carbonyl groups is involved in hydrogen bonding as the -NH acceptor. It has been postulated that, substantial degree of hydrogen bonding of the -NH group occurs with the ether oxygen of the polyether segment(169). Hydrogen bonding between -NH and carbonyl groups of urethane is assumed to take place in hard segment aggregates while hydrogen bonding between -NH and ether oxygen of polyol is supposed to take place at the domain interface and between urethane segments dissolved in the soft segments. Based on these assumptions, the ratio of hydrogen bonded to free urethane carbonyl peaks has been considered as a measure of phase separation(74). Additionally, the ratio of absorbance of bonded carbonyl to bonded -NH peaks has been considered as an

TABLE-4.1.

RELEVANT PARAMETERS OF THE SYNTHESIZED POLYMERS

Polymer	Hard segment content (Wt%)	$Mw \times 10^{-5}$	$Mn \times 10^{-5}$	D(Mw/Mn)	Tg of soft segment (°C)
PU-0	0	2.02	1.0	2.02	-71
PU-1	23	2.10	1.05	2.01	-53
PU-2	33	2.32	1.09	2.12	-42
PU-3	47	1.93	1.03	1.87	-31
PU-4	66	1.83	0.95	1.93	--
PU-5	100	1.75	0.85	2.06	--

indication of the extent of phase mixing of hard and soft segment phases(74).

A typical infrared spectrum of the polymer is shown in figure 4.1. The -NH peak centered around 3300 cm^{-1} appears to be an indication of high degree of hydrogen bonding. The free -NH peak around 3460 cm^{-1} appears as an extremely weak shoulder. An expanded version of the carbonyl absorption region, illustrated in the in - set of figure 4.1, shows two peaks, one at 1730 cm^{-1} of free -C=O groups and another at 1702 cm^{-1} indicative of bonded -C=O groups. Considering the molar extinction coefficient of both bonded and free-C=O groups as equal(170), the peak ratio of bonded to free -C=O groups was computed for all the polyurethane samples having varied hard and soft segment contents. Similarly

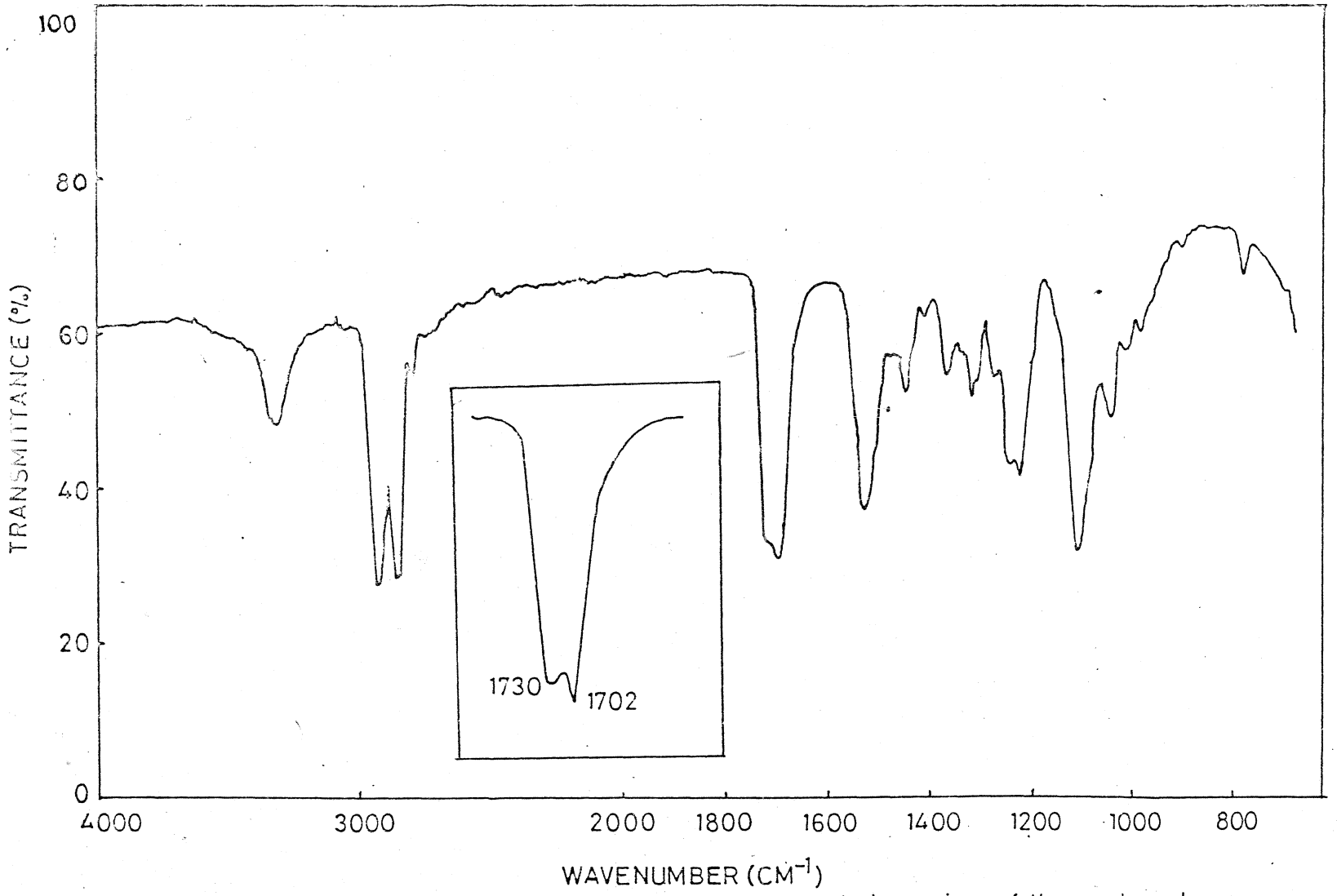


Fig. 4 - 1. Typical infrared spectrum of polyurethane. Expanded version of the carbonyl absorption is shown in the inset.

the ratios of bonded -C=O and bonded -NH groups were also estimated. These values are summarized in Table 4.II.

It can be seen from the data shown in this Table that bonded to free -C=O ratio progressively decreases as the % hard segment content increases indicating enhanced phase mixing. The ratio of 1702 and 3300 absorption peaks of bonded -C=O and -NH groups, also shows the decreasing trend with the increase of hard segment content. An indication of phase separation is said to be the constancy of this ratio regardless of the amount of soft segment(74). The decreasing trend of this ratio as in the case of -C=O absorption ratio further support the phase mixing with the increase of hard segment content.

The infrared spectroscopic analyses indicate that the polyurethanes used in present studies are extensively hydrogen bonded. Further it shows that the extent of phase mixing numerically increases with the increase of hard segment content.

4.1.1.2. Differential scanning calorimetric studies:

Seymour et al(171) and Van Bogart et al (166) have extensively studied the thermal behaviour of various types of polyurethanes. Apart from the glass transistion temperature (Tg) of the soft segment, above room temperature three regions of themal transistion have been observed. The first endotherm centered around 70°C is attributed to the disruption of domain with limited short range order. The endothermic peak around 120-190°C has been assigned to the dissociation of domains having

TABLE.4.11

INFRARED SPECTROSCOPIC DATA

Polymer	Hard Segment (Wt %)	IR absorption ratio	
		$(A_{1702}/A_{1730})X100$	A_{1702}/A_{3300}
PU-0	0	-	-
PU-1	23	71	3.10
PU-2	33	58	2.70
PU-3	47	28	1.96
PU-4	66	--	--
PU-5	100	--	--

long range order and the endotherms above 200°C is attributed to the melting of microcrystallities.

DSC traces are depicted in figure 4.2. Tg of soft segment is found below room temperature. This transition progressively shifts to higher temperature scale depending upon the extent of hard segment content. This upward shift is due to the mixing of more hard segments in the soft segment domains. Tg values obtained from the DSC traces are summarized in Table 4.I. This parameter is higher than the pure PTMG(-79°C) and increases with the % of hard segment contents indicating solubilization of hard segment sequences in soft segment phase. The Tg values apparently support the infrared spectral evidence of enhanced phase mixing

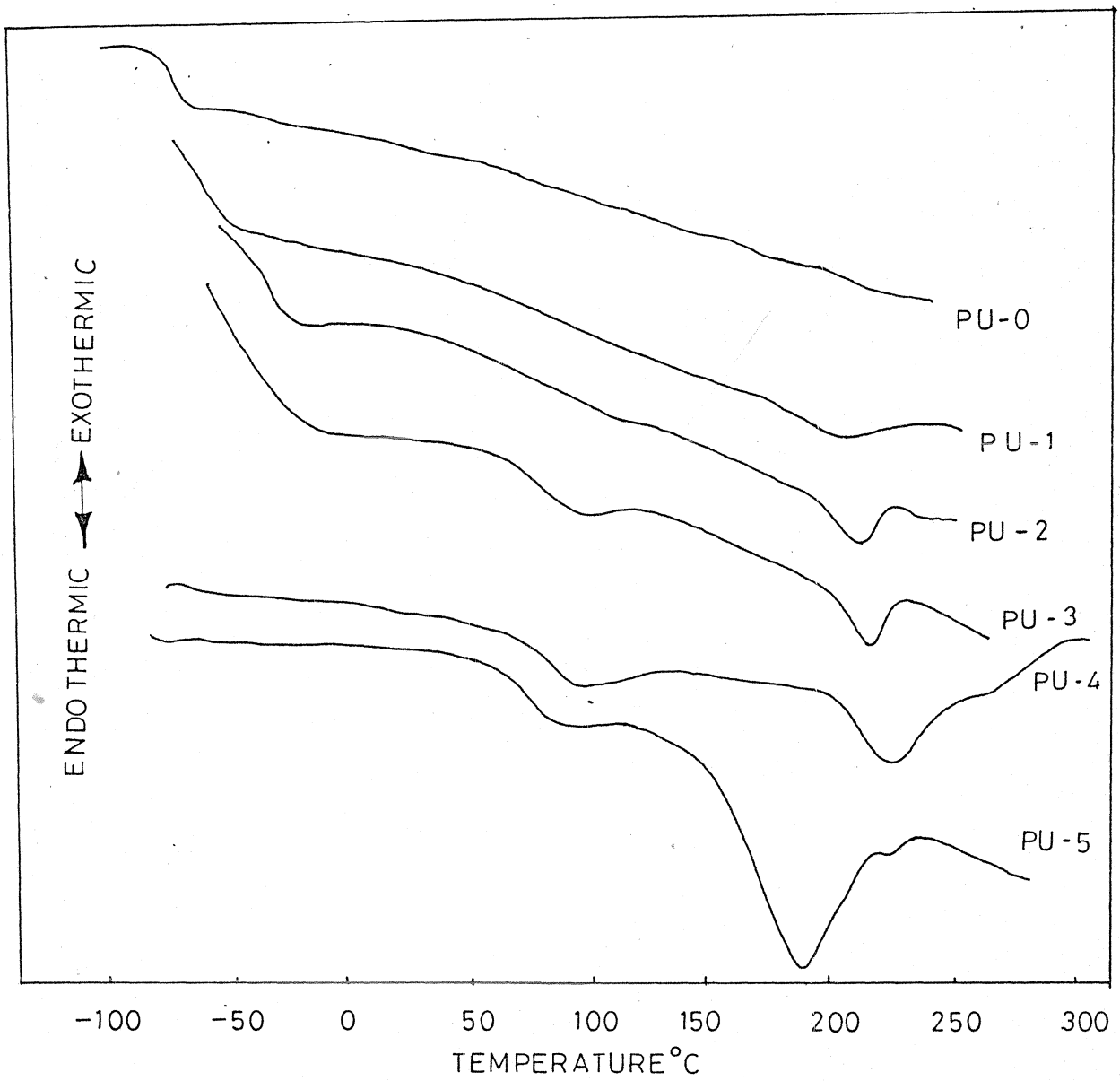


Fig. 4 - 2. DSC Thermo grams for the Polyurethane samples having hard segment contents of 0% (PU-0), 23% (PU-1), 33% (PU-2), 47% (PU-3), 66% (PU-4) and 100% (PU-5).

with the increase of hard segment content. PU-4 (66% HS) did not show any soft segment Tg apparently due to very low quantity of soft segment content and possibly due to differed morphology from other polymers.

The absence of any endotherm at lower temperature in the DSC scans indicates the lack of soft segment crystallinity. The soft segment crystallinity arise only if the molecular weight of the polyol soft segment is around 2000 or more(172). Even if possible, the more dispersed hard domains in the soft segment domains rule out the ordering required to realize the crystallinity.

PU-3, PU-4 and PU-5 show a broad and comparatively weak endotherm centered around 90°C. This endotherm may be arising from the disordering of hard segment domains with a relative degree of short range order. All the DSC scans except PU-0 (100% soft segment), show broad endotherm centered around 200 °C which shifts to upper scale as the % hard segment increases. The endotherm could be due to the melting of the crystallities.

The crystallinity in polyurethane, based on H_{12}MDI has been stated to be low(166). This is attributed due to the existence of isomers of H_{12}MDI namely cis-cis, cis-trans and trans-trans. The configurational isomers lead to form a random hard segment structure from which the probability of crystallization is rather low. However, hard segments composed of trans-trans sequences can give some degree of crystallinity. Bryne et al(173) have demonstrated increased shore hardness in polyurethanes based on H_{12}MDI containing nearly 70% trans-trans isomer and the increased hardness has

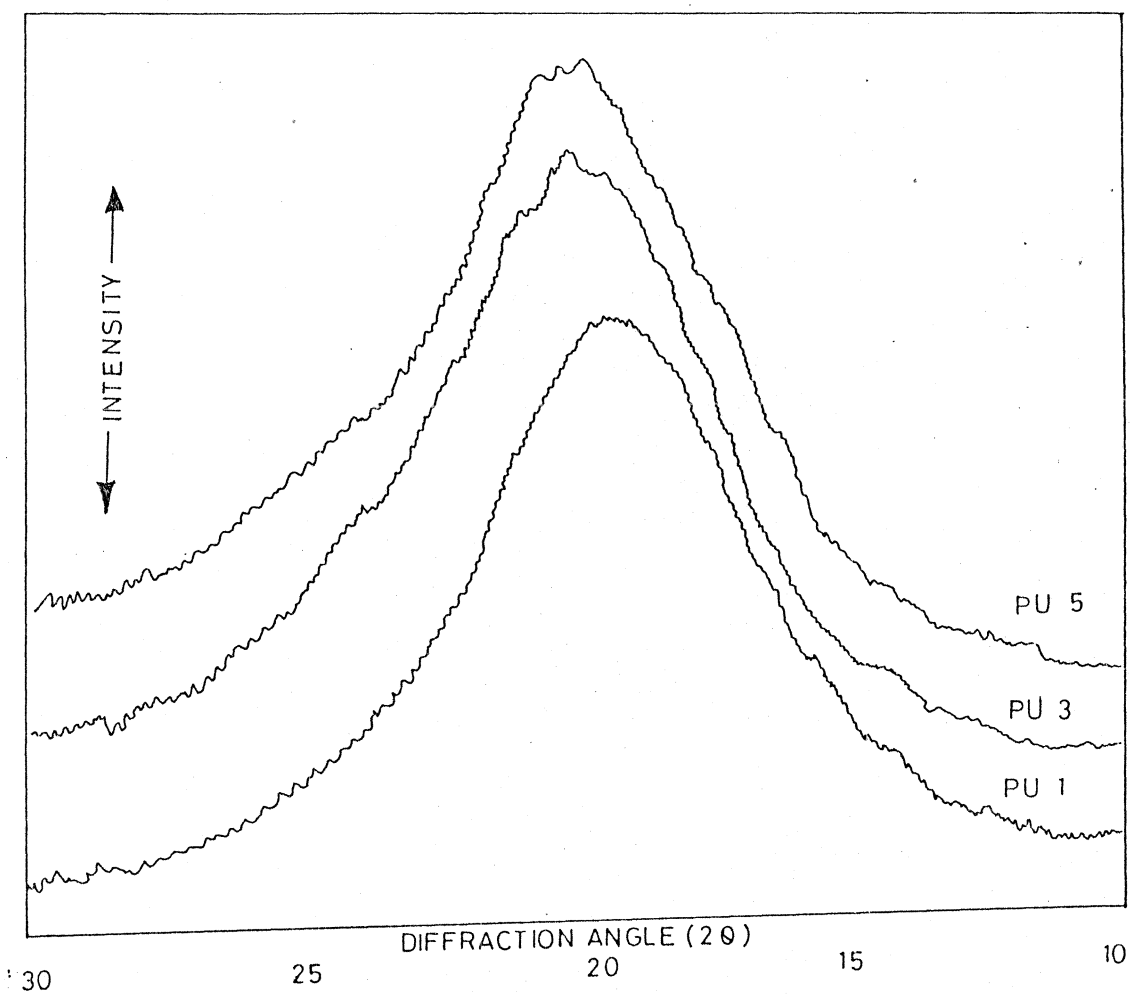
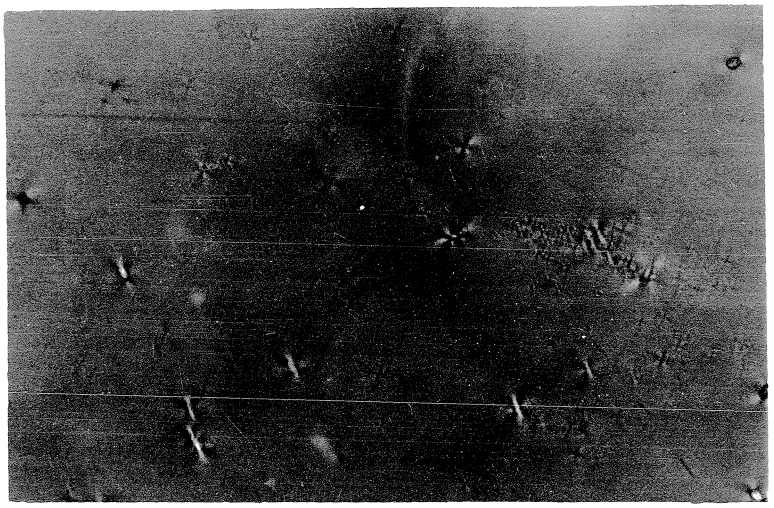
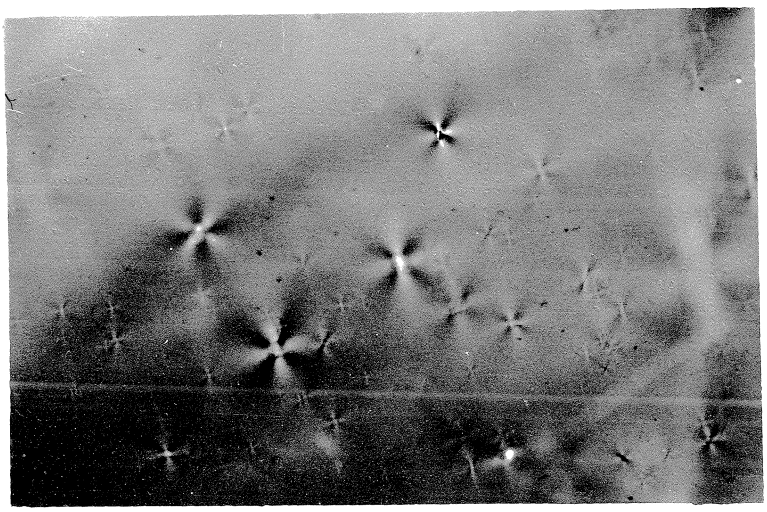


Fig.4-3. Wide angle X-ray diffraction traces of polyurethane samples havig hard segment conent 23% (PU-1), 47% (PU-3) and 100% (PU-5)



A

B



C

Fig.4.4. Polarized optical microphotographs of polyurethanes: A-PU-1, B-PU-3 and C-PU-4.Original magnification,40X

that they increase in number with the increase of hard segment content.

4.1.1.5. Mechanical Properties.

Figure 4.5 illustrates the tensile stress-strain curves of the polyurethane samples. Polymers having 66% (PU-4) and 100% (PU-5) hard segment content show characteristic yield stress typical of plastics. The behaviour of other polymers having 23,33 and 47% hard segment content is that of elastomers. Table 4.111 summarizes the ultimate mechanical parameters and modulus at 100% strain.

The stress-strain behaviour changes with the composition of the continuous phase of the material from a predominantly soft segment to a predominantly hard segment.

A graphical representation of ultimate tensile stress versus hard segment content is shown in figure 4.6. The ultimate stress increases steadily upto 47% hard segment content. Around 52% hard segment content, the curve shows an inflection. That is, beyond 52% hard segment content, the ultimate stress decreases. Such inflection may be arising from the phase inversion. The phase inversion of soft to hard segment has been noted earlier by Zdrahala et al(175). The curve depicted in figure 4.6, apparently indicates a phase inversion from a soft segment rich matrix to a hard segment rich matrix occuring at about 52% hard segment content. The ultimate stress in PU-4 and PU-5 is found to be lower compared to PU-3. This could be due to the low soft segment content in PU-4 and its absence in PU-5 apart from the phase

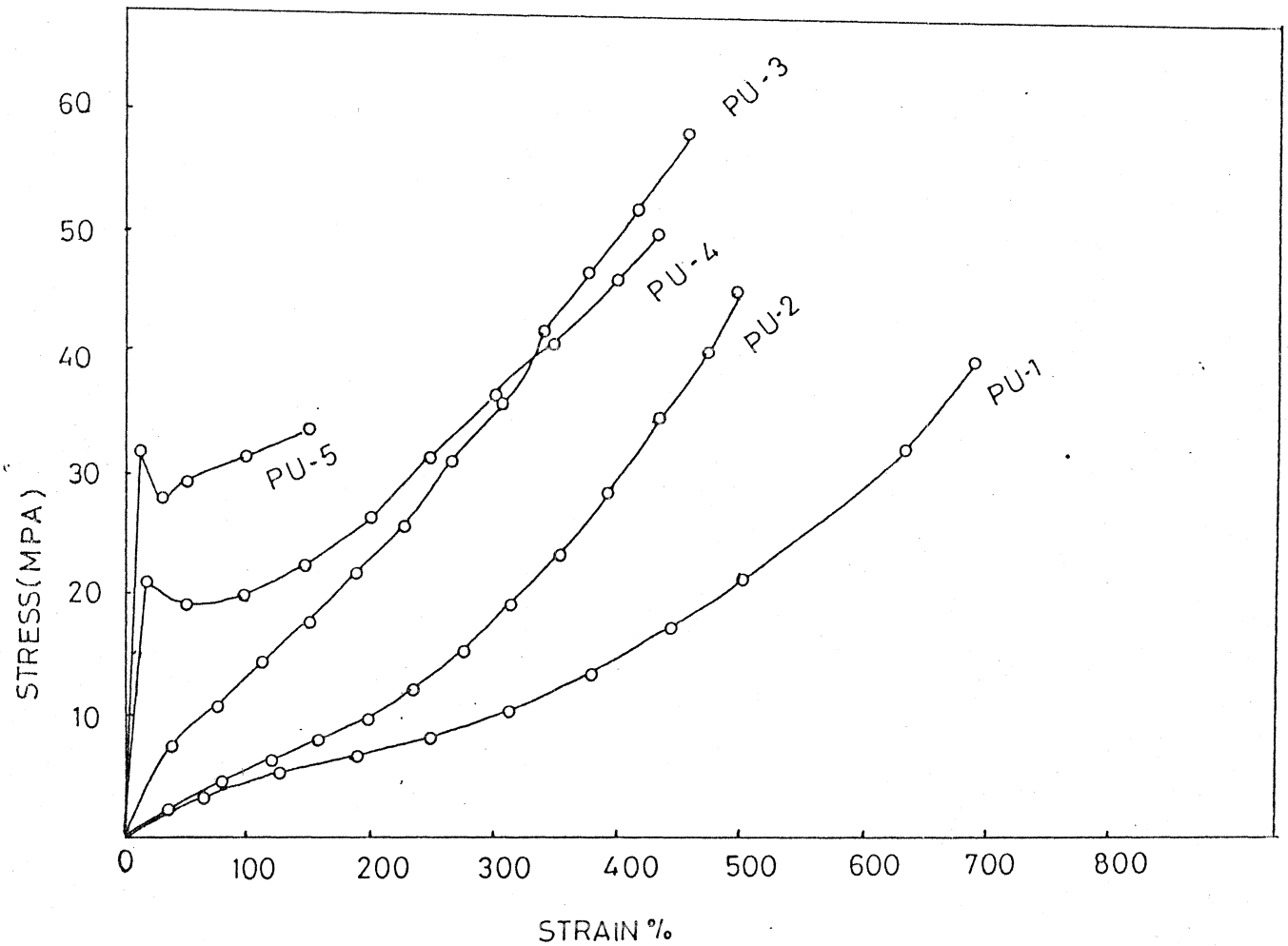


Fig. 4 – 5. Stress-strain curves for the polyurethane samples.

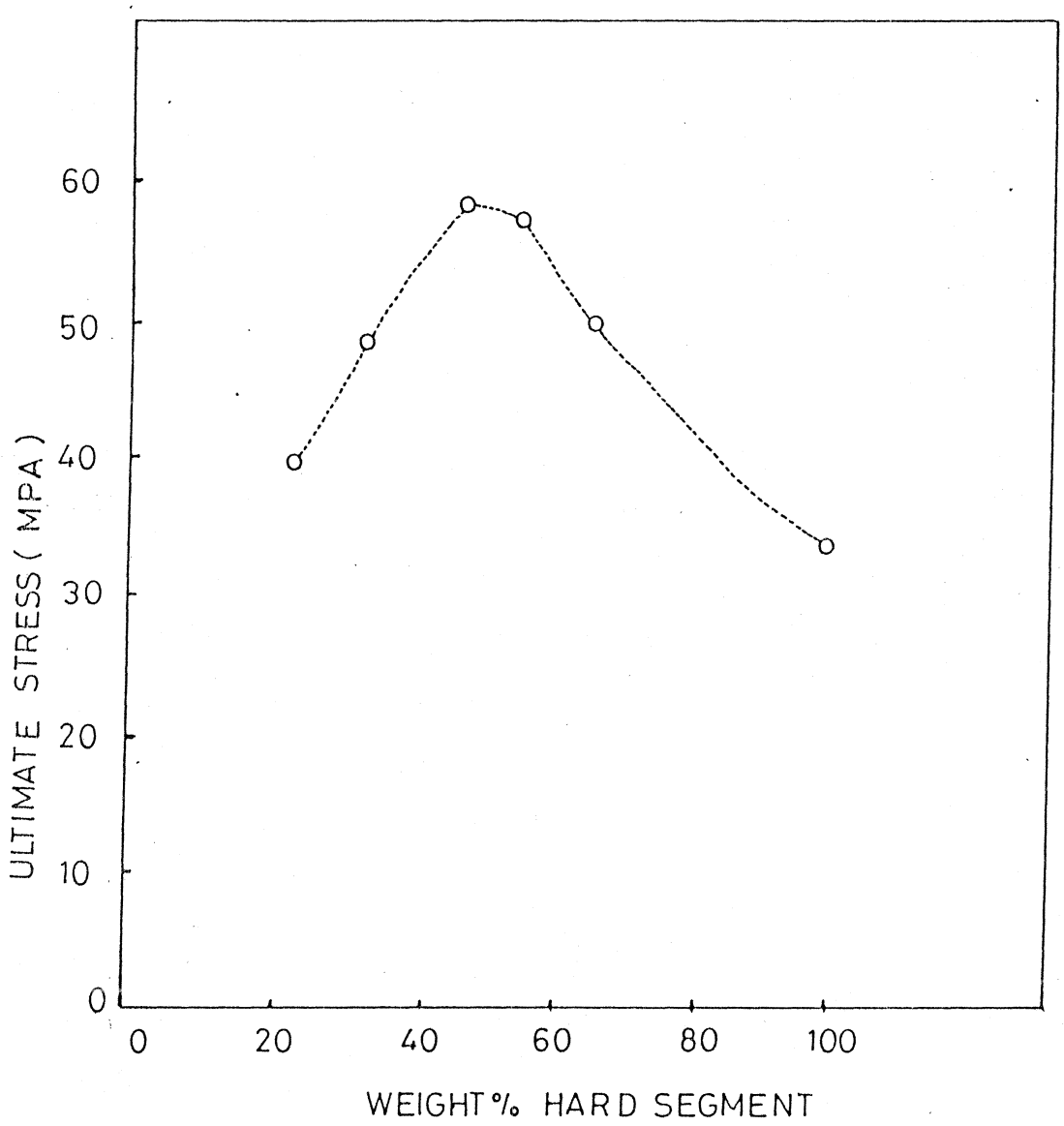


Fig. 4 – 6. Variation of ultimate tensile stress with hard segment content.

TABLE-4.111

MECHANICAL PROPERTIES OF THE POLYURETHANE SAMPLES

Polymer	Wt% hard segment	Stress (MPa)	Strain (%)	Modulus at 100% strain
PU-1	23	39.0±0.8	690±16	4.5±0.40
PU-2	33	44.5±1.2	498±13	5.2±0.20
PU-3	47	57.8±1.4	456±9	12.5±0.4
PU-4	66	49.6±0.6	435±7	19.5±0.1
PU-5	100	33.7±1.0	150±4	31.2±0.3

inversion. It may be relevant to point out that, the ultimate stress in polyurethanes considerably depends also on the soft segment content due to the ability of soft segment to orient along the stress direction and the possibility of strain- induced crystallization(176). The reduction in soft segment content,could therefore,affect the ultimate stress.

It appears from the generated data that,the polymers possess two phase amorphous structure. Both DSC and IR spectral data indicate enhanced phase mixing with the increase of hard segment content.

4.1.2
CHARACTERISATION OF STRETCHED POLYURETHANES

Studies on molecular orientation in segmented polyurethanes under strain have been reported extensively with a view to understand the mechanism of deformation as well as to get a deeper insight of structure-property relationship(177-180). The orginal morphology may be altered by stretching to high elongation(44,181). Since the diffusion and permeation of molecules through polyurethanes, to a large extent, are governed by the complex macromolecular structure ; the strain- induced alteration in the polymers would affect the diffusion of lipids. The reorganization of soft segment molecular chains is possible, by applying strain at room temperature due to the existence of considerable degree of freedom in chain mobility arising from the below room temperature glass transition temperature of soft segment. To the best of our knowledge,no studies have been reported on the diffusion of biological components in connection with the stretch- induced structural alteration. The following section attempts to understand the altered morphological feature of polyurethane effected by the uni-directional stretching.

4.1.2.1. Wide angle X-ray diffraction studies.

Figure 4.7 illustrates the WAXD curves for PU-1 stretched to 0%, 200%, 400% and 600% elongation respectively. The first trace (A) of unstretched sample is free from any reflections associated with orientation or crystallinity. The material stretched to 200% elongation, however, shows weak, relatively sharp peaks at diffraction angles of 18.6 and 19.6 degrees. These two peaks become weaker in the material subjected to 400% elonga-

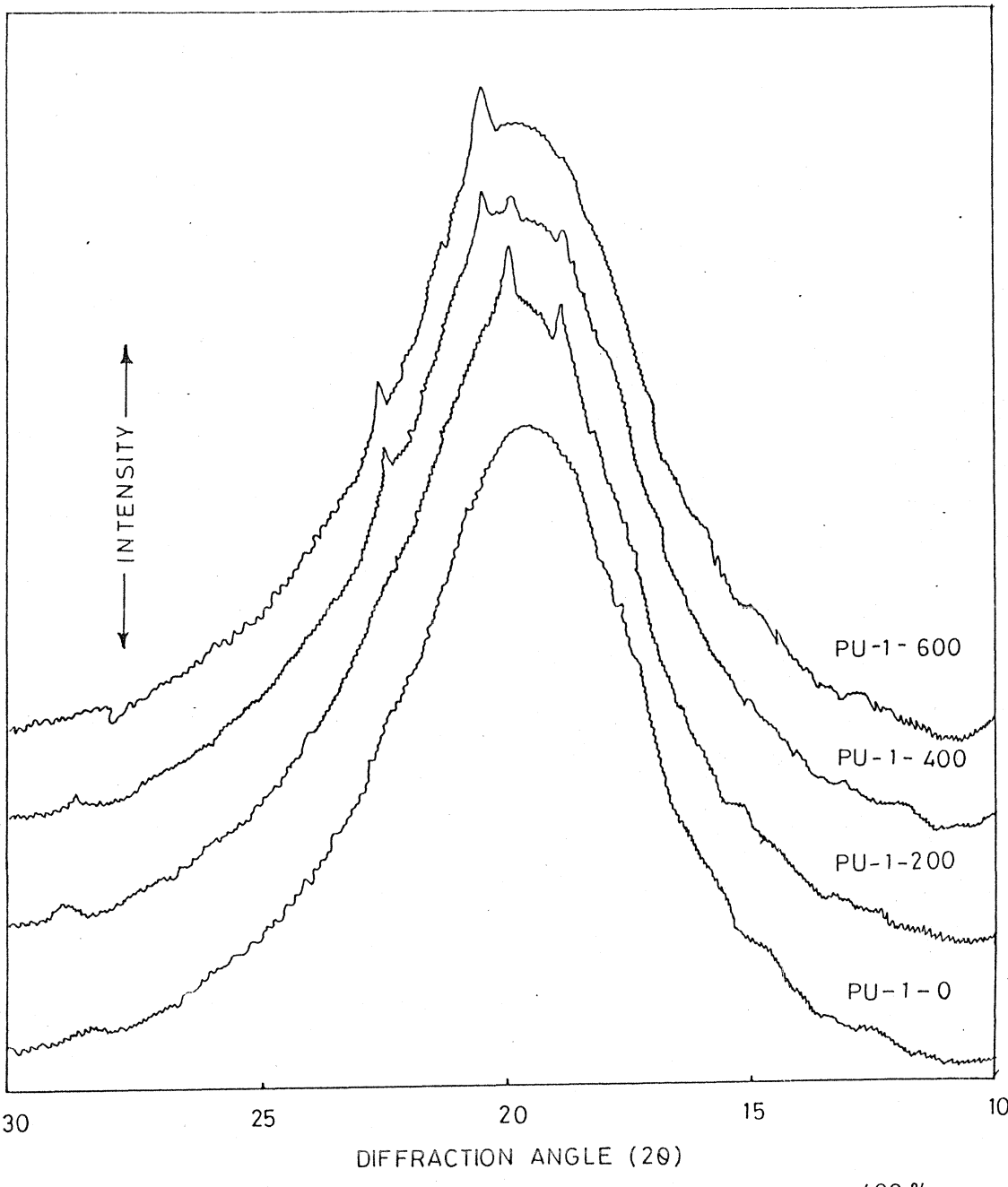


Fig.4-7. WAXD traces for PU-1 (23%HS) stretched to 0%, 200%, 400% and 600% elongation.

tion. Addtionally two weak reflections appear at 20.2 and 22.4 degrees. 20.2 peak becomes relatively stronger in material stretched to 600%. The 'd' spacings estimated for these angles are summarized in Table.4.IV.

The structural features of PTMG have been studied using X-ray diffraction method(182). The prominent peaks arising from the Zig-Zag unit cell of PTMG have been found at 4.40 and 3.60A. The presence of 4.40 A peak in the present case can be assigned to the PTMG soft segment. The WAXD curves for H_{12}MDI/BD hard segment alone and stretched to 100% elongation are shown in figure 4.8. The first trace points out the lack of any crystalline order. The second trace,however,shows relatively sharp peaks at diffraction angles corresponding to'd'spacings of 4.77 and 4.54A.

The morphology of MDI/BD hard segment has been widely studied and as many as 12 reflection arising from different (h,k,l)plane,have been assigned by Blackwell et al(183). Cooper et al(165) have found major crystalline peaks of MDI/BD hard segment at'd'spacings of 4.7 and 4.53A in segmented polyurethane samples. The H_{12}MDI/BD hard segment is of course different from MDI/BD. However, by comparing the results of these studies with that of the present investigations, it seems that,the two peaks at 4.77 and 4.54A of H_{12}MDI/BD are associated with the similar ordering in the aromatic counter part. One noticeable difference between the X-ray diffraction results of MDI/BD and H_{12}MDI/BD, is the strikingly low intensity of the peaks of the H12MD/BD. It is reasonable to presume that these peaks are associated with the

TABLE 4.IV : SUMMARY OF WAXD RESULTS

Polymer	Elong-ation	Diffraction angle(2θ)	"d" spacing	Nature of peak
PU-1	200	18.6	4.76	RS
		19.6	4.62	RS
	400	18.6	4.76	W
		19.6	4.62	M
		20.2	4.40	W
		20.4	3.96	VW
	600	20.2	4.40	RS
PU-2	200	18.6	4.76	RS
		19.6	4.62	RS
		20.2	4.40	VW
		22.4	3.90	VW
	400	18.6	4.76	M
		19.6	4.62	W
		20.2	4.40	RS
		22.4	3.90	W
	480	20.2	4.40	RS
PU-3	200	18.6	4.76	W
		19.6	4.62	RS
		20.2	4.40	W
		22.4	3.96	VW
	400	18.6	4.76	W
		19.6	4.62	W
		20.2	4.40	RS
		22.4	3.90	W
	450	20.2	4.40	RS

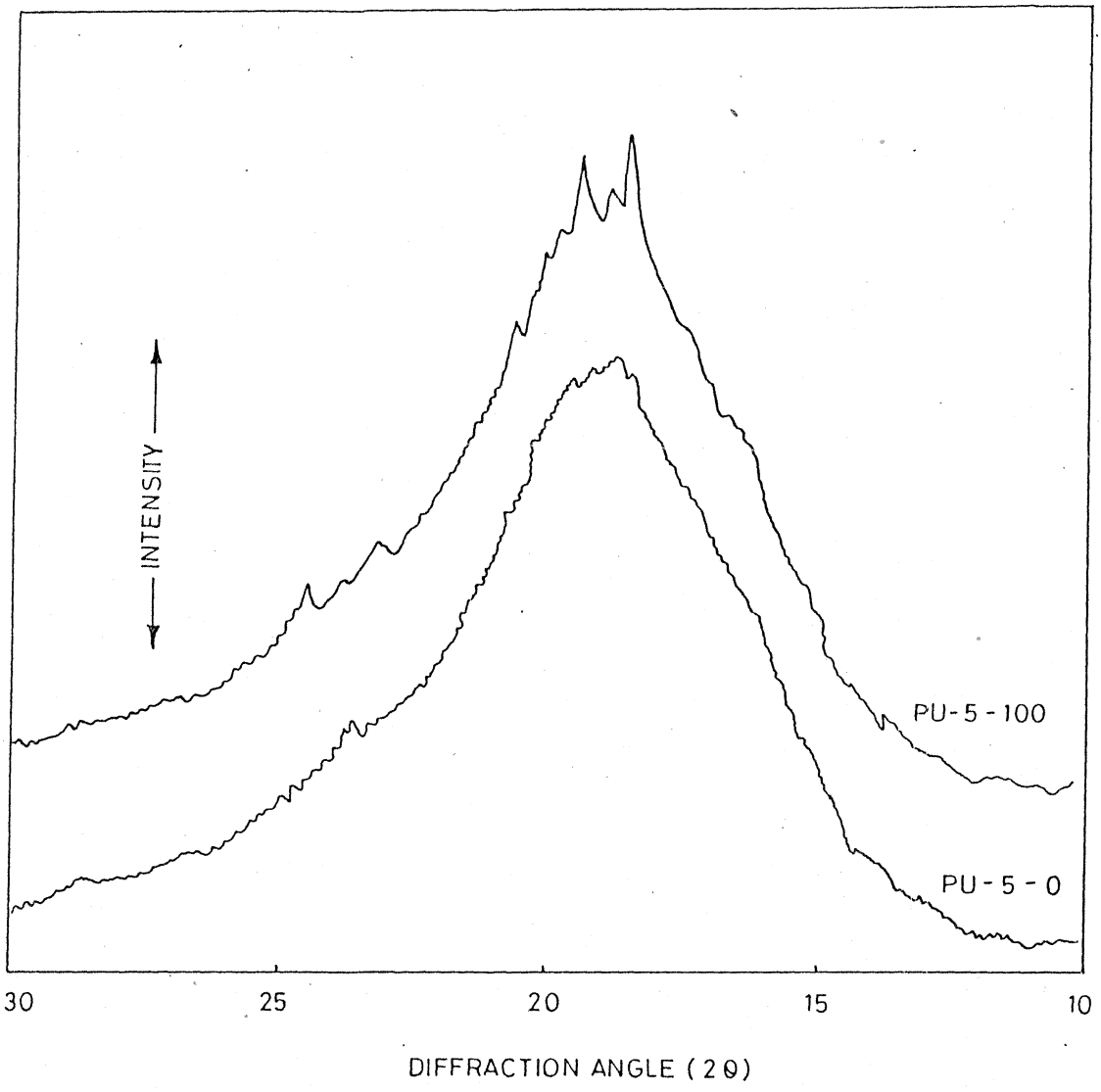


Fig. 4.-8. WAXD traces for PU 5 (100 % HS) stretched to 0% and 100 % elongation.

orientation and noncrystalline ordering (Short range order) of the segments rather than the crystalline order.

The two peaks appeared at 4.76 and 4.52A in 200% stretched PU-1 could be due to the orientation and ordering on the hard segments. Cooper et al(46,184) have shown that when both soft and hard segments are amorphous, both segments orient along the stretch direction. It is apparent now that, stretch-induced ordering in hard segment is retained even after removing the stress. The lack of any peaks associated with the soft segment in 200% elongated material, however, indicates the complete relaxation of the soft segment chains to randomness.

The presence of more hard domains in the soft segment phase can enhance the viscosity and subsequently reduce the probability of relaxation resulting in the retention of orientation or ordering(164). PU-1, in fact, contains less hard segment domains and naturally their concentration in soft segment domains would be low. The retention of stretch-induced orientation is therefore absent. When PU-1 is subjected to 400% elongation, the diffraction trace(C)shows reflections at 4.40 and 3.96A indicating the retention of orientation in soft segment. Simultaneously hard segment ordering begins to decrease as reflected in the weakening of 4.76A peak. There is a dramatic alteration in material stretched to 600% elongation (D). The peak at 4.76A nearly disappeared indicating the disruption of hard segments ordering. 4.40A reflection of soft segment becomes relatively stronger reflecting considerable degree of retained orientation and ordering in soft

segment.

The orientation behaviour of hard and soft segments in polyurethanes, particularly based on aromatic diisocyanates, as a function of stretch has been studied by several researchers(185-187). The aromatic hard domains orient transversely at lower elongation Ca 200%. At higher elongation the hard domains disrupt and orient along the stretch direction. Kong et al(188) have shown considerable disruption of hard domains at higher elongation leading to enhanced phase mixing. Recently Shibayama et al(53) using Small angle light scattering(SALS)and Small angle X-ray scattering(SAXS) techniques have demonstrated similar behaviour in polyurethanes. They found beyond 200% elongation, SAXS pattern became diffuse and is spread out towards the meridian suggesting disintegration of hard segment lamellae and broadening of the interlamellar spacing. SALS analysis showed, deformation of the hard domain spherulitic texture with increased elongation. The infra red spectroscopic studies of Yamamoto et al(189) have also demonstrated enhanced phase mixing in polyurethanes by stretching. These authors have shown that the spherulitic structures of hard segment domains were selectively destroyed at the equatorial zone of the spherulities with respect to the stretching direction and then fragmented hard segment domains were dispersed in soft segments.

PU-2 (33% HS content) also showed a similar behaviour of PU-1. The only difference is the presence of weak reflection at 4.40A of PTMG soft segment even at 200% elongation. This could be

expected due to the presence of more hard domains in the soft segment which enhance the possibility of the retention of orietation. In fact, Bonart(47) has shown the profound influence of hard segment domains in the retention of orientation in polyurethanes. PU-3 (47% HS content), on the other hand,exhibited relatively stronger 4.40A reflection when stretched to 200% (Fig.4.9). This material has a higher hard segment content and relatively has more dissolved hard segment domains in soft segment phase, which in fact, retain the soft segment orientation by checking the relaxation. Generally all these three materials behave more or less similarly except in the relative intensity of the various peaks.For the purpose of comparison, the results of WAXD studies on these polymers are summarized in Table 4.IV.

The X-ray analysis results indicate three stages of alteration in the materials. At 200% elongation, hard segment domains,attain some degree of orientation and ordering and the orientation of soft segments is rather less or even absent as in PU-1. At the second stage,the behaviour is slightly different from material to material.In PU-1,the disruption of hard segment domains starts and subsequently soft segment achieve some orientation. In PU-3 and to a lesser extent in PU-2,drastic changes occur in hard segment domains, in the form of considerable disruption and a greater degree of soft segment orientation is retained. At the third stage, that is at elongation closer to the breaking point, PU-1 exhibits relatively high degree of soft segment orientation subsequently leading to the complete disruption

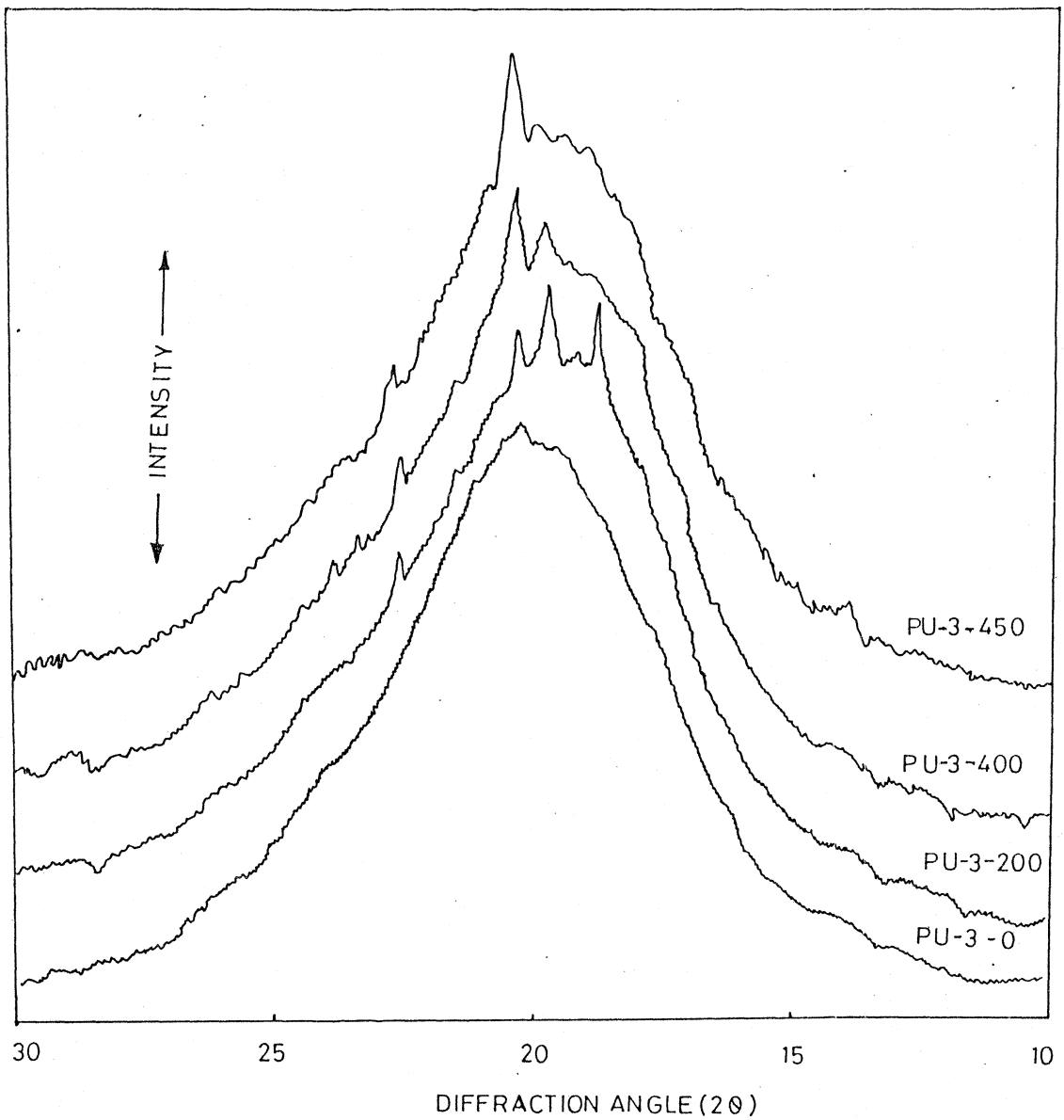


Fig.4 – 9. WAXD traces for PU-3 (47% HS) stretched to 0%, 200%, 400% and 450% elongation.

of hard segment domains. PU-2 and PU-3 show nearly the second stage behaviour except the lack of any trace of ordering in hard segment domains indicating their complete disruption.

4.1.2.2. Differential Scanning Calorimetric Studies.

DSC studies have been carried out on the polyurethane samples to get further insight into the altered features of morphology. DSC thermograms for the three polyurethane samples, unstretched and stretched close to the breaking points are depicted in figure 4.10. The soft segment glass transition temperatures of the samples obtained from the thermograms are shown in Table 4.V.

In all the three cases, the Tg showed an upward shift, indicating morphological changes induced by stretching. The increase in Tg has been repeatedly stated as resulting by the dissolved hard segment domains in the soft segment phase(164,165). The enhanced cohesiveness in the oriented soft segments induced by stretching could also increase the Tg. It seems, however, that disrupted hard segment domains, resulted by stretching, solubilize in the soft segment domains leading to increased phase mixing leading to observed upward shift in Tg. In fact, WAXD results also showed the disruption of hard segment domains at higher elongation. It may be relevant to point out that, Tg could also be increased due to the stress-induced soft segment microcrystallinity. The DSC scans, however, do not show any low temperature endotherm (<50°C) which is normally associated with the soft segment crystallinity(165). The lower molecular weight of polyol

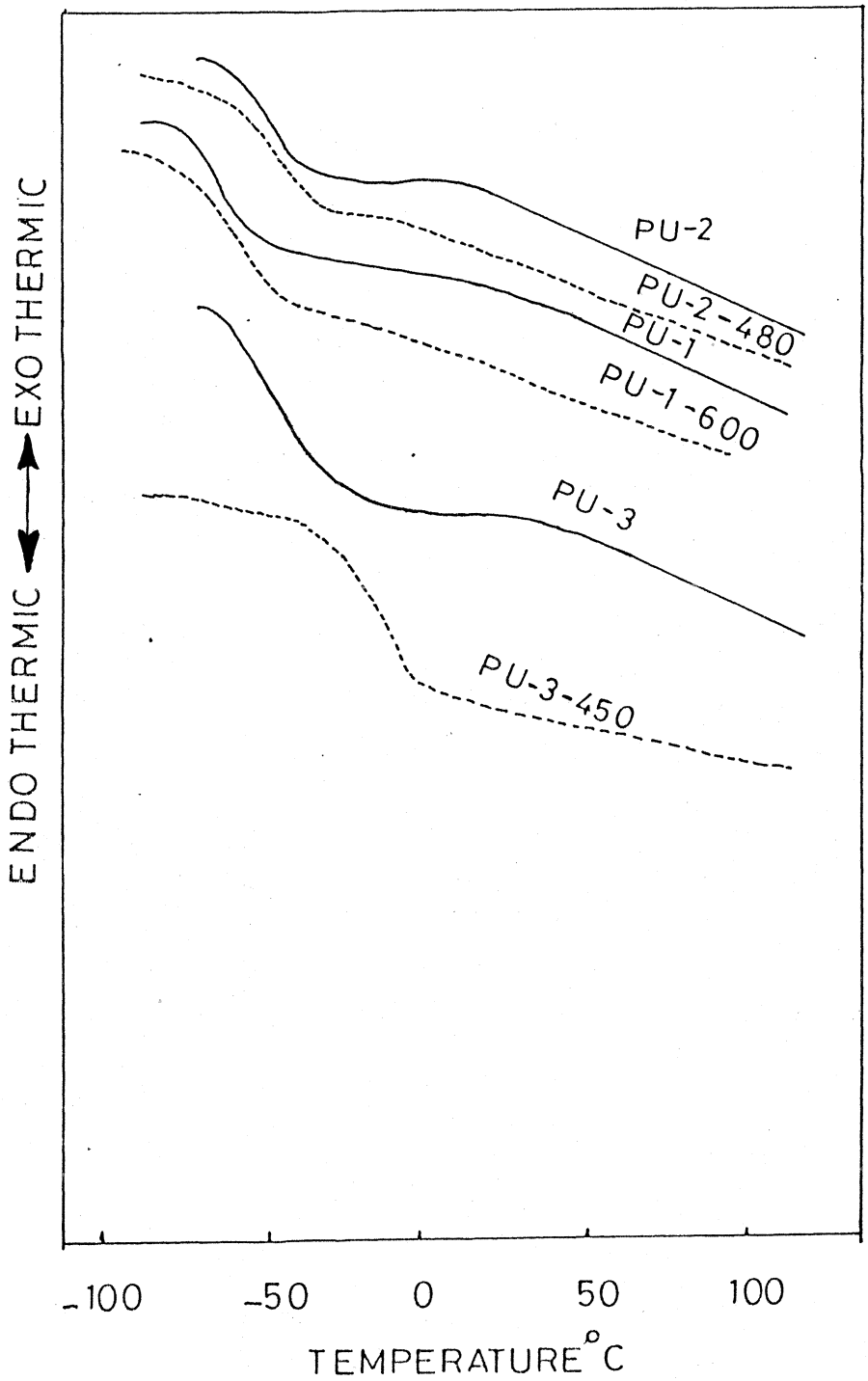


Fig. 4 -10. DSC thermograms for polyurethane control and stretched samples.

TABLE 4.V

STRETCH INDUCED VARIATION IN GLASS TRANSITION TEMPERATURE OF SOFT SEGMENT

Polymer	Hard segment content (Wt%)	Extent of stretching	Soft Segment T_g(°C)		Delta Tg
			Control Tg_I	Stretched Tg_{II}	(Tg_{II}-Tg_I)
PU-1	23	600	-53	-50	3
PU-2	33	480	-42	-34	8
PU-3	47	450	-31	-17	14

soft segment together with the more dispersed hard segment domains which prevent the long range ordering required to realize the microcrystallinity, may be the factors responsible for the lack of the crystallinity.

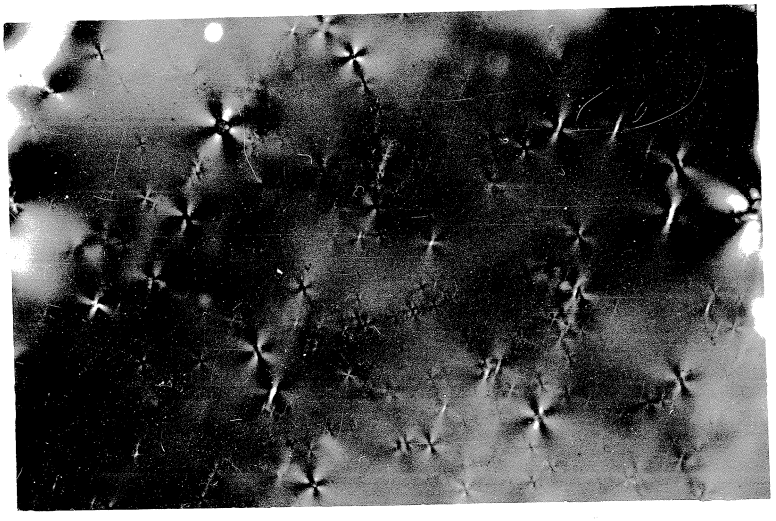
4.1.2.3. Polarized Optical Microscopic Studies.

The optical micrographs of controls and samples stretched close to the breaking points, viewed under crossed polarizers are shown in figure 4.11. The star-like structures have already been shown due to the hard segment aggregates in section 4.1.1.4. Drastic changes can be seen in the stretched materials. The increase in spherulitic-like structures in the materials subjected to stretching could be arising either due to the induced crystallinity in soft segments or due to the more dispersed hard segment domains altering the localized polarizabilities leading birefringence. The DSC studies summarized in the previous section, clearly rule out the presence of any microcrystallities in soft segment induced by stretching. Then the second alternative seems to be operative.

4.1.2.4. Thermogravimetric Studies.

TGA is perhaps the straight forward technique which could provide the thermal stability of a polymeric material. The disruption of a polymer under heat certainly depends on the extent of interaction between the molecular entities of the polymer. TGA, therefore, can reflect the stretch-induced morphological changes leading to the alteration in molecular interactions. Typical TGA thermograms of control and a polymer sample stretch

A



B

ig.4.11.Polarized optical microphotographs of A: PU-3(control) and B:PU-3 (stretched to 450%).Original magnification,40X

close to the breaking point (PU-3) are shown in figure 4.12. The enhanced thermal stability of stretched polymer is evident from the traces.The temperature at 50% dissociation of the polymers is taken as a simple measure of thermal stability(190). These values for the polymers are tabulated in Table-4.V1. The difference in temperature between control and stretched polymers increases in the order PU-3>PU-2>PU-1. The thermal stability in terms of this parameter is more prominent in polymer having higher hard segment content. More dispersed hard segment domains in soft segment,can reduce the segmental mobility which in fact increases the energy barrier for the dissociation process.Further,the dispersed hard segment domains can be stabilized through hydrogen bonding between the -NH and ether oxygen of the soft segment. A wide variety of conformation having a range of energies are possible in an amorphous polymer depending upon the -N-H...O bond distance. The stretching of these materials could lead to the homogenization of the hydrogen bonds.In fact a number of studies have reported substantial changes in -N-H stretching vibration in polyurethanes under deformation indicating alteration in hydrogen bonding index (191). The increased thermal stability could be due to the stronger,more uniformly distributed hydrogen bonds. Born et al(192) have demonstrated all trans conformation of the chain extended sequence -O-(CH2)4-O-using X-ray scattering studies. On stretching the sequence is twisted by 9.6 degree out of the phase of the neighbouring urethane groups. The hydrogen bonds between

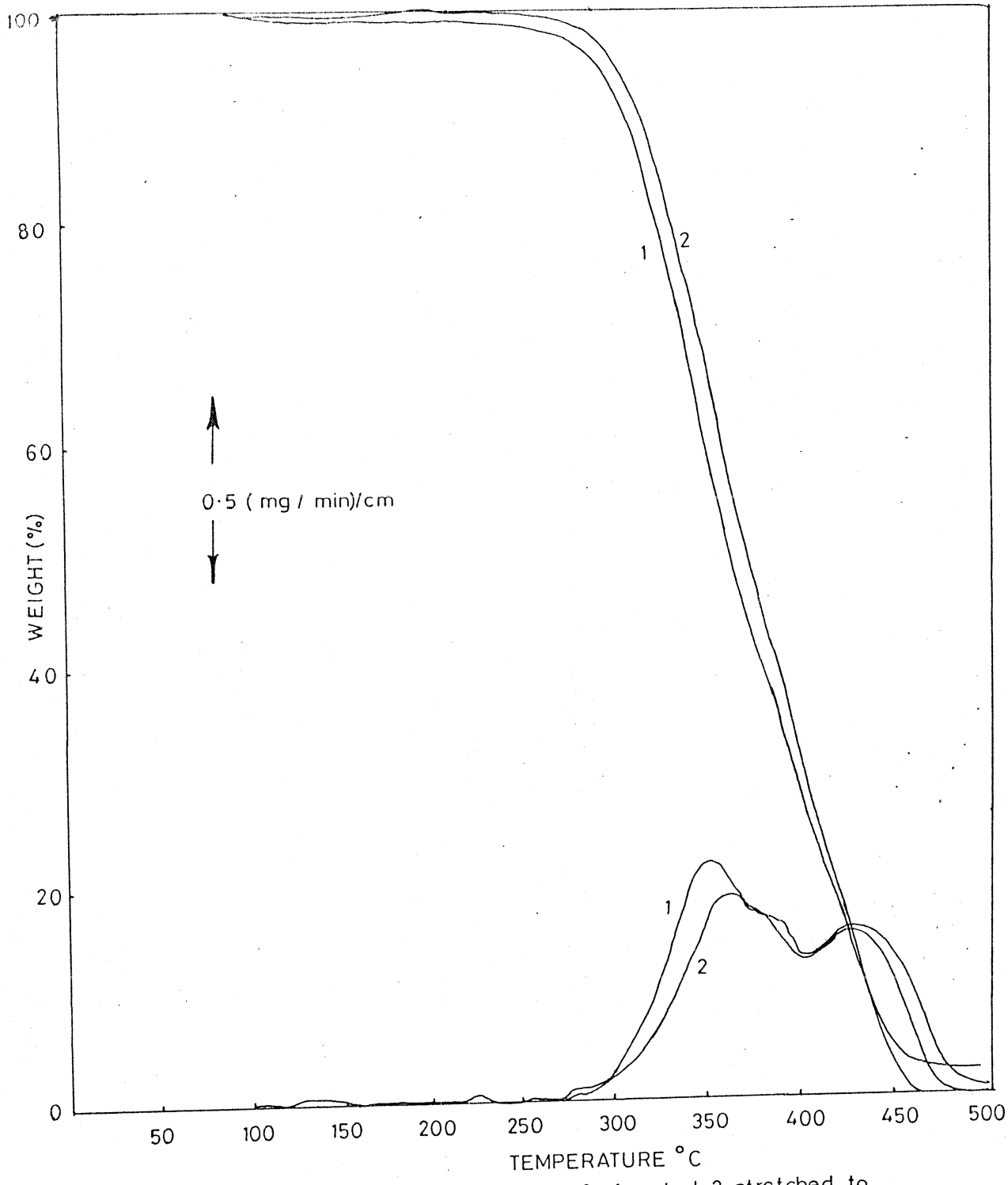


Fig. 4 -12. Typical TGA Thermograms of PU-2 1.control, 2. stretched to 480 % elongation.

TABLE 4.VI

EFFECT OF ROOM TEMPERATURE STRETCHING ON THE THERMAL STABILITY OF THE POLYURETHANES

Polymer	Hard segment content (wt%)	Extent of stretching (%)	50% Dissociation Temperature		Delta T
			Control(T_1)	Stretched(T_2)	($T_2 - T_1$)
PU-1	23	600	400	406	6
PU-2	33	480	378	392	14
PU-3	47	450	360	383	23

adjacent molecules are parallel forming a two dimensional array, which certainly favours a higher thermal stability.

The results emerged out from the four independent techniques apparently show morphological changes induced by room temperature stretching. WAXD studies suggest ordering in hard segment at relatively low elongation. At higher elongation, hard segment domains disrupt leading to an enhanced phase mixing. Subsequently soft segment retain orientation which is more in materials having higher hard segment content. DSC and Polarized microscopic techniques indicate more phase mixing. TGA reflecting higher thermal stability show better stabilization presumably by the formation of more hydrogen bonds.

4.1.3
CHARACTERISATION OF GRAFT COPOLYMERS OF POLYURETHANE

Segmented polyurethane, in different forms, is one of the extensively used material for blood contacting devices. Most of the favourable properties of these materials are considered due to the formation of microphase separated structure arising from the clustering of hard and soft segment domains into different entities. In spite of the several inherited desirable properties, chemical modifications of polyurethanes, with an aim to functionalize their specificity further towards blood compatibility have been the subject of numerous studies (90-97). The behaviour of such modified materials in harsh biological environment has also been studied (7,117,193) extensively. However, all these studies have not thrown much light regarding the diffusion and absorption of lipids which are abundant in blood. With an aim to understand the problem of lipid absorption in graft copolymers of polyurethanes, different graft copolymers consisting of hydrophilic as well as hydrophobic moieties were synthesized and the efforts to characterize these materials are sketched in the following sections.

4.1.3.1. Characterization of hydrophilic grafts.

Poly(urethane-g-HEMA).

Typical infrared spectrum of Poly(urethane-g-HEMA) is shown in figure 4.13. The spectrum shows peaks centered around 3500 Cm^{-1} and 900 cm^{-1}, characteristic of grafted Poly(HEMA).

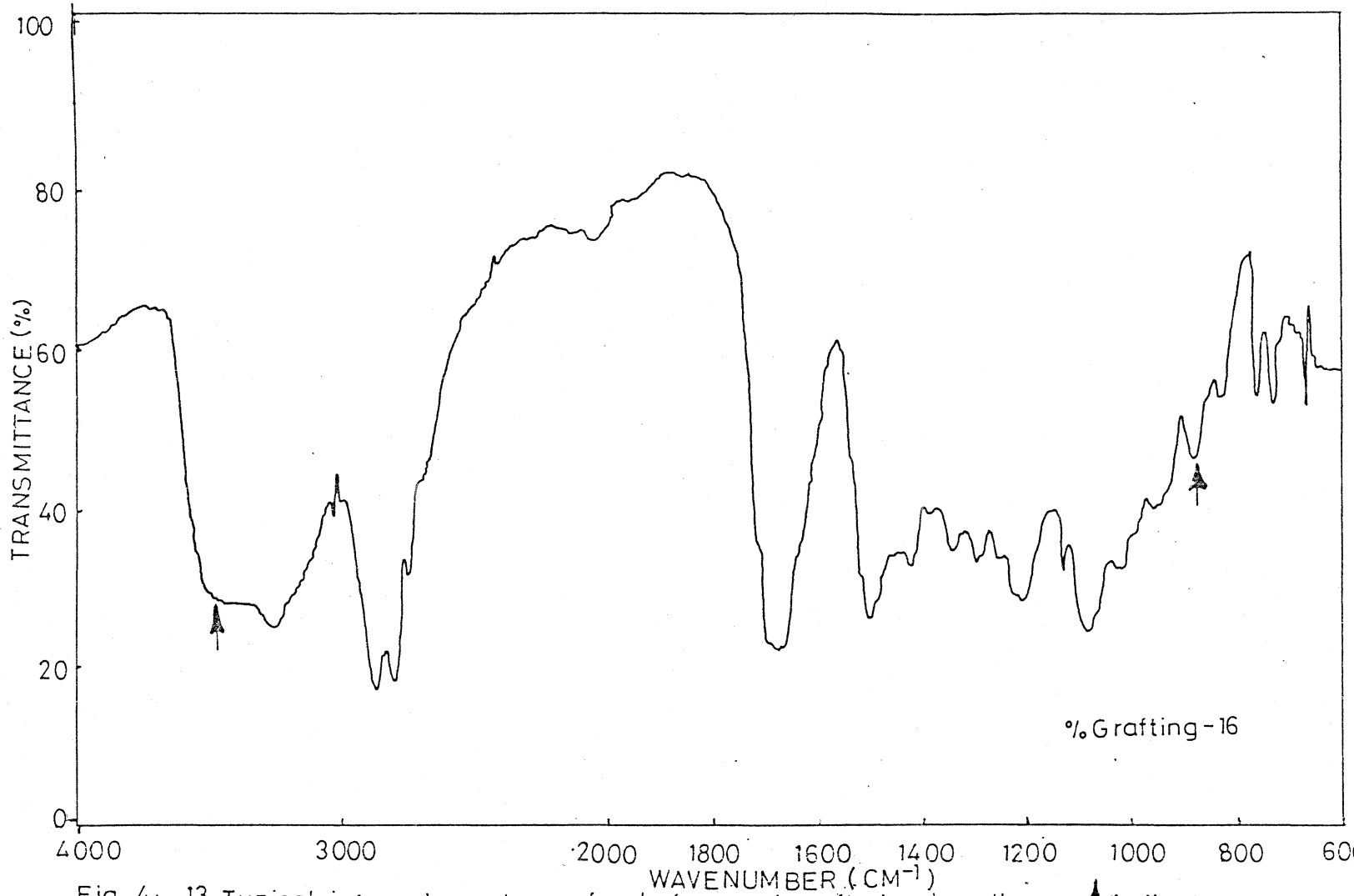


Fig 4 – 13. Typical infrared spectrum of poly (HEMA) grafted polyurethane, ↑ indicates characteristic absorption peaks of grafted poly(HEMA) chains

SEM microphotographs of homo and Poly(HEMA) grafted polyurethane, are shown in figure 4.14. When the homo polyurethane is viewed, the surface appeared to be smooth (A). When Poly(HEMA) is grafted the surface gets altered and seems that the grafted species are localized (B). However, as the % grafting increases, the whole surface is spreaded with the grafted Poly(HEMA) chains (C). Table 4.VII provides the under water air bubble contact angle of ungrafted and grafted polymers with increased percentage of grafting. The decrease in contact angle with the increase in % grafting indicates the enhanced hydrophilicity of the graft or in other words the contact angle values further suggest the grafting of Poly(HEMA) onto polyurethane.

It seems that the grafting is taking place at the soft segments. This conclusion is tentatively arrived by performing the grafting studies in 100% hard segment polymer (H_{12}MDI/BD). The material is found to be impermeable to HEMA(Table.4.VIII). Both ATR-IR and SEM techniques further confirmed the absence of grafting on 100% hard segment polymer.

The ultimate mechanical parameters of the Poly(HEMA) graft polyurethanes are shown in Table 4.IX. The ultimate strain is considerably reduced in the grafts. The flexibility of polyurethanes, as is known, is arising from the soft segments. The reduction in strain with % grafting reflects the confinement of grafting to the soft segment as mentioned in the previous

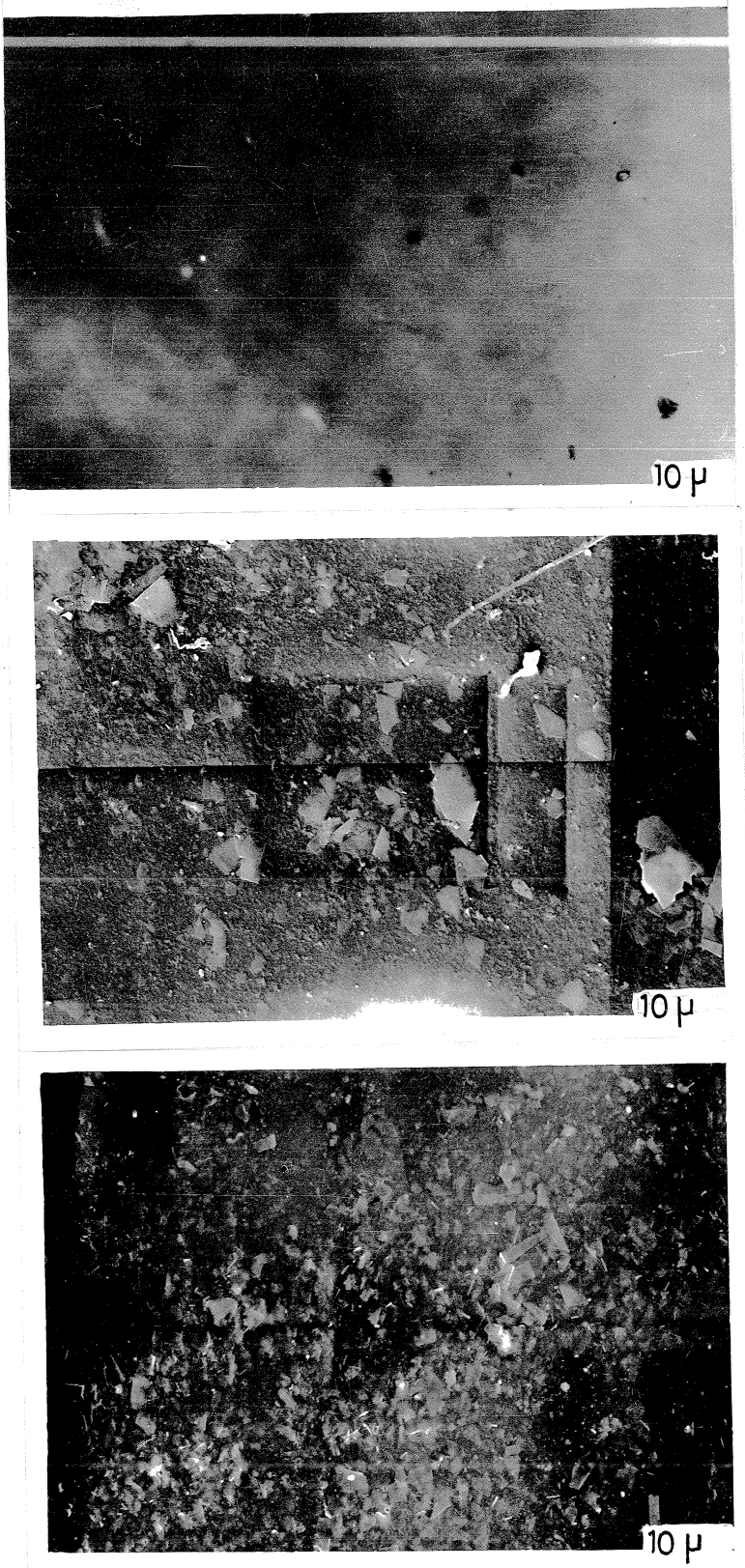


Fig.4.14. SEM micrographs of A-polyurethane (PU-2) control, B-PHEMA grafted PU (grafting-4%) and C-PHEMA grafted PU (grafting-12%). Original magnification 1000X

TABLE 4.IX

EFFECT OF POLY(HEMA) GRAFTING ON THE ULTIMATE STRESS - STRAIN PARAMETERS OF THE POLYURETHANES

Polymer	Grafting	Stress(MPa)	Strain(%)
PU-1	0	39.0±0.8	690±16
	4.5	33.5±0.6	635±21
	16	26.5±1.2	525±16
	23	19.5±0.9	450±11
PU-2	0	44.5±1.2	498±13
	4	40.5±0.7	440±17
	12	36.0±1.1	310±4
	16.5	29.0±0.9	280±16
PU-3	0	57.8±1.4	456±9
	3.3	55.0±1.1	390±6
	6.5	49.5±0.7	325±16

TABLE.4.V111

EFFECT OF HARD SEGMENT CONTENT ON THE UPTAKE OF MONOMER

Polymer	Weight % HS	% absorption*
PU-1	23	51
PU-2	33	39
PU-3	47	16
PU-5	100	0

* Exposed to 30 miniutes.

paragraph. The reduction in ultimate stress and strain,as reported in previous works (117) may be a manifestation of morphological changes induced by grafting. The probabilities of soft segment orientation along the direction of stress and stress-induced soft segment crystallinity have been stated to be additional factors deciding the ultimate mechanical parameters (176) The grafting of Poly(HEMA) chains, particularly to the soft segments, certainly affect these factors resulting in a gross reduction of mechanical properties.The interaction among the domains could also be affected by the grafting process. The solubility parameter of Poly(HEMA) is substantially higher [11.6(Calcm^{-3})$^{1/2}$] than the soft segment [8.7(Calcm^{-3})$^{1/2}$] and the subsequent thermodynamic incompatibility rules out the segmental miscibility leading to the formation of a homogeneous phase

which would also affect the mechanical properties. The thermal stability of the graft copolymer, as apparent from the TGA traces(figure 4.15) is higher than the homo polyurethane. The grafted Poly(HEMA) chains increase the rigidity of the polymer. To increase the segmental mobility leading to a reduction of the cohesiveness of polymer chains and subsequently to the dissociation need more thermal energy. All these factors namely, the decrease in cohesiveness among the domains, reduction in flexibility of the soft segments resulted by the introduction of Poly(HEMA) chain to the backbone, the thermodynamic incompatibility and the interference of the grafted chains in the orientation of the soft segment chains under stress,are responsible to reduce the ultimate mechanical properties of the graft copolymers.

Poly(urethane-g-NVP) grafts.

Figure 4.16 illustrates GPC traces of homo polyurethane and NVP grafted polyurethane. The shift to the lower time scale of the graft sample, indicates a higher molecular weight or in other words the GPC analysis confirms the grafting process. The infrared spectrum of the graft copolymer recorded as thin film between sodium chloride windows, is shown in figure 4.17. The peak centered around 1670 cm^{-1} arising from the -C=O stretching mode of P(VP) branches, further shows the grafting of NVP onto polyurethane. The peak at 1702 cm^{-1} is due to the -C=O groups of

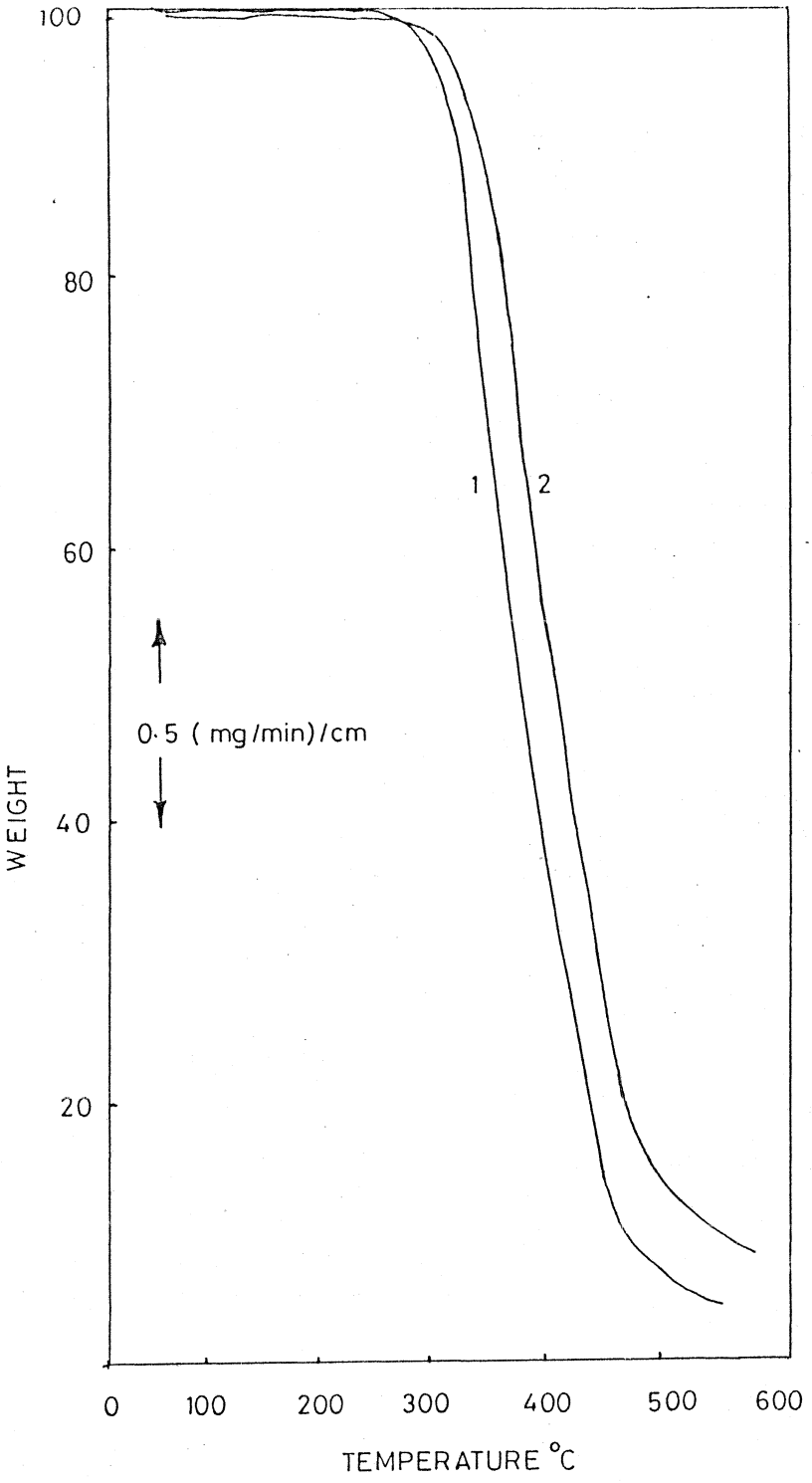


Fig. 4 – 15. Typical TGA thermogram for
1-Polyurethane (PU-2) and
2-Poly (HEMA) grafted PU-2 (% grafting ~16)

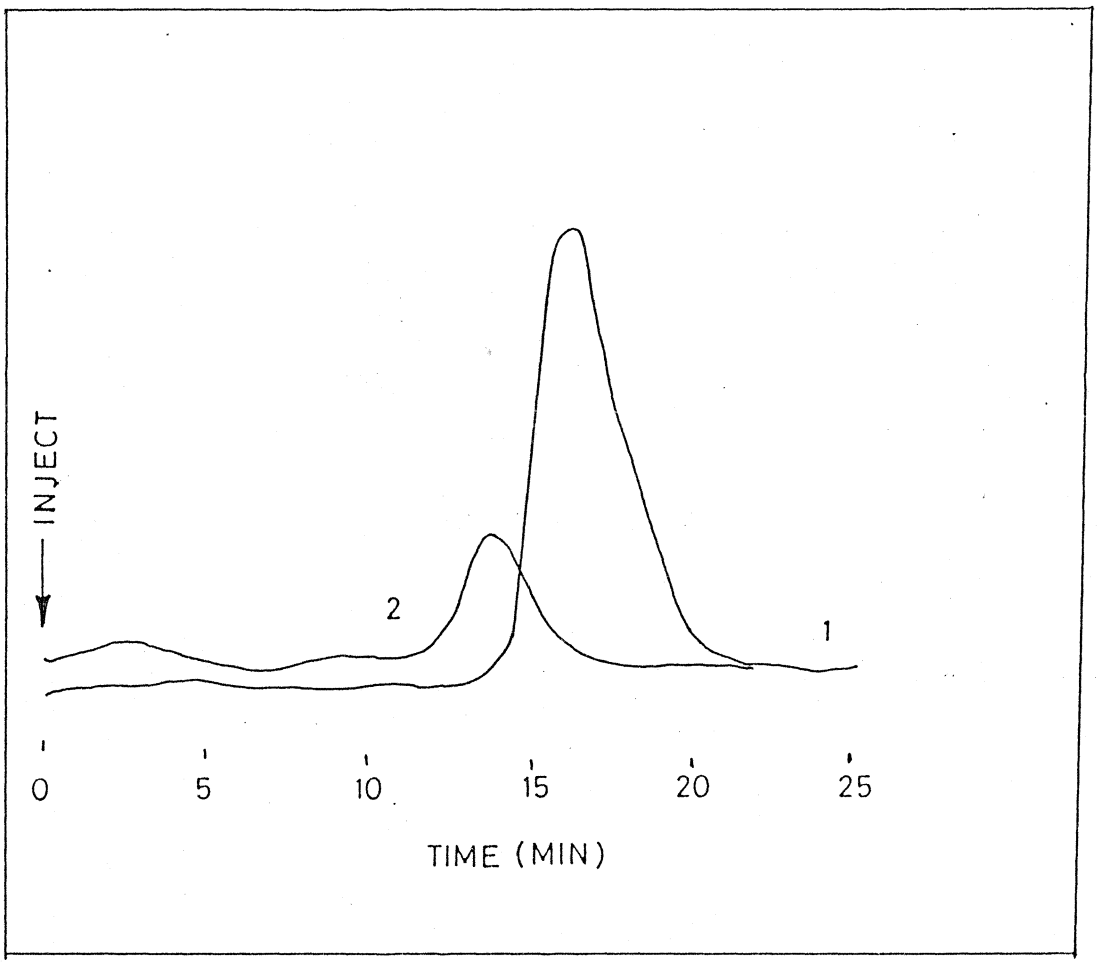


Fig. 4 - 16. Representative GPC traces of (1) PU-2 and (2) Poly (VP) grafted PU-2 (% grafting -29)

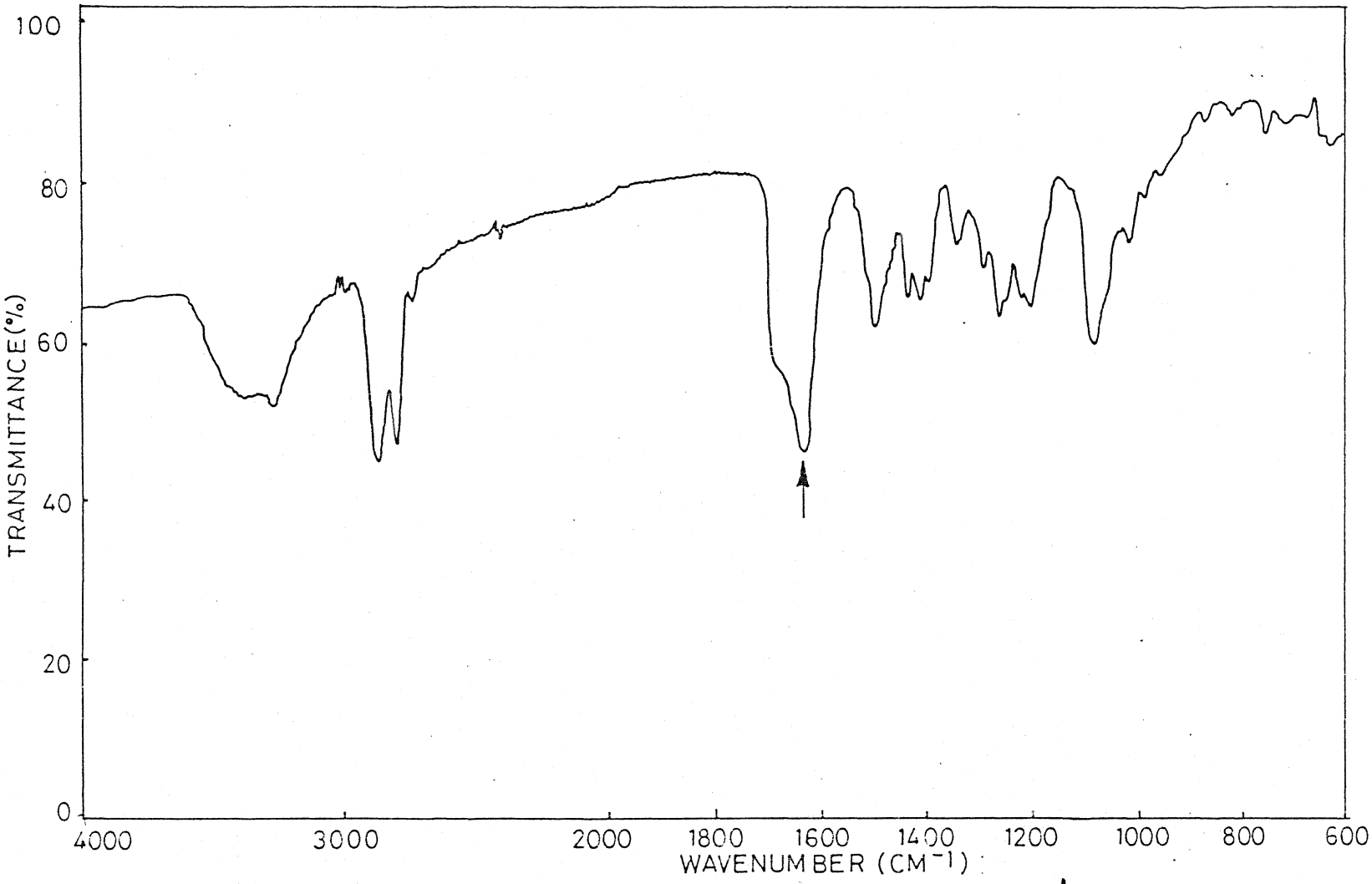


Fig. 4 - 17. Infrared spectrum of poly (VP) grafted polyurethane (PU-2), ↑ indicates characteristics absorption peak of grafted poly (VP) chains (% grafting - 23)

polyurethane. Typical TGA traces for the graft copolymer together with a homo polyurethane sample are illustrated in figure 4.18. The P(VP) graft registered an enhanced thermal stability. The shielding of the -NH-CO-O-groups by graft ends forming hydrogen bonds between the backbone and -C=O groups in the grafts has been assumed for the increased thermal stability (121).

4.1.3.2. Characterization of hydrophobic graft copolymers of polyurethanes:

Though polyurethane grafted with typical hydrophobic species for improving the biocompatibility are uncommon in the literature, these studies are undertaken to know how diffusion and absorption of lipids are effected in polyurethane matrix enriched with hydrophobic grafted components. With this aim, graft copolymers of PBA, PMA and PMMA with polyurethanes are synthesized. Characterization of these materials are attempted in the following paragraphs.

Poly(urethane-g-BA).

Infrared specturm of PBA-g-PU is shown in figure 4.19. By comparing the spectra of homo PBA and PU, the peaks at 1720 cm^{-1} and 1420 cm^{-1} are assigned to the grafted PBA branches. The -C=O absorption of polyurethane is centered around 1700 cm^{-1} as a separate peak. The typical GPC traces of polyurethane and a graft sample are depicted in figure 4.20. The graft polymer elutes at lower time scale indicating higher molecular weight resulted by

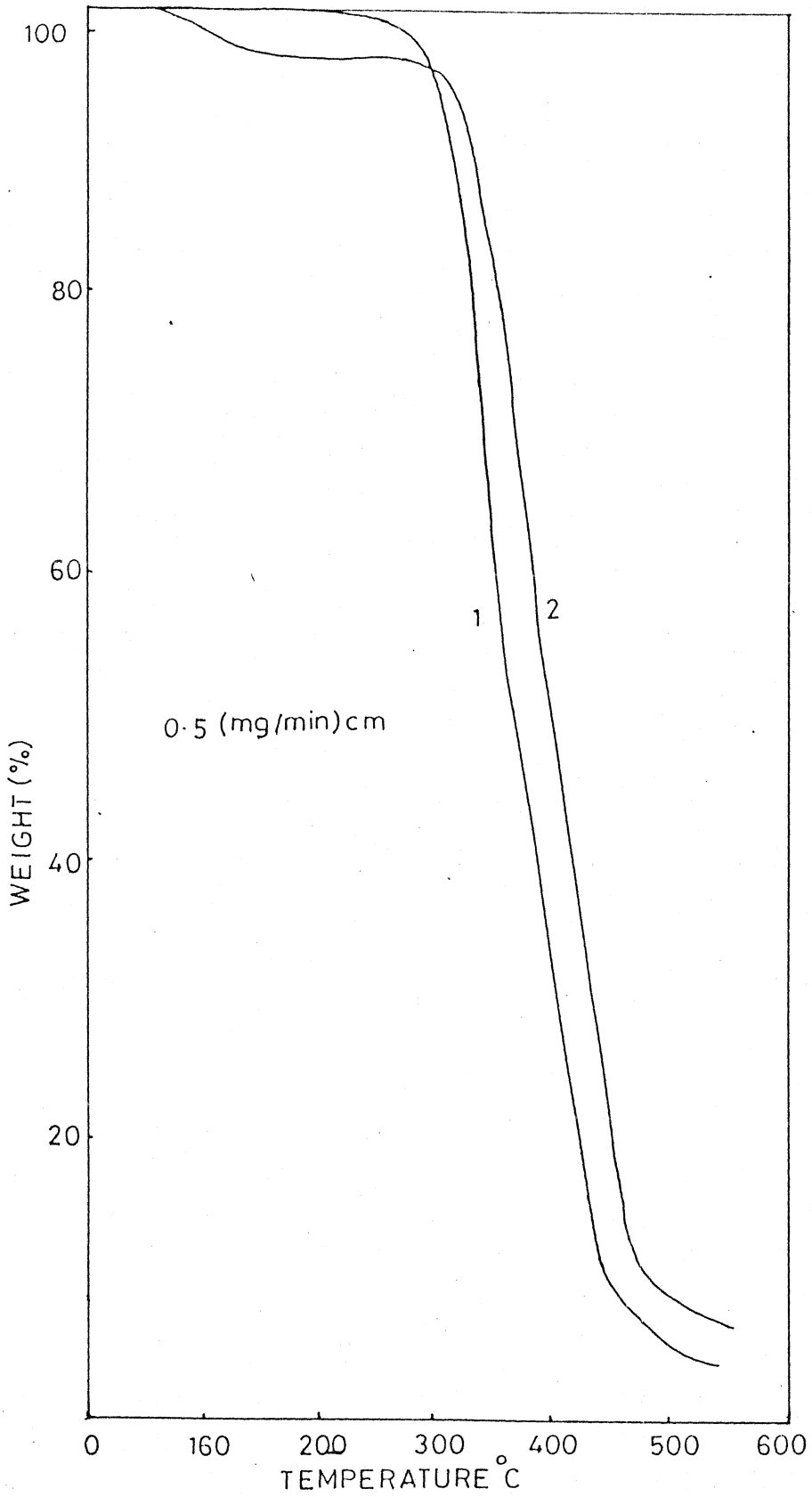


Fig. 4 – 18. TGA thermogram for 1. Polyurethane (PU-2)
2. Poly (VP) grafted PU-2 (% grafting – 29)

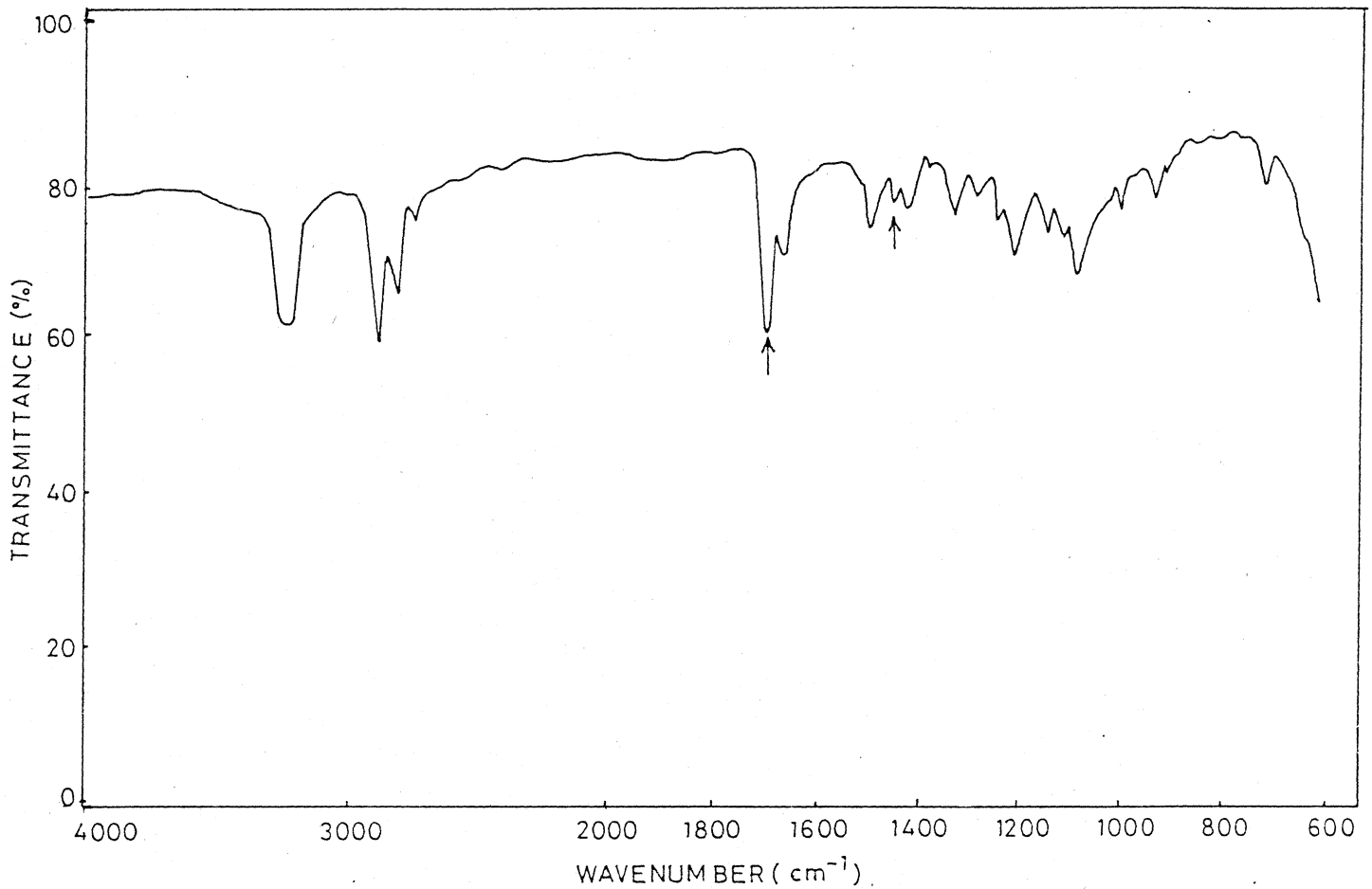
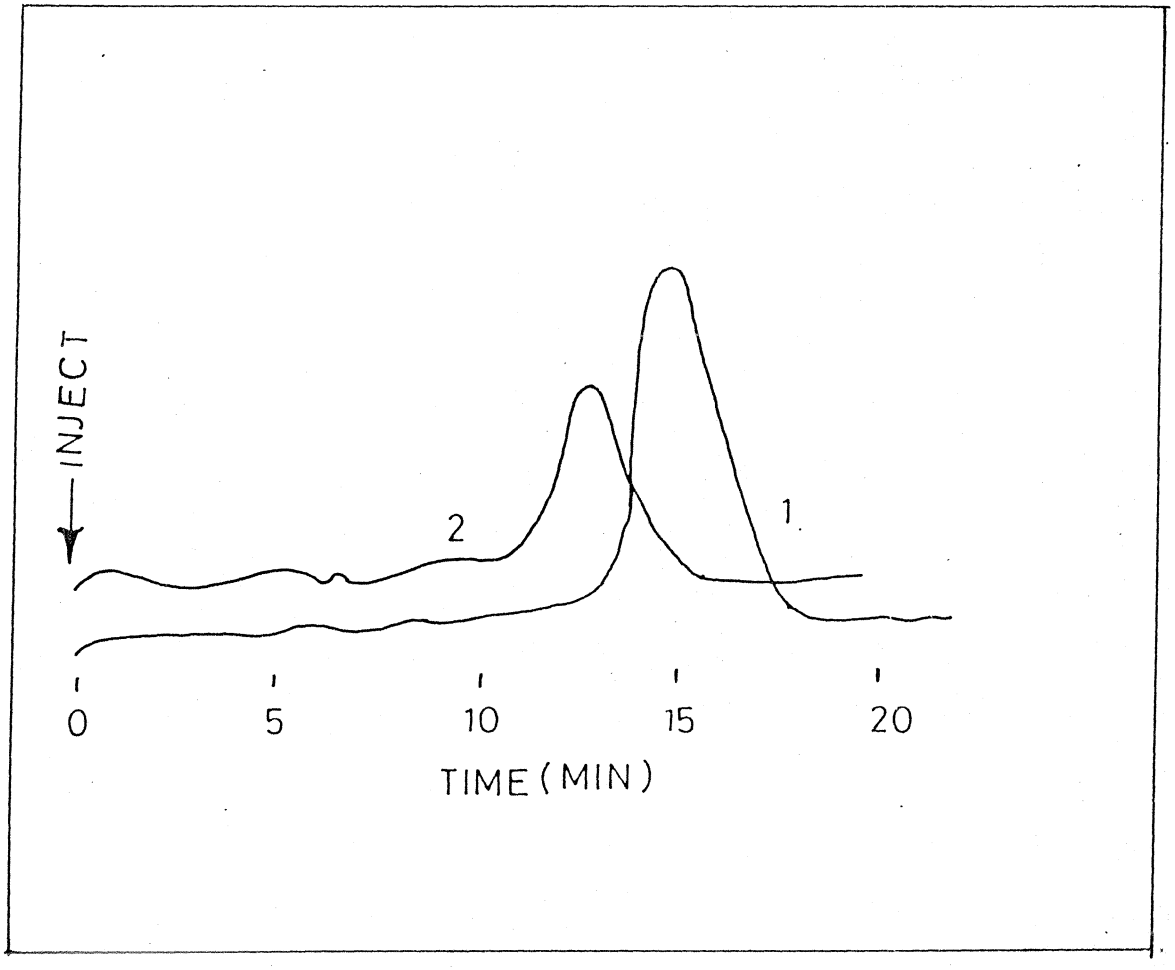


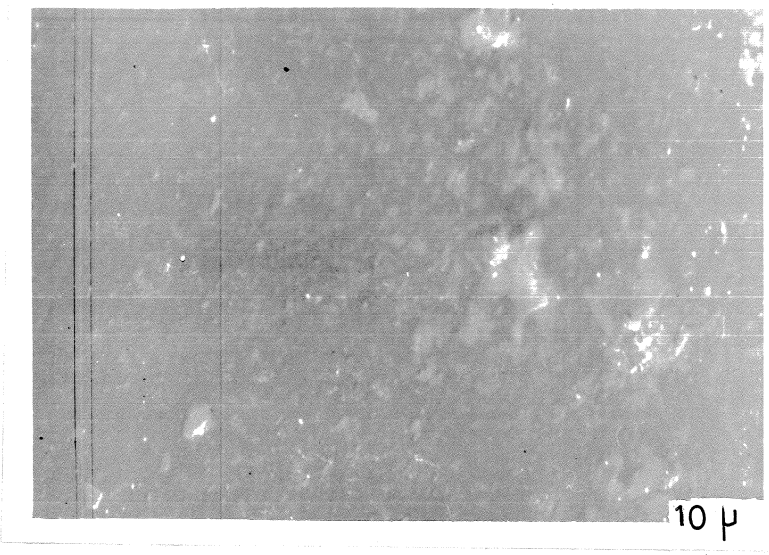
Fig. 4 – 19. Infrared spectra of poly(n-butyl acrylate)grafted polyurethane
↑ indicates characteristic peaks of grafted poly n-butyl acrylate chains (% grafting - 21)



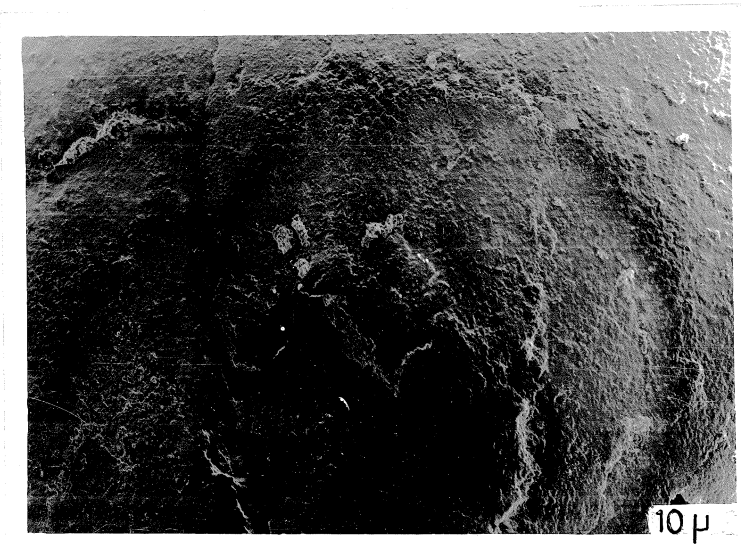
Fig·4 – 20. GPC traces of 1. PU-2
2. Poly (n-butyl acrylate) grafted PU-2 (% grafting-36)

grafting. The surface morphology of the grafts visualized by SEM are shown in figure 4.21. The altered surface resulted by grafting is evident from the SEM analysis. The under water air bubble contact angle values of the PBA grafts are shown in Table 4.X. The graft copolymer at a low % grafting registers nearly identical or even less contact angle values of homo polyurethane. This is indeed surprising, considering the hydrophobicity of PBA which should show an enhanced contact angle. This anomaly, reflects the less concentration of hydrophobic PBA chains on the surface. The contact angle, however, increases as the % grafting increases indicating the spreading of PBA on the surface. The SEM picture (figure 4.21-A) of the graft having a low degree of grafting indicates the surface is almost simillar to that of polyurethane. The graft containing a higher extent of grafting (B) evidently show altered surface in the form of a grafted layer.

In the first case, prior to irradiation, the polymer strips are exposed to th n-butyl acrylate monomer to a shorter period and at best the monomer might have penetrated only to a few layers. Nevertheless, the concentration gradient already established drive the monomer to the bulk depleting the surface concentration. The grafting, persumably due to this, majorly take place in sub surface rather than at the surface. Internal stresses may be set up when the monomer diffuses into the polymer(194). It is to be expected that the inner, unswollen part



A



B

g.4.21. SEM micrographs of A,PBA grafted PU-2(grafting-4.2%) B, PBA graft (grafting-21%). orignal magnification 1000X

TABLE 4.X

EFFECT OF PBA GRAFTING ON THE UNDER WATER AIR BUBBLE CONTACT ANGLE OF POLYURETHANES

Polymer	Graft yield(%)	Contact angle
PU-1	0	62±1.0
	6.6	59±1.2
	34	65±0.7
PU-2	0	59±0.7
	5.4	54±0.5
	35	63±1.0
PU-3	0	57±0.5
	3.3	51±0.6
	12	58±1.0

(hard segment domains) of the polymer will exert a compression force on the outer swelling part while the swollen part will exert on the unattached region, a force which tends to expand the polymer. The polymer chains will tend to relieve these stresses by changing the conformation. That is, a reorganization would be possible pushing the unswollen hard segment domains to the surface resulting in a slight enhancement of surface polarity. The observed results on contact angle value, and the SEM could be traced to these possibilities. At a substantially high degree of swelling, the monomer is distributed nearly uniformly through out the polymer leading to the grafting reaction both at surface and bulk. Both SEM and contact angle data again favour this situation. The ultimate mechanical parameters of the graft copolymers are summarized in Table 4.X1. The reduction in ultimate stress, unlike in Poly(HEMA) graft is rather low in PBA grafts. The relatively low reduction in stress may be traced to the structural variation of the graft copolymer in comparison with-polyurethanes, like the reduction in the interaction between the domains. The ultimate strain of graft copolymers, however, increases considerably indicating the increased flexibility upon polyurethanes. The increased strain may be a manifestation of the formation of a homogene ous phase between the soft segment and grafted PBA chains. From a thermodynamic point of view, the homogenisation is quite possible due to the closeness of the

TABLE 4.XI

ULTIMATE STRESS - STRAIN PARAMETERS OF MIXED GRAFTS

Grafted chains	PU - 1		PU - 2		PU - 3	
	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
PBA	38.7±1.1 (14%)	1060±60	39.2±.2 (12%)	725±25	52.5±1.9 (10%)	480±28
P(HEMA)	26.5±1.2 (16%)	525±16	29.0±0.9 (14%)	280±11	49.5±1.1 (6.3%)	335±7
PBA+PHEMA	27.8±1.2 (23%)	740±25	34.2±1.4 (26%)	515±22	40.0±1.6 (12.3%)	380±14

The values in brackets is the % grafting of respective samples

solubility parameters of soft segment [8.7(Calcm^{-3})$^{1/2}$] and PBA chains [8.8(Calcm^{-3})$^{1/2}$].

Poly (urethane-g-PMA).

The grafting of MA onto polyurethanes is confirmed by different methods already used to characterize other grafts. In comparsion with PBA grafts, the mechanical properties of PMA grafts (Table.4.X11) show some interesting aspects. The ultimate % strain is higher than the homo poyurethanes. The ultimate stress is, however, lesser than that of the trunk polymer (polyurethane). It seems that, the change in mechanical properties of PMA grafts can be compared with that of a rubber toughened brittle polymer. In a typical rubber toughening procedure, rubber particles are dispersed in a brittle polymer. The elongation at break of the material by this process increases from about 3% to over 40%, subsequently showing a reduction in stress and an increase in tougheness (195). The Young's modulus of the rubber particle is several orders of magnitude lesser than that of the matrix. This leads to a stress concentration arround the particles and shear yielding or crazing throughout a large volume of the material rather than just at the crack tip and hence the polymer absorbs more energy during deformation resulting in improved toughness, though showing a reduction in the ultimate stress.

Poly(urethane-MMA graft).

Comparing to PBA and PMA, PMMA is glassy at ambient temperature and morphologically PMMA grafts would be different from the other two hydrophobic grafts. The IR spectrum and GPC traces of graft copolymer are illustrated in figures 4.22 and

TABLE-4-X11

EFFECT OF PMA GRAFTING ON THE STRESS-STRAIN PARAMETERS OF POLYURETHANE

Polymer	% Grafting	Stress(Mpa)	Strain(%)
PU-1	0	39.0 ±.80	690±16
	17.4	31.0 ±.12	750±21
PU-2	0	44.5 ±.11	498±13
	16.8	34.6 ±.90	610±22
PU-3	0	57.8 ±.14	456±09
	16.6	44.6 ±.16	548±18

4.23 respectively. The characteristic absorption peaks of PMMA are around 1145 cm^{-1} and 740 cm^{-1} (196). The other characteristic -C=O bands are, however, merged with the peaks of polyurethanes, more or less in the same regions The peaks at 1145 CM^{-1} and 740 CM^{-1} indicate the grafting of MMA onto PU. The peak around 1700 cm^{-1} broadended due to the mixing of the absorption peaks of the two polymers. The GPC analysis conclusively confirms the grafting

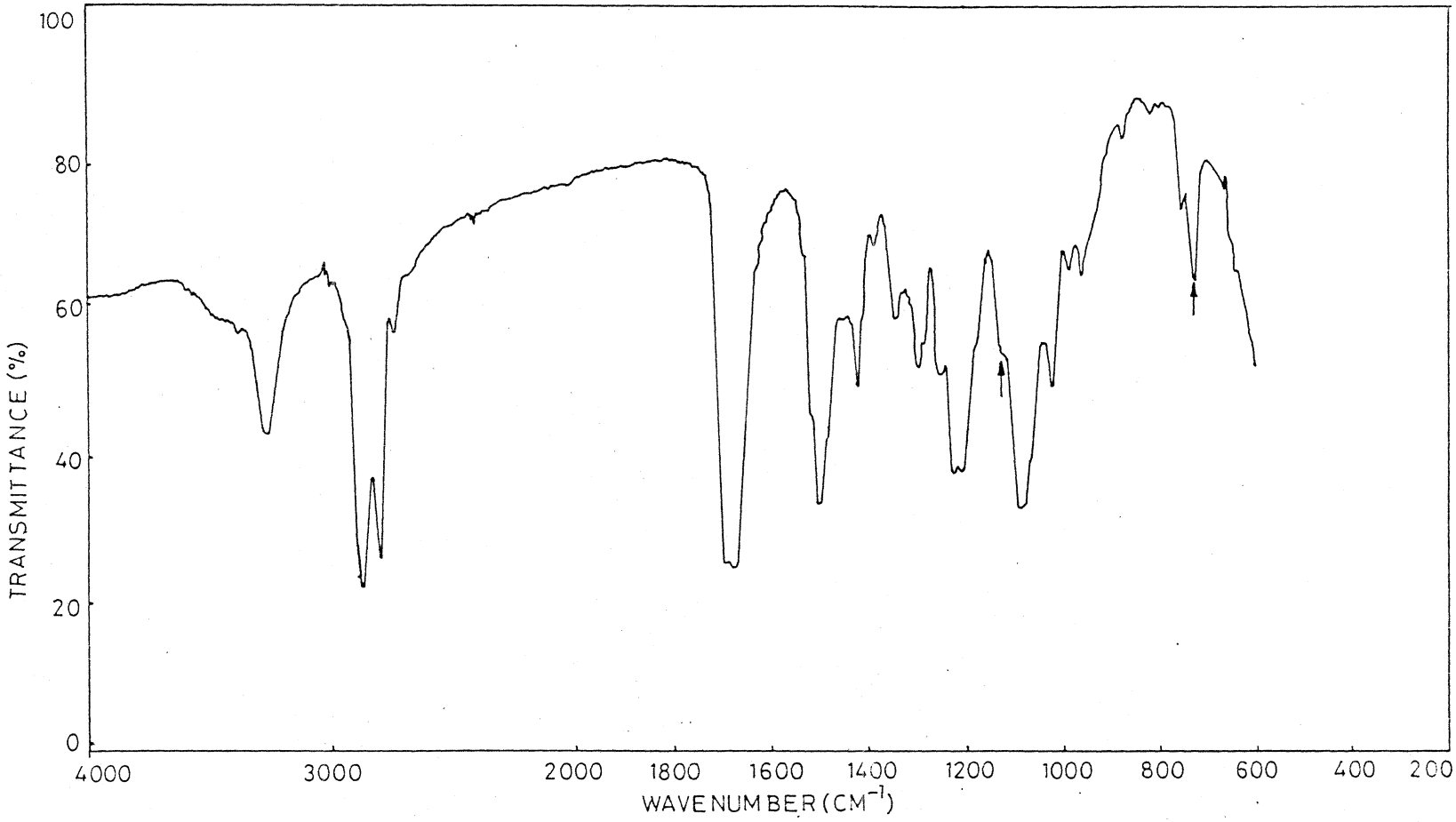


Fig. 4 - 22. Infrared spectrum of poly methyl methacrylate grafted polyurethane (% grafing - 40)
↑ indicates characteristic peaks of grafted PMMA chains

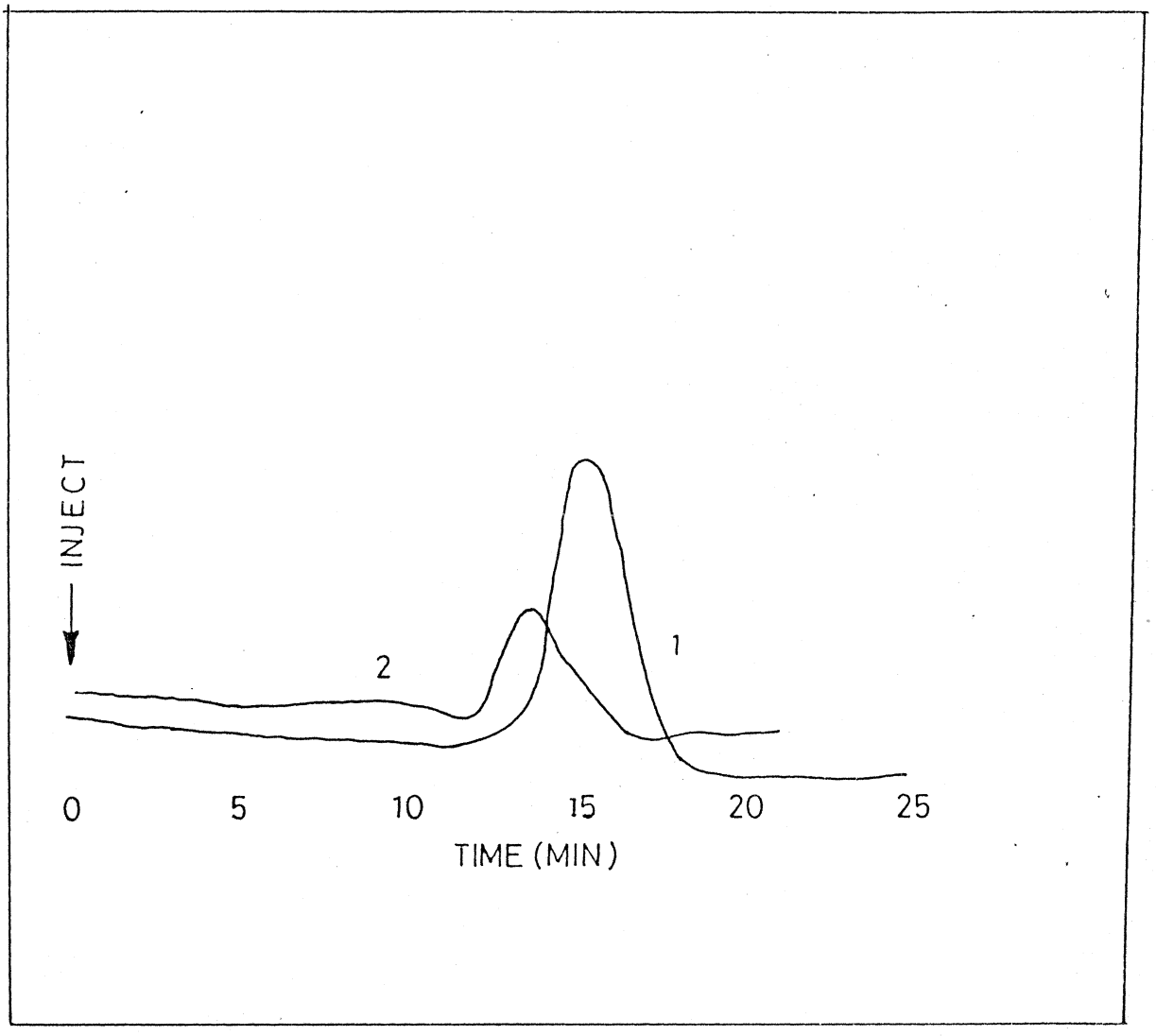


Fig. 4 - 23. GPC traces of 1. PU-2
2. PMMA grafted PU-2 (% grafing-40)

process since the GPC trace of graft copolymer shifted to lower time scale favouring higher molecular weight. Distinctively the altered surface resulted by grafting is evident in the SEM (figure 4.24). The grafted PMMA chains in the form of clusters almost cover the entire surface.

Binary Graft:[Poly(urethane-g-HEMA/BA).

To date most of the studies of chemical modification of polyurethane by grafting have been restricted to a single hydrophilic monomers(97,117-120). Grafting from a binary mixture consisting of two types of functionally different monomers could be beneficial because of a large spectrum of properties. To understand the absorption of lipids in graft copolymers consisting of two different entities with independent hydrophobic and hydrophilic chains, binary grafts of polyurethane are synthesized by grafting n-butyl acrylate and HEMA simultaneously from a mixture. The efforts to characterize these grafts are traced in the following paragraphs.

Figure 4.25 shows the infrared spectrum of the isolated graft containing both PBA and Poly(HEMA) chains. The peak centered around 3500 cm^{-1} is assigned to the grafted Poly(HEMA) chains. The grafting of PBA is confirmed by the presence of two characteristic peaks of PBA chains at around 1720 cm^{-1} and 1420 cm^{-1} respectively. The -C=O absorption peak of polyurethane appears around 1700 cm^{-1}.

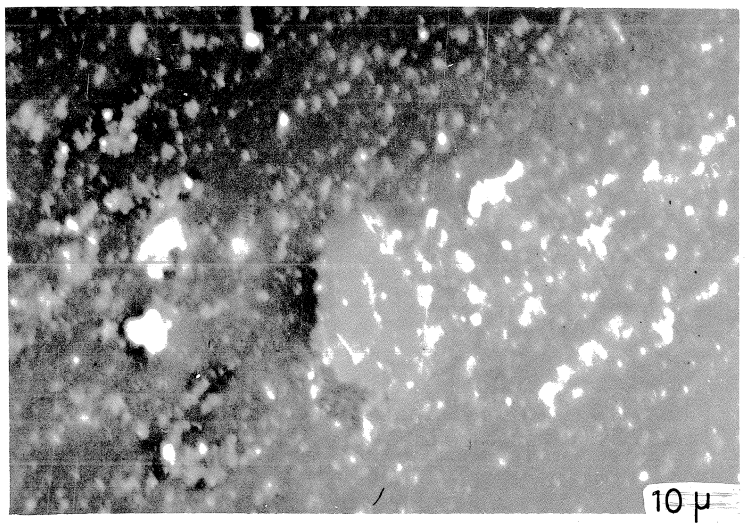


Fig.4.24. SEM micrograph of PMMA grafted PU-2 (grafting-16%).
Original magnification 1000X

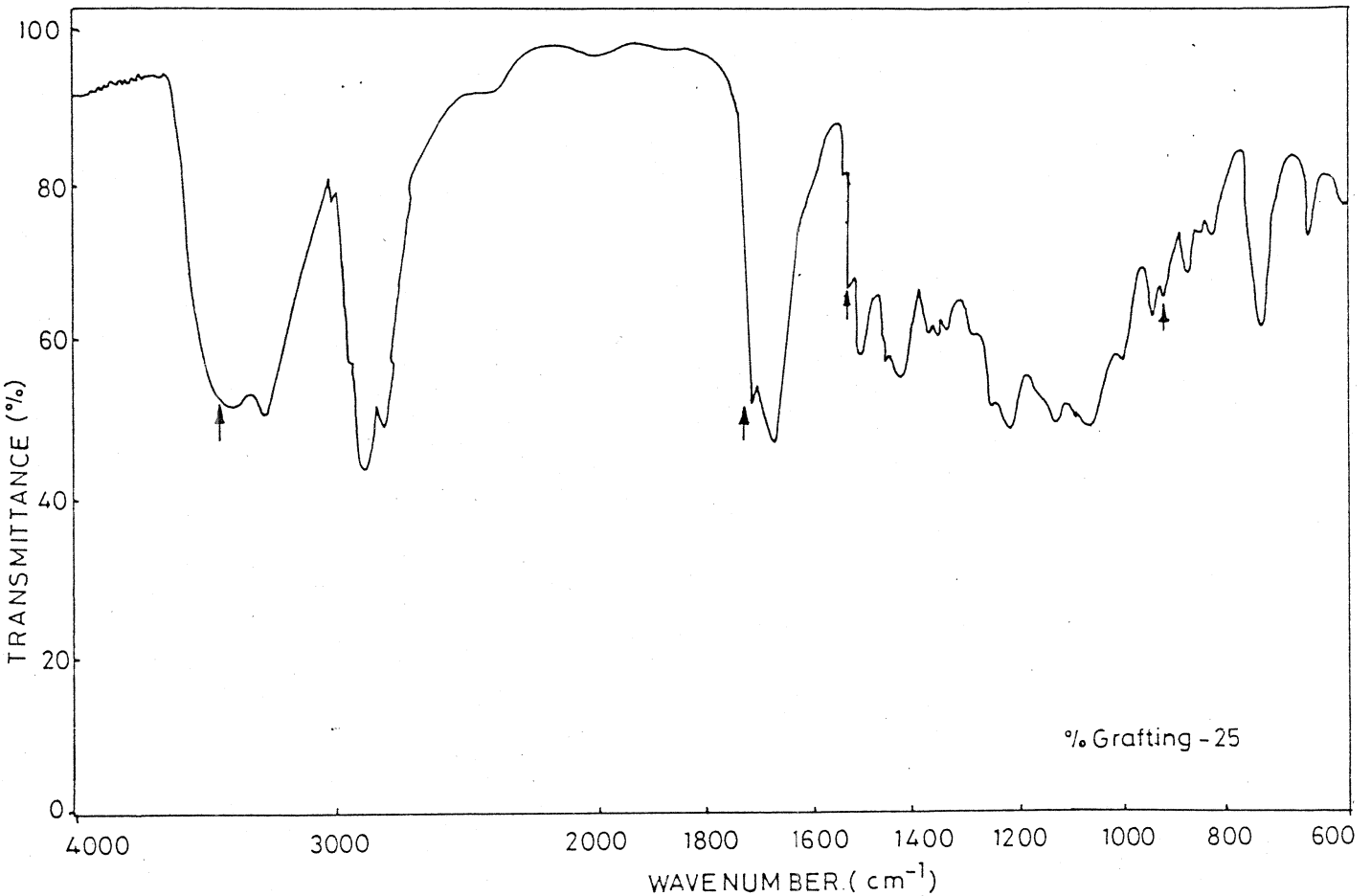


Fig. 4 – 25. Infrared spectrum of polyurethane (PU-2) grafted with poly (HEMA) and poly butyl acrylate, ↑ indicates characteristics peaks grafted species.

The SEM microphotograph of the binary graft is shown in figure 4.26. The SEM microphotographs of Poly(HEMA) grafts and PBA grafts are shown in figures 4.14 and 4.21 respectively. The binary graft shows uniformly distributed thick bunches. In comparison, however, the surface roughly resembles to that of Poly(HEMA) grafted surface. This observation probably can be deduced as; Poly(HEMA) is mainly responsible for the surface modification while PBA is grafted to a large extent in bulk when grafting is carried out from the mixture of these two. The BA monomer, presumably due to its better thermodynamic interaction with the soft segment, rapidly move into bulk. This aspect, based on solubility parameter concept, has already been discussed in section 4.1.3.2. The swelling of the polymer prior to grafting when carried out from the mixture of these two monomers, BA monomer preferably move to the bulk while the hydrophilic HEMA prefers the surface.

The underwater air bubble contact angle data summarized in Table 4.XIII further points out this possibility. The contact angle value of the mixed graft decreases, with increase in % grafting, indicating increased concentration of Poly(HEMA) chains on the surface. The angle would have increased if the surface contain more PBA chains.

The ultimate mechanical parameters of the binary grafts are summarized in Table 4.XI. One noticeable difference between the

Fig.4.26. SEM micrograph of PU-2 grafted with PHEMA and PBA (grafting-22%). Original magnification 1000X

TABLE 4.XIII

VARIATION OF UNDER WATER AIR BUBBLE CONTACT ANGLE IN MIXED GRAFTS

Polymer	Grafting (%)	Contact angle (O)
PU-1	0	62±1.0
	15	49±0.7
	33	47±1.1
PU-2	0	59±0.7
	10	51±0.3
	25	46±1.0
PU-3	0	57±0.5
	6	44±1.0
	12	41±0.6

Poly(HEMA) grafts and the mixed graft, is the less reduction of ultimate mechanical parameters in the mixed graft. The influence of flexible PBA chains can be seen in the ultimate strain of the mixed grafts. The % strain is higher than the Poly(HEMA) grafted polymers.

Graft copolymers having functionally varied components with a distinctively altered morphology from polyurethane may provide interesting insights into the process of absorption and diffusion of lipids. Generalization in terms of the characteristics of the graft copolymers and lipid absorption is also expected.

SECTION 4.2

DIFFUSION IN POLYURETHANES

4.2.1
DIFFUSION IN
LINEAR SEGMENTED POLYURETHANES

The effort in this section is to understand the diffusion process of lipids in connection with the morphological features of the polymers.

4.2.1.1. Probing the diffusants in the bulk of the polymers:

Figure 4.27 illustrates the infrared spectrum of the carbon tetrachloride extract of a polyurethane sample (PU-1) conditioned with silicone oil(A). The spectrum shows characteristic absorption peaks of silicone oil indicating the absorption of silicone oil by the polymer. Additionally the spectrum shows weak absorption band in the -C=O region indicating the presence of polymeric species, presumably oligomers in the extract. Figure 4.27B is the infrared spectrum of the extract versus the same extract (in the reference beam of the instrument). The spectrum looks almost like a straight line indicating a prefect balancing. In recording the infra red spectra of the diffusants extracted from the polymers, the extract of control polymer strips, kept in the silicone oil, was used the in the reference beam to cancel the absorption peaks of silicone oil and other species to avoid the interference. Typical infrared spectra of the diffusants extracted from the polyurethane (PU-2) are shown in figures 4.28, and 4.29, and 4.30 respectively. These spectra are identified as that of stearic acid, methyl palmitate, butyl oleiate, Triolein, cholestrol and cholestryl acetate which are used individually for diffusion studies. These spectra apparently confirm the diffusion

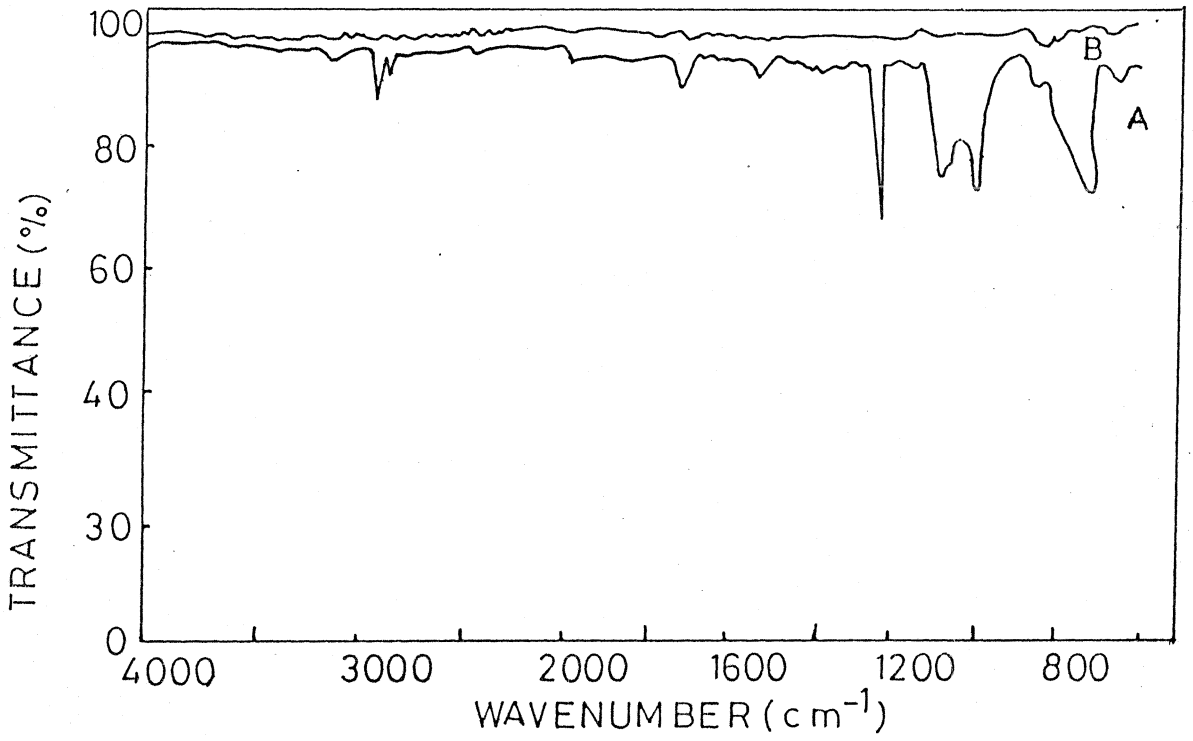
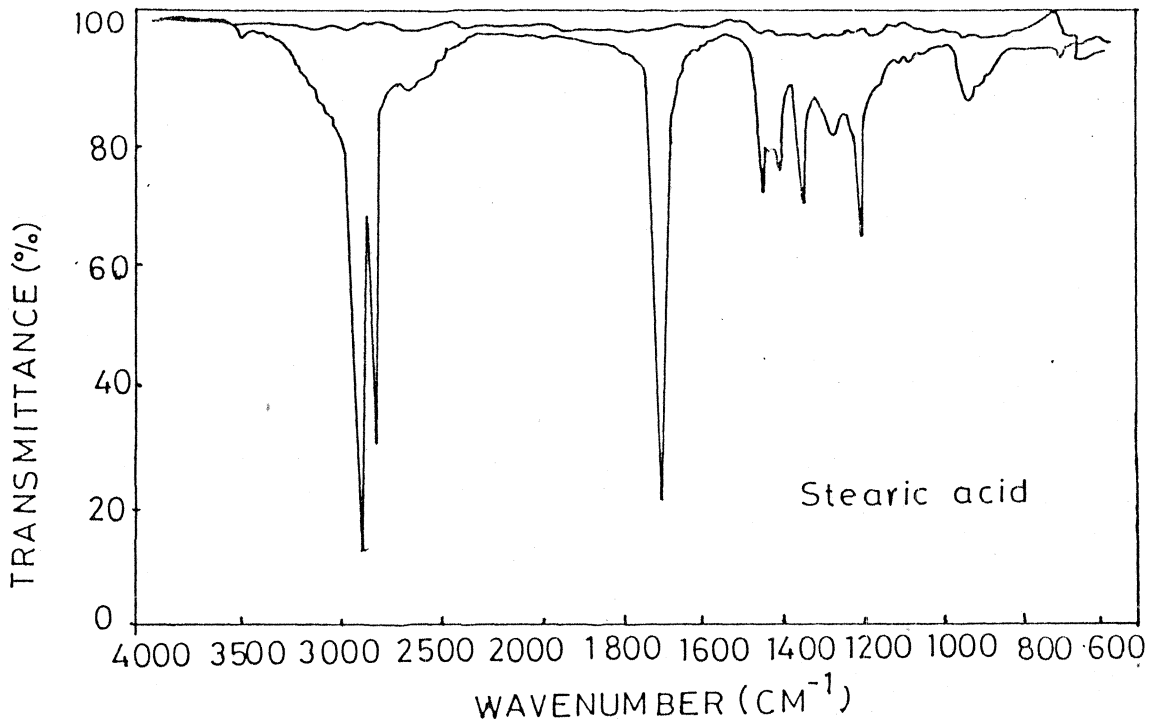


Fig 4-27 . IR Spectra of CCl_4 extract of polyurethane (PU-2) conditioned in silicone oil. A-CCl_4 extract Vs CCl_4, B-CCl_4 extract Vs same extract



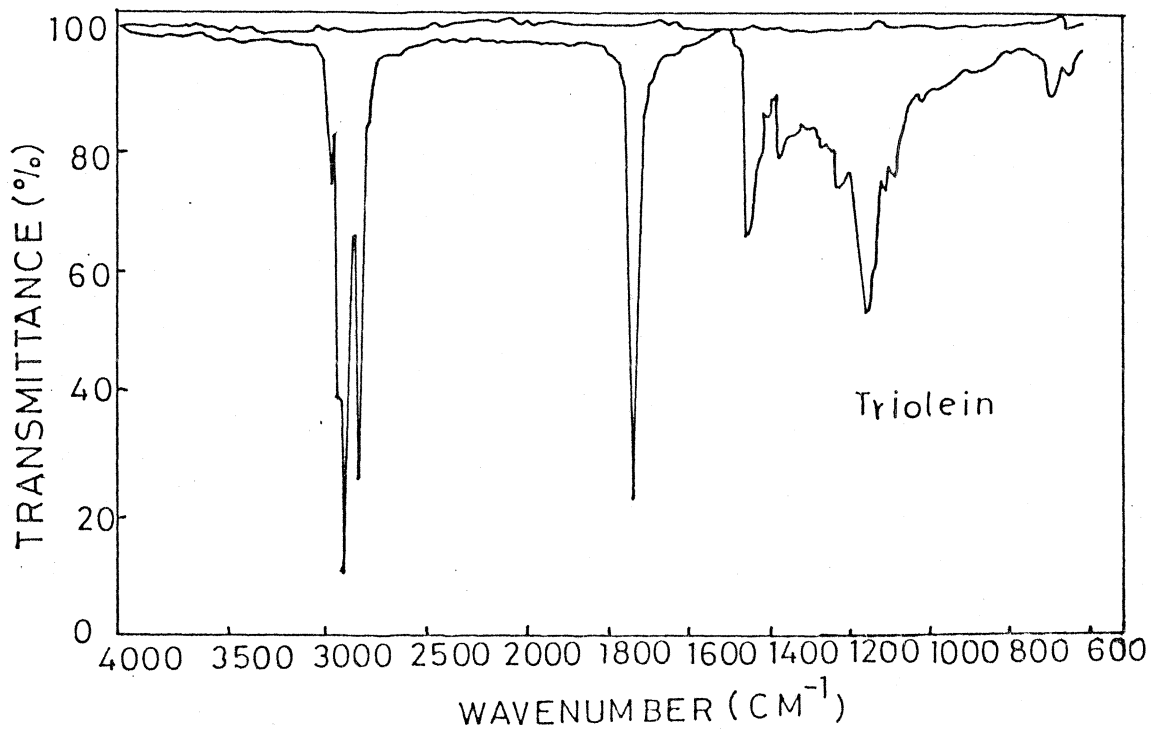


Fig.4-28. IR Spectra of diffusants extracted from PU-2

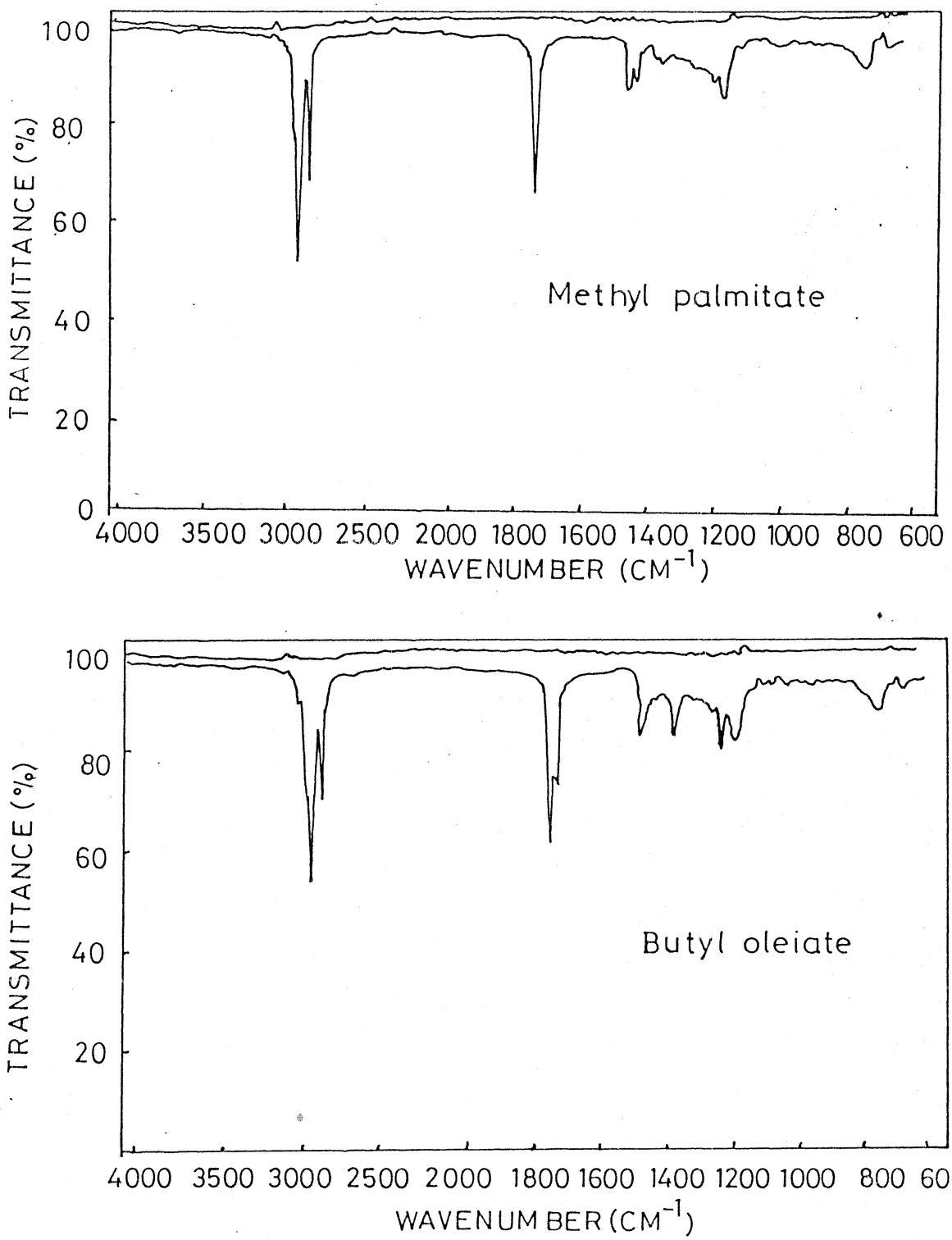


Fig. 4-29. IR spectra of diffusants extracted from PU-2

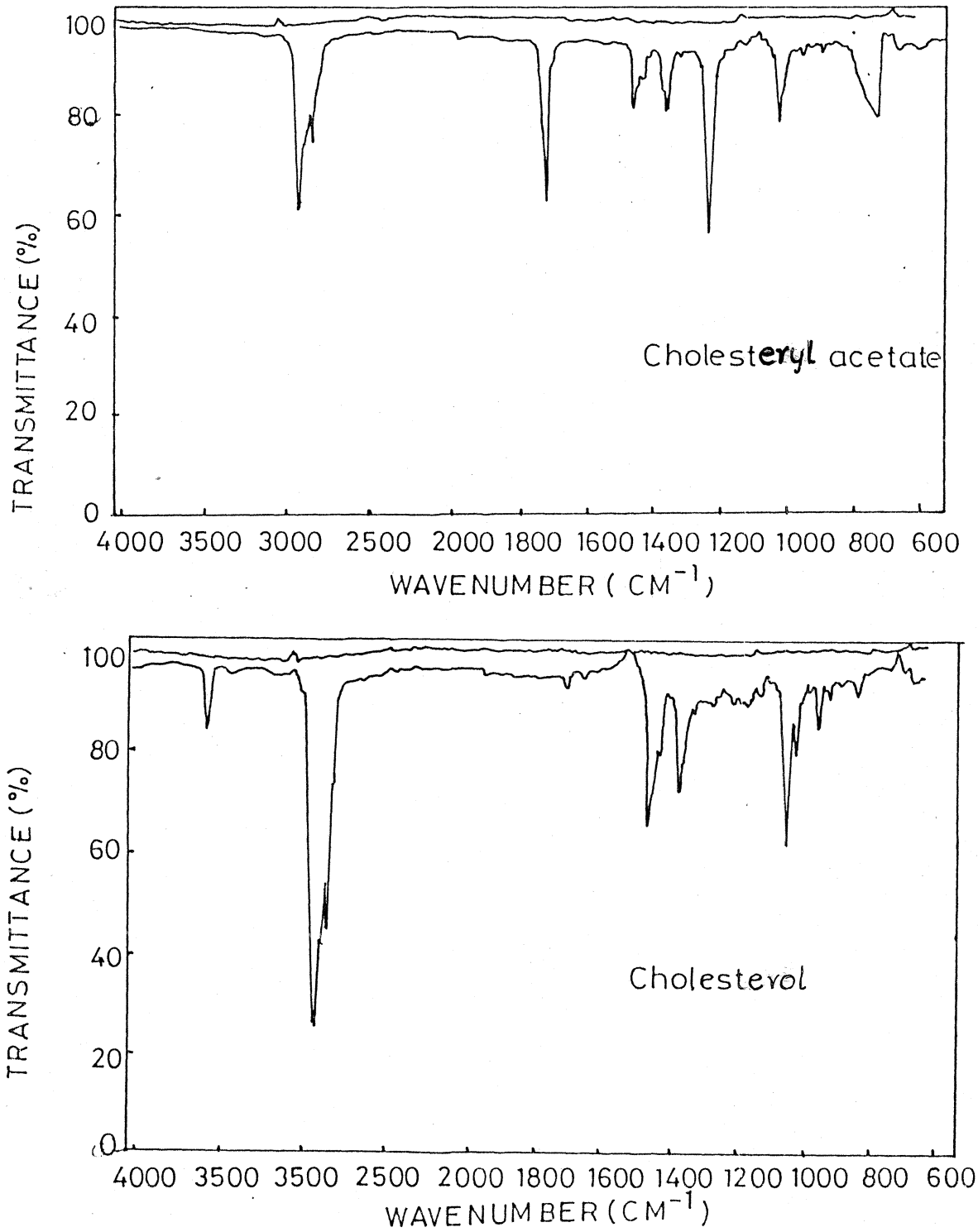


Fig. 4.30 . IR spectra of diffusants extracted from PU-2

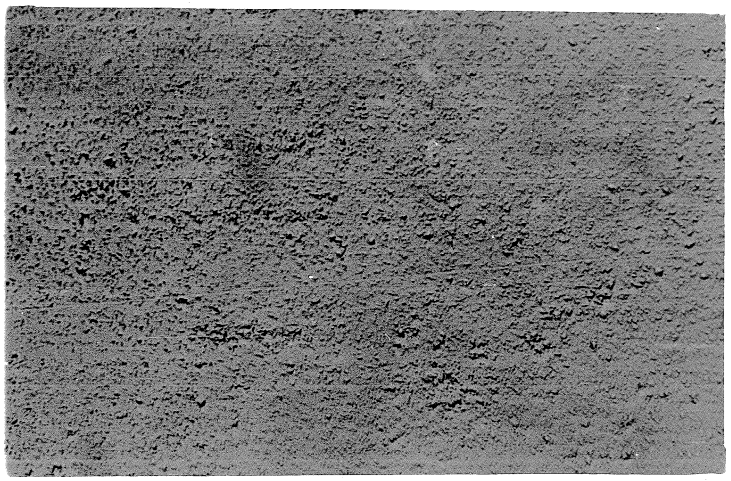
of the lipids into the polymer.

Figures 4.31 shows the representative phase contrast optical photomicrograph of a thin section of PU-1 kept in silicone oil(A). Figures B-D show the photomicrographs of the same polymer strips exposed to the silicone oil solutions of stearic acid, cholestrol and cholestryl acetate. The white patches in the respective photographs could be attributed to the diffused species. The concentration of these patches appears to be increasing in the order of stearic acid > cholestrol > cholestryl acetate which is reasonable considering the increased molecular weights of these species in the same order. Both IR spectroscopy and photomicrographs conclusively point out the diffusion of the lipids into the bulk of the polymer.

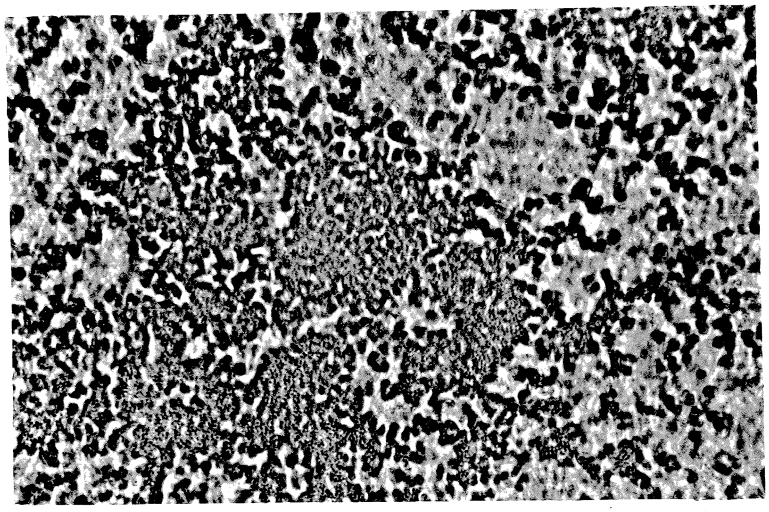
4.2.1.2. Diffusion Coefficients of the diffusants:

The mass uptake at any time 't'(Mt) and at infinite time (M_∞)were monitored by weighing. Parallely IR spectroscopic method was also used to estimate these quantities. Table.4.X1V summarizes a typical example of these parameters determined using both methods. It appears that, the values obtained using these two independent methods are comparable.

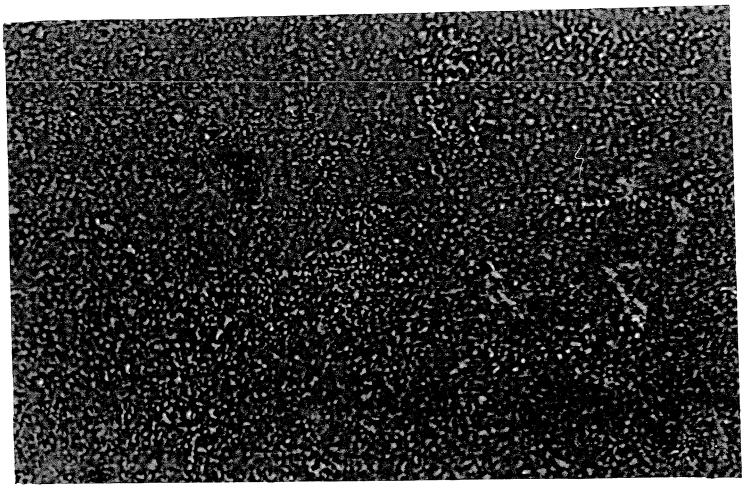
Typical M_t/M_∞ versus $t^{1/2}$ plots are shown in figures 4.32 and 4.33 respectively. The Fickian nature of the absorption process is apparent from these plots. The diffusion coefficients (D) estimated from the slope of the straight line portions of the



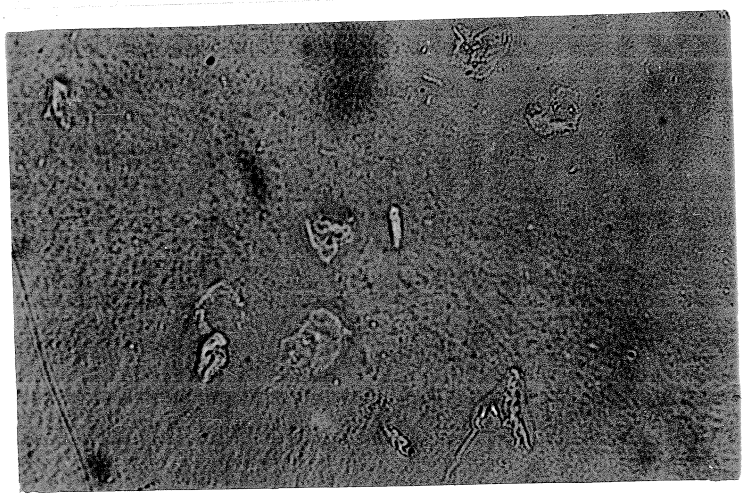
A



B



C



D

Fig.4.31. Phase contrast microphotographs of polyurethane (PU-1) A-Control, B-Equilibrated with stearic acid solution, C-Equilibrated with cholesterol solution, D-Equilibrated cholesteryl aceate solution. Original magnification, 40X

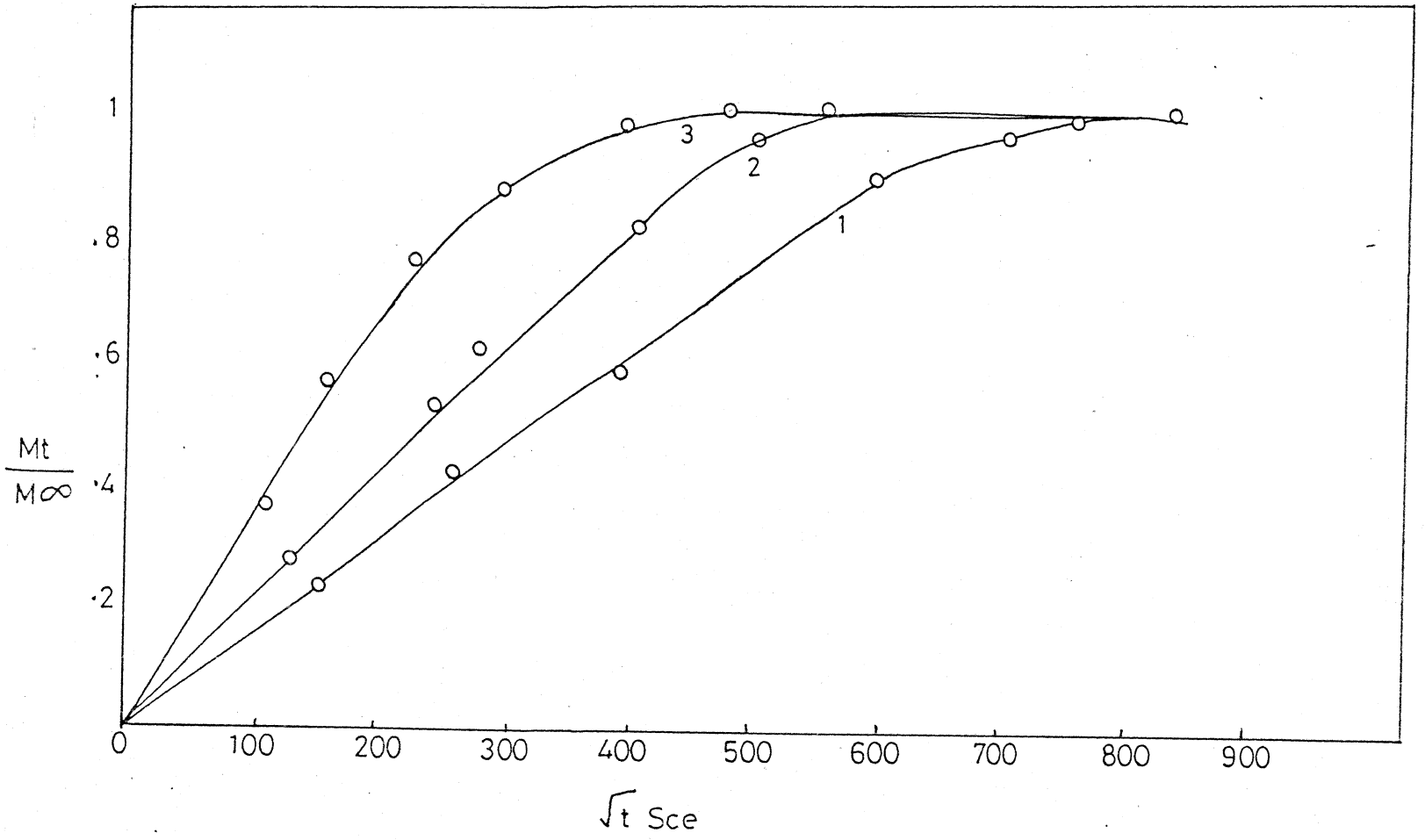


Fig. 4-32. Absorption curves for 1-Cholesterylacetate, 2-Cholesterol and 3-Stearic acid in polyurethane (PU-2)

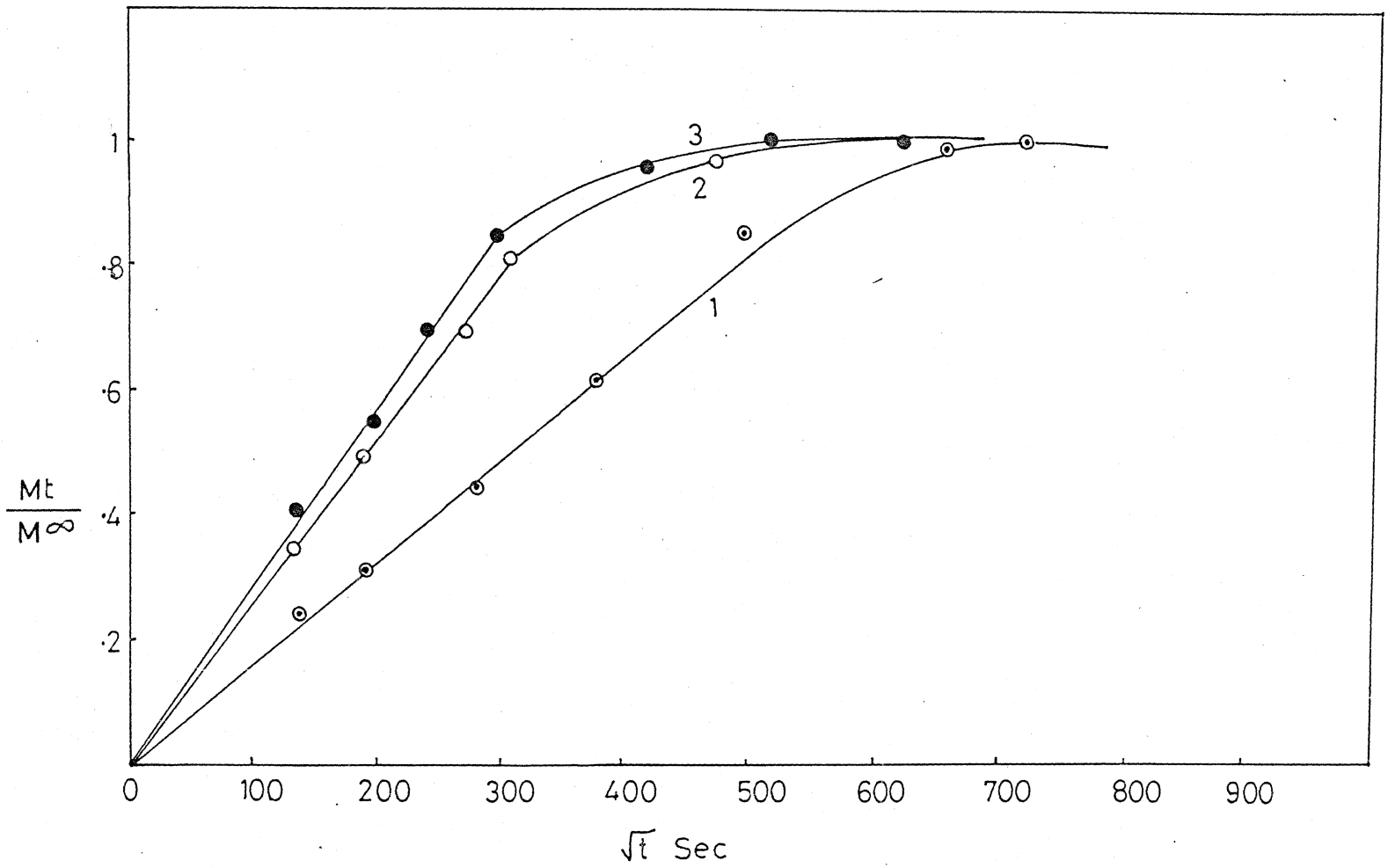


Fig. 4-33. Absorption curves for 1-Triolein, 2-Butyl oleiate and 3-Methyl palmitate in PU-2.

curves are given in Table 4.XV

TABLE.4.X1V

ESTIMATION OF Mt AND M_∞ FOR STEARIC ACID IN PU-1

Method	Mt(mg)*	M_∞(mg)
Weighing	1.10	3.70
IR	1.05	3.64

* After 24 hours

The diffusion coefficients are found to be independent of concentration of the diffusants and thickness of the polymer strips. The 'D' values estimated for stearic acid and cholesterol, typical examples of linear and bulky molecules in PU-1, using concentration and thickness as variables are shown in Table 4.XV1.

Zentner et al (197) have reported 0.47×10^{-9} cm²/sec as the diffusion coefficient of progesterone in biomer, a biomedical grade polyurethane based on MDI, PTMG and ethylene diamine. Although the present systems are different from the reported one, 'D' obtained for steroids is in the same order of the present values. It is interesting to see that 'D' of all diffusants(Table.4.XV) decreases with the increase of hard segment content.' D 'sharply drops from 100% soft segment material

TABLE 4.XV

DIFFUSION COEFFICIENT OF LIPIDS IN POLYURETHANES: EFFECT OF HARD SEGMENT

Polymer	Hard segment content(wt.%)	Diffusion Coefficient ($1x10^9$ cm^2/sec.)					
		Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
PU-0	0	4.87±0.06	3.83±0.3	3.37±0.01	1.9±0.02	4.38±0.04	3.91±0.0
PU-1	23	3.41±0.03	1.62±0.02	1.35±0.03	0.73±0.01	3.13±0.05	2.01±0.0
PU-2	33	2.37±0.04	1.16±0.04	0.72±0.03	0.56±0.04	1.77±0.2	1.62±0.0
PU-3	47	2.01±0.02	0.63±0.03	0.57±0.05	0.42±0.02	1.21±0.02	0.92±0.4
PU-4	66	1.17±0.03	0	0	0	0	0
PU-5	100	0	0	0	0	0	0

(PU-0) to Zero in 100% hard segment material (PU-5). In other words 100% HS material is impermeable to the diffusants. Such a

TABLE.4.XV1

EFFECT OF CONCENTRATION AND THICKNESS ON THE DIFFUSION COEFFICIENTS

Concentration	Diffusion coefficient ($X10^7$)cm^2/sec	
	Stearic acid	Cholesterol
1 mg/ml	3.40 ± 0.03	1.60 ± 0.02
3 mg/ml	3.39 ± 0.02	1.62 ± 0.04
6 mg/ml	3.42 ± 0.01	1.59 ± 0.03
Thickness of polymer strips (cm)		
0 .041	3.38 ± 0.02	1.61 ± 0.03
0 .08	3.37 ± 0.03	1.58 ± 0.02
0 .15	3.41 ± 0.01	1.62 ± 0.02

behaviour can be expected for polymers of 100% HS domains as they are glassy with least segmental mobility at the experimental temperature. In fact hard segment domains are shown to be impermeable

even to gases (198).

Diffusion in block polymers are known to be affected by the presence of domains, the extent of orientation of the domains and also the nature of the interfacing regions (199). The presence of impermeable hard segment domains increases the tortuosity thereby curtailing the diffusion. Further, dissolved HS domains in the SS matrix act as physical crosslinks restricting the segmental mobility in the SS domains which in turn fails to create adequate space for the diffusion of molecules. The restricted movement increases the length of the "Path of least resistance" of the rigid molecules like cholesterol which certainly scale down the diffusion coefficient by many fold.

4.2.1.3. Influence of hard segment domains on the equilibrium absorption of lipids:

The % equilibrium absorption of the lipids in polyurethanes having varied HS contents is summarized in Table 4.XV11. The influence of HS in the absorption process is apparent from the data shown in the Table. The role of HS in reducing the absorption is further illustrated in figure 4.34. The spectra shown in the figure is that of stearic acid extracted from polyurethanes having HS contents 0 to 100%. The absorption of stearic acid is maximum in 0% HS polymer (i.e. 100% SS material) as seen from the peak heights of the spectra. The absorption data conclusively point out that the diffusion is confined to the SS domains.

TABLE 4.XVII

HARD SEGMENT CONTENT AND EQUILIBRIUM ABSORPTION OF LIPIDS

Polymer	Hard segment content(wt.%)	% Absorption					
		Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
PU-0	0	5.85±0.12	3.92±0.2	3.39±0.1	2.71±0.1	1.91±0.03	1.74±0.06
PU-1	23	4.25±0.05	3.05±0.06	2.42±0.07	1.81±0.06	0.9±0.03	0.79±0.09
PU-2	33	3.35±0.07	2.04±0.03	1.57±0.08	1.21±0.04	0.73±0.04	0.58±0.07
PU-3	47	2.27±0.10	1.26±0.07	0.86±0.06	0.6±0.03	0.42±0.02	0.37±0.06
PU-4	66	0.85±0.02	0	0	0	0	0
PU-5	100	0	0	0	0	0	0

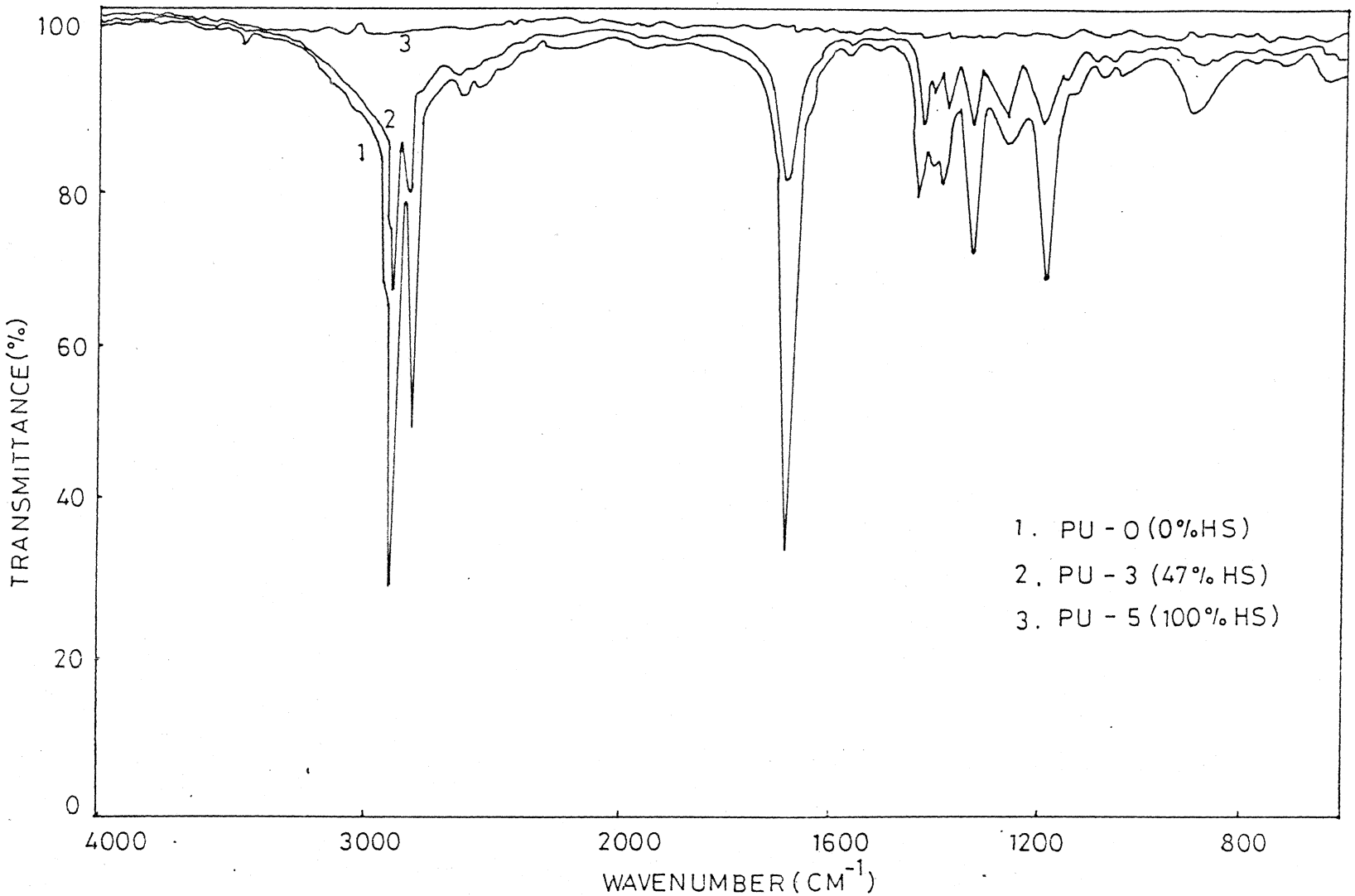


Fig. 4-34 . . IR Spectra of stearic acid extracted from polyurethanes having varied hard segment content.

Several theories have been proposed to model the diffusion of molecules in polymers. An excellent summary of earlier models of diffusion in macromolecular systems was given by Kumins and Kwei(200). The work of Barrer(201), Meares(202),Bueche(203), Brandt(204), Di-Beneedetto(205) and Paul(206)are of special promienence. Fuijita et al(207) within the frames of free volume concept proposed a theory of diffusion in polymers. The theory is based on the assumption that a diffusing molecule can move only from one another when the local free volume around that molecule exceeds certain critical value. The Cohen-Turnbul(208)theory provides an explicit expression for the diffusion especially of small molecules above Tg in terms of the average available free volume. Vrentas and Duda (209) formulated a theory of polymer-penetrant diffusion with slight modification of standard free volume theory. Pace and Datyner (210) have provided an elaborate statistical mechanical model for the diffusion in polymers. While these theoretical formulations are highly impressive, their utility in explaining the diffusion process of lipids in polyurethanes appears to be quite limited since the polyurethanes are a complex systems having different domains and interfacial regions.

To visualize the diffusion in multiphase polymer, an effective medium theory has been proposed (211). This theory predicts the overall transport properties for randomly inhomogeneous system

and predicts acceptable results when the ratios of pure permeants diffusivities are large(>100). It replaces an actual heterogeneous system that exhibits the same steady state transport properties as the original composite. Accordingly the absorption should be linear with the absorbing medium, i.e. the soft segment content. This argument may be used to derive a simple equation similar to that of Barrer's(212).

$$A = A_s V_s / T \text{-------} (1)$$

where A is the equilibrium absorption. A_s is the % absorption in 100% soft segment ploymer and V_s is volume fraction of soft segment. T is the tortuosity factor which can be obtained from Nielson equation.

$$T = 1 + 0.5 V_h \text{----------} (2)$$

where V_h is the volume fraction of the hard segment content.

The % equilibrium absorption estimated using equ - 1 is summarized in Table.4.XV111. The values are comparable with the experimental results (Table4XV11) only for stearic acid and in polymers having low hard segment content. As the % HS content increases the deviation is substantial. The difference between the theoretical and experimental values for rigid and bulky molecules like cholesterol is considerably high indicating the lack of adequate segmental mobility in soft segment domains to create space for accommodating them. It seems, that the phase mixing is the factor responsible for this deviation. In fact increase in

phase mixing with the increase of HS contents has been shown in these materials (section 4.1.1.). More dispersed HS domains in the SS matrix act as inert fillers as well as physical crosslinks resulting in an overall reduction in the segmental mobility in the SS domains grossly affecting the diffusion of the lipids.

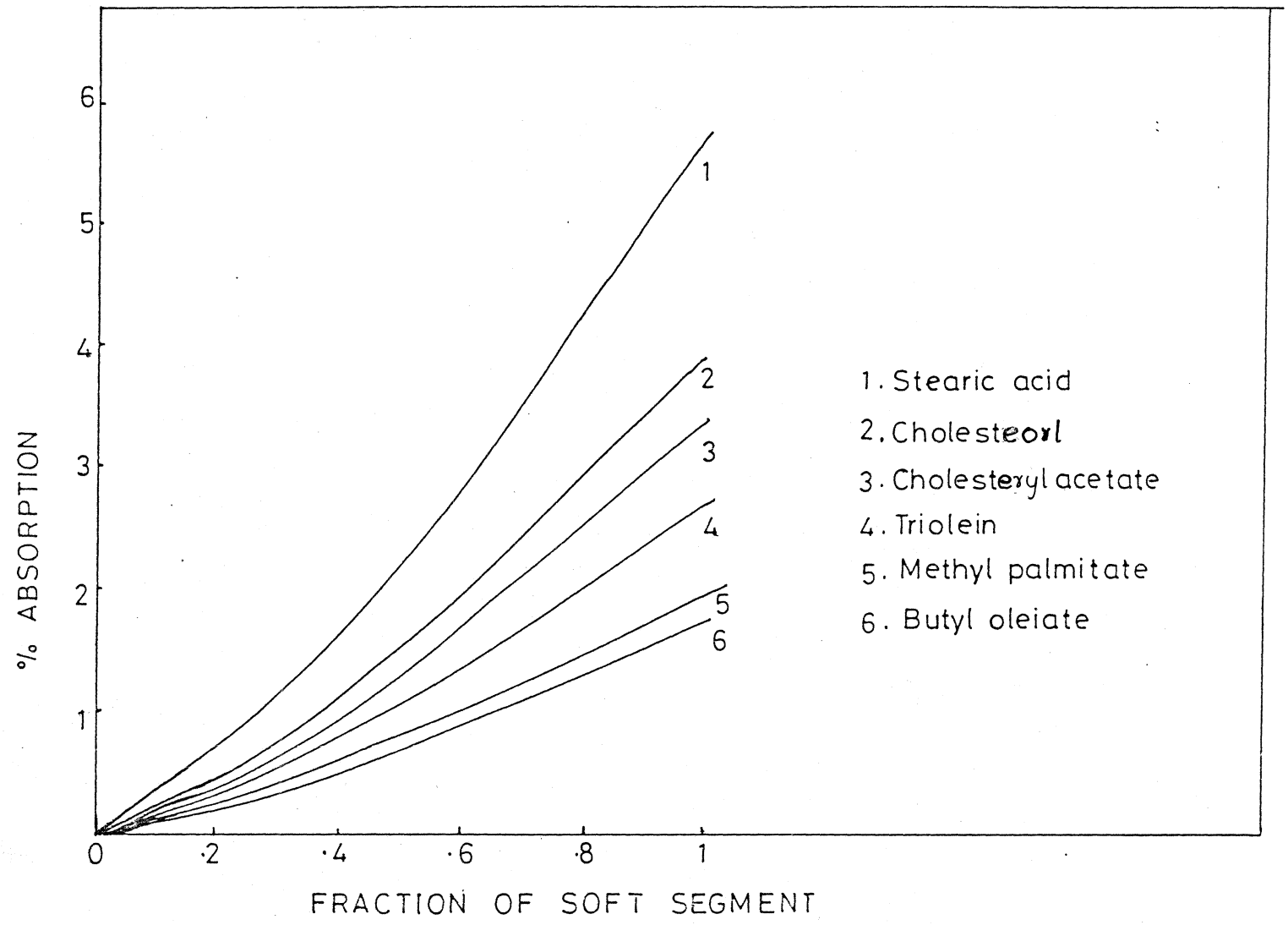
4.2.1.4. Prediction of % absorption:

The graphical representation of % equilibrium absorption versus fraction of SS content of the polyurethanes is illustrated in figure 4.35. It seems that, the curves reasonably fit into an equation of the form

$$S = So\ (1-e^{-x})^2 \quad \text{----------} \quad (3)$$

where S is % equilibrium absorption of a diffusant, So is a constant for a given diffusant and X is the fraction of SS content.

The exponential variation of absorption with SS content may be arising from the presence of significant interfacial regions along with phase mixing which has already been confirmed. Van Bogart et al (164) have reported that polyurethanes based on H_{12}MDI inhibit soft segment crystallization to a greater extent than in MDI based polymers suggesting that more HS are dispersed in the SS. domains. The proposed equation, though incapable of providing a deeper insight into the involvement of structural intricacies of the polymer in diffusion, it is simple and enables a theoretical prediction of the absorption of lipids in polyurethanes.



Fig·4-35 .Variation of % equilibrium absorption of diffusants with soft segment content.

4.2.1.5. Role of size and shape of the diffusants in the diffusion:

The effect of size and shape of diffusants on the diffusion process has been cited in the literature (214,215). Flattened or elongated molecules diffuse many fold faster than spherical molecules of equivalent molecular volume. This implies that anisotropic molecules are oriented and move along their long dimension during diffusion. This means that linear flatterned molecules having flexibility can diffuse into the polymer having restricted movement (216). The trend would be different if the size exceeds certain limit.

Reduction in diffusion coefficients with crosslink density has been reported at low to moderate level of crosslinking in several studies (156,217,218). The crosslinking reduces the mobility of the polymer segment and tends to make the diffusivity more independent on the size and shape of the permeant molecules. The reduction in both 'D' and absorption of the molecules with the increase of HS content, can be compared to that of crosslinked polymers. This is quite reasonable, in the sense that, HS domains act as crosslinks restricting the chain motion.

4.2.1.6. Anomaly in the absorption of lipids:

An interesting anomaly has been noticed in the absorption of lipids. The absorption of methyl palmitate and butyl oleiate is considerably low comparing to other diffusants. These two molecules are somewhat linear and of less molecular weight than cholesterol, cholesteryl acetate etc. The bulky methyl group in

methyl palmitate and butyl group in butyl oleiate may have a role in reducing the absorption. However, the extent of absorption is too low, which cannot be accounted using this fact alone. The absorption of these molecules seems to be controlled to a large extent by thermodynamic factors.

Using solubility parameters, an approximate understanding on the interaction of the diffusants with the polymer may be obtained. The solubility parameters of the soft segment (PTMG) diffusants and the medium (Silicone oil) are shown in Table 4.X1X. By comparing these values, it appears that, methyl palmitate and butyl oleiate preferably remain in the silicone oil (medium).

TABLE 4.X1X

SOLUBILITY PARAMETERS OF DIFFUSANTS

Component	Solubility parameter [(Cal/cm^3)]$^{1/2}$
Soft segment	8.7
Silicone oil	8.1
Cholesterol	8.9
Cholesteryl acetate	8.5
Stearic acid	8.6
Tri-olein	8.3
Methyl palmitate	8.2
Butyl oleiate	8.1

In contrast to our observations, a silicone polymer was found to absorb more methyl palmitate eventhough the experiment was conducted using a silicone oil solution of the diffusant (219). This is due to the nearly identical solubility parameters of the polymer and the diffusant. A thermodynamic stability can be expected whether the diffusant is in the medium or in the polymer. By comparing the present data to this observation, it seems that the observed anomaly in absorption among the diffusing species may be due to the thermodynamic factors.

4.2.1.7.Activation energy of diffusion: Variation with HS content

Figure 4.36 presents a typical ln D versus 1/T plot. A linear relationship between ln D and 1/T indicates that the temperature dependence on diffusion obey Arrhenious type expression. Estimated activation energy values are listed in Table 4.XX. The following trend can be seen in the activation energy values. The activation energy for a given diffusant increases with the increase of HS content. The diffusant size also results in an increase in activation energy in a polymer. The increase in activation energy with the increase in HS content suggests that the HS domains are acting as crosslinks restricting the segmental mobility.

The polyurethanes can be compared with three other systems, semicrystalline polymers, polymers with reinforcing fillers and chemically crosslinked polymers. Michaels and Bixler (220) observed that the diffusivity decreased as the amorphous content decreased in semicrystalline polyethylene. However, until the

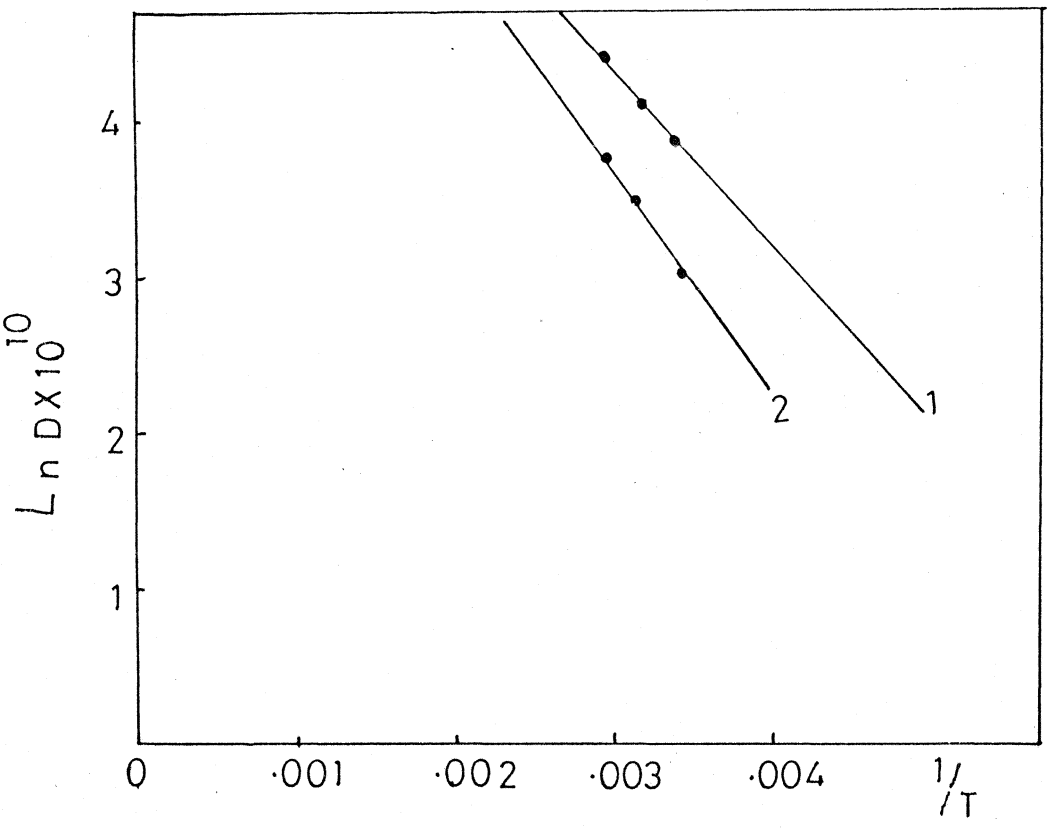


Fig. 4-36 .Arrhenius plot for diffusion through polyurethane

1. Stearic acid 2. Triolein

TABLE 4.XX

EFFECT OF HARD SEGMENT CONTENT ON ACTIVATION ENERGY

Polymer	Hard segment content(wt.%)	Activation energy (K.Cal/mole)					
		Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
PU-0	0	3.8±0.2	5.23±0.3	5.81±0.4	8.87±0.1	4.25±0.2	5±0.4
PU-1	23	7.23±0.4	11.38±0.1	14.34±0.2	17.51±0.3	10.17±0.12	12.54±0.3
PU-2	33	10.48±0.1	17.39±0.4	18.27±0.3	20.89±0.1	12.5±0.3	14.62±0.2
PU-3	47	12.39±0.2	23.04±0.2	24.8±0.1	28.08±0.2	16.53±0.2	20.93±0.17
PU-4	66	16.55±0.5	+	+	+	+	+
PU-5	100	+	+	+	+	+	+

+ The diffusants are found to be impermeable

crystallities became very large, the activation for diffusion did not change. Thus, the crystallities did not act to reduce the chain mobility but served to create a more tortuous route for the diffusant. Similar results have been obtained by Van Amerongen (221) for natural rubber filled with a reinforcing agent. The situation is quite different for the case of chemically crosslinked polymers. Generally as the degree of crosslinking increases, the activation energy for diffusion increases. The crosslinks then, serve to restrict chain mobility. It seems that the capability of HS domains to diminish chain mobility is comparable to that of a chemical crosslinks. This is true despite the fact that HS domains are physically rather than chemically crosslinked.The summarized results permit to make the following inferences.

The diffusants are confined to the soft segment. The extent of diffusion decreases as the % hard segment increases. Phase mixing seems to be the major factor reducing the diffusion and absorption in the polymers.

4.2.2
DIFFUSION IN STRETCHED POLYURETHANES

4.2.2. Diffusion and absorption of lipids in stretched polyurethanes:

It is well known that orientation can cause considerable changes in the transport properties of polymers. The origin of such effect due to theoretical and practical interest, has been studied for many years. Peterlin et al(222) first reported the reduction of sorption and diffusion of organic vapors in drawn high density polyethylene. Subsequently several studies were made on the effect of drawing on the transport of a variety of molecules in semicrystalline polymers (223-226). Orientation in polymers has been found to reduce the transport rate when diffusion occurred mainly perpendicular to the draw direction. This behaviour has been attributed to the loss of chain mobility after drawing. Most of the reported studies are related to the diffusion of gases or organic vapors through polyethylene, polypropylene, polyethylene terephthalate etc. To the best of our knowledge, studies on the diffusion of biological molecules have not been reported for polyurethanes. Data on diffusion of gases and organic vapors are scarce even for unstretched polyurethanes. In this section, the effect of stretching on the diffusion and absorption of lipids through polyurethanes has been discussed.

4.2.2.1. Variation in diffusion coefficients with stretching:

The diffusion coefficients (D) of the diffusants in PU-1, PU-2 and PU-3 subjected to various degree of stretching are shown in Tables.4.XX1, 4.XX11 and 4.XX111 respectively. In PU-1 'D' decreases slowly with the increase of stretching for all the

TABLE 4.XXI

EFFECT OF STRETCHING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN PU-1

Elongation (%)	Diffusion Coefficient ($1x10^9$ cm^2/sec.)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	3.4±0.03	1.62±0.02	1.35±0.03	0.73±0.01	3.13±0.05	2.01±0.03
200	3.36±0.06	1.38±0.04	1.14±0.04	0.66±0.01	2.84±0.04	1.76±0.01
400	2.85±0.04	0.94±0.01	0.86±0.05	0.42±0.04	2.16±0.05	1.06±0.04
600	2.66±0.07	0.91±0.03	0.77±0.06	0.31±0.03	1.98±0.06	0.89±0.02

TABLE 4.XXII

EFFECT OF STRETCHING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN PU-2

Elongation (%)	Diffusion Coefficient ($1x10^9$ cm^2/sec.)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	2.37±0.04	1.16±0.04	0.72±0.03	0.56±0.04	1.77±0.02	1.62±0.01
200	2.17±0.02	0.86±0.05	0.47±0.04	0.42±0.02	1.32±0.02	1.29±0.03
400	1.56±0.05	0.57±0.06	0.22±0.02	0.18±0.04	0.96±0.04	0.74±0.05
480	1.54±0.02	0.49±0.01	0.17±0.01	0.14±0.02	0.83±0.03	0.66±0.04

TABLE 4.XXIII

EFFECT OF STRETCHING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN PU-3

Elongation (%)	Diffusion Coefficient ($1x10^{9}$ cm^2/sec.)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	2.01±0.02	0.63±0.03	0.57±0.05	0.42±0.01	1.21±0.02	0.92±0.04
200	1.56±0.01	0.32±0.01	0.22±0.02	0.19±0.01	0.9±0.03	0.62±0.02
400	1.04±0.05	0.14±0.02	0.09±0.01	0.03±0.00	0.42±0.01	0.26±0.02
450	0.98±0.03	0.12±0.03	0.06±0.02	0.03±0.00	0.39±0.04	0.21±0.03

six diffusants. This polymer contain relatively less hard segment content (23%). The reduction in D is negligibly small for molecules like stearic acid in PU-1 stretched to 200%. For rigid and bulky molecules like cholesterol the decrease in 'D' is slightly more. The negligibly small reduction of 'D' in this material could be attributed to the immediate relaxation of the soft segment chains after removing the stress. In 200% drawn PU-1 orientation was apparent only in hard segment. Since hard segment domains are impermeable to the diffusants, their orientation do not have any influence on the diffusion. However, in PU-1 stretched to 400% and 600% elongation, D is reduced to some extent. The phase mixing resulted by the disruption of hard segment domains induced by stretching together with the retention of orientation could be the factors reducing the 'D' in 400% and 600% drawn PU-1. The morphological changes like phase mixing in PU-1 by stretching has already been shown in section 4.1.2.

PU-2 and PU-3 also showed similar behaviour. However, the reduction in the 'D' values were more visible and the extent of reduction is in the order PU-1 < PU-2 < PU-3. The presence of more hard segment domains in the soft segment of these materials favour the retention of orientation of the soft segment chains. The stretch-induced phase mixing would also be higher in these materials due to the higher hard segment content. The higher concentration of hard segment domains in the stretched materials enhances the viscocity of the soft segment phase further increasing the energy barrier for diffusion resulting in an overall reduc-

tion in the diffusion coefficients. The variation in 'D' for two representative linear and rigid molecules e.g. stearic acid and cholestrol, in these materials stretched close to the breaking point are shown in Table 4.XX1V.

TABLE 4.XX1V

EXTENT OF REDUCTION OF 'D' AND % ABSORPTION OF TWO REPRESENTATIVE DIFFUSANTS IN THE POLYMERS STRETCHED CLOSE TO THE BREAKING POINT.

Polymer	% stretching	Reduction in 'D (%)		Reduction in absorption(%)	
		stearic acid	Cholesterol	Stearic acid	Cholesterol
PU-1	600	22	44	36	54
PU-2	480	35	58	47	68
PU-3	450	51	81	56	85

The parameters evidently confirms the morphological alteration induced by stretching as suggested by the WAXD and other methods discussed in section 4.1.2. Depending upon the hard segment content, the diffusion coefficient decreases particularly for rigid molecules and it is as high as 81% for cholestrol in PU-3 stretched to 450%.

4.2.2.2. Absorption of lipids in stretched polymers.

The % equlibrium absorption of lipids in PU-1, PU-2,and PU-3 subjected to varied degree of stretching are summarised in Tables 4.XXV, 4.XXV1,and 4.XXV11 respectively. The variation in absorption is governed by the extent of stretching as well as the hard segment content. The absorption changes are also more or less in the same pattern observed as in the case of D.

The % reduction in absorption for stearic acid and cholesterol, typical examples of linear and rigid molecules in the three polymers stretched close to the breaking point is also shown in Table.4.XX1V.

Orientation in an amorphous polymer can result in a reduction of absorption around 10-15% (228). In the present polymers, which are amorphous, the reduction in absorption is in between 36-85% depending on the nature of the diffusants and hard segment content. It seems, therefore, that orientation alone cannot be the factor responsible for the reduction in absorption. The hard segment domains undoubtedly play major role in reducing the absorption by influencing the movement of soft segment chains. The stretch induced phase mixing has already been highlighted in section 4.1.2. The anchoring effect of dissolved hard segment domain in the soft segment domains can bring down the absorption. The improved interchain interaction through altered structural features in the stretched materials is reflected in the enhanced thermal stability (Fig.4.12 and Table 4.V1). As the diffusion process takes place by the passage of molecules through the

TABLE 4.XXV

EFFECT OF STRETCHING ON THE ABSORPTION OF LIPIDS IN PU-1

Elongation (%)	Absorption (%)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	4.25±0.05	3.05±0.06	2.42±0.07	1.81±0.06	0.90±0.03	0.79±0.09
200	3.96±0.06	2.40±0.03	1.97±0.06	0.98±0.06	0.78±0.06	0.71±0.03
400	3.20±0.01	1.90±0.01	1.06±0.02	0.58±0.02	0.58±0.02	0.48±0.05
600	2.73±0.02	1.39±0.02	0.98±0.04	0.55±0.01	0.55±0.01	0.45±0.02

TABLE 4.XXVI

EFFECT OF STRETCHING ON THE ABSORPTION OF LIPIDS IN PU-2

Elongation (%)	Absorption (%)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	3.35±0.07	2.04±0.03	1.57±0.08	1.21±0.04	0.73±0.04	0.58±0.07
200	2.74±0.05	1.37±0.06	1.12±0.02	0.71±0.01	0.69±0.03	0.36±0.03
400	1.88±0.04	0.70±0.03	0.64±0.03	0.43±0.04	0.43±0.04	0.26±0.01
480	1.76±0.03	0.66±0.04	0.36±0.04	0.46±0.04	0.46±0.04	0.24±0.02

TABLE 4.XXVII

EFFECT OF STRETCHING ON THE ABSORPTION OF LIPIDS IN PU-3

Elongation (%)	Absorption (%)					
	Stearicacid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyloleiate
0	2.27±0.10	1.26±0.07	0.86±0.06	0.60±0.03	0.42±0.02	0.37±0.06
200	1.48±0.05	0.74±0.04	0.49±0.07	0.36±0.05	0.41±0.04	0.24±0.05
400	1.12±0.04	0.48±0.04	0.28±0.01	0.26±0.05	0.38±0.06	0.19±0.03
450	1.01±0.02	0.19±0.05	0.25±0.03	0.19±0.02	0.34±0.02	0.11±0.01

interstices between adjacent molecular chains, the orientation and separation between them will control the diffusional jump. The decrease in absorption with the increase of stretching, in fact, reflects structural changes induced by stretching. These changes are attributable to the decrease of amount of free volume in the soft segment domains. In oriented polymers, additional flow resistance could develop due to change in chain mobility.

The absorption data apparently indicate that simple stretching could curtail the extent of absorption of lipids to a considerable degree. Though the orientation of segment can influence the absorption, remarkably high degree of reduction is due to the stretch-induced phase mixing which further impart restriction on soft segment mobility.

SECTION 4.3

EFFECT OF NATURE AND MOLECULAR WEIGHT OF POLYOL ON THE ABSORPTION OF LIPIDS

It is not uncommon to use various types of polyol as soft segment in segmented polyurethanes with an aim to synthesize polymers having required mechanical and physico - chemical properties (7,19,229). The influence of polyols on the morphology of polyurethanes has been demonstrated by several authors (40,230,231). One of the simplest way to influence the phase separation process in polyurethanes is to use different types of polyols. Variation in the soft segment type commonly lead to polarity differences between hard and soft segments and the tendency for hydrogen bonding. Among various polyols, those with higher ether group content are more compatible with urethane hard segment and generally exhibit lower degree of phase separation (229,232). The effect of the nature of the polyethers (polyols) and their molecular weight on the absorption of lipids in polyurethanes is discussed in the following sections.

4.3.1. Effect of the nature of the polyol on the absorption of lipids:

For comparing the influence of soft segment type on the absorption process, three types of polyols, namely PTMG, PPG and PEG having the same molecular weight (1000) were used for synthesizing the polyurethane samples. The weight % of the hard segment content in all the three materials was 33% so that the soft segment could be the continuous phase. The molecular weight parameters of synthesized polymers are shown in Table 4.XXV111.

The molecular weights and dispersities of these material are nearly identical.

TABLE-4.XXV111

MOLECULAR WEIGHT AVERAGES OF THE POLYURETHANES

Polyol	Weight average molecular weight (Mw)x10^{-5}	Number average molecular weight (Mn)x10^{-5}	Dispersity (Mw/Mn)
PTMG 1000	2.32	1.09	2.13
PPG 1000	2.12	1.07	1.98
PEG 1000	2.06	0.98	2.10
PTMG 2000	2.60	1.19	2.18
PPG 2000	2.80	1.27	2.20
PEG 2000	2.47	1.11	2.23

The equilibrium % absorption of the diffusants in the polymers containing different polyol, as soft segment are shown in Table 4.XX1X. The table suggests that, the equilibrium absorption of the diffusants is lowest in polyurethane consisting of PEG as soft segment and highest in PTMG based polyurethane. The variation in the extent of absorption with the nature of the polyols can possibly be traced to the differences in the morpho-

TABLE 4.XXIX

EFFECT OF NATURE OF POLYOL ON THE ABSORPTION OF LIPIDS

Polyol Type	Molecular Weight	Equilibrium Absorption (%)					
		Stearic acid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyl oleiate
PTMG	1000	3.08±0.04	2.04±0.05	1.52±0.02	1.21±0.06	0.51±0.03	0.48±0.07
PPG	1000	3.13±0.06	1.25±0.07	0.51±0.03	0.80±0.04	0.31±0.04	0.21±0.03
PEG	1000	1.32±0.02	0.75±0.05	0.16±0.02	0.30±0.05	0.15±0.02	0.09±0.01

logical features of the polymers arising from the alteration in the interaction of hard and soft segments.

The physics of molecular interaction in polyurethanes has been addressed from simple thermodynamic principles to rigorous mean field theoretical approaches (31-39). The simplest approach is perhaps the one based on the solubility parameter concept. Using the group contribution method and tabulated values for molar attraction constants, solubility parameter (δ) for both hard and soft segment phases can be calculated (233). For determining the interaction parameter between the hard and soft segment phases, χ_{HS}, an equation of the form

$$\chi_{HS} = \frac{M}{dRT}\left(\delta_1 - \delta_2\right)^2 = \frac{M}{dRT}\left(\Delta\delta\right)^2 \quad \text{---------- (1)}$$

was used (234). In equation 1, $\delta 1$ and $\delta 2$ are the solubility parameters of hard and polyol soft segment respectively. d and M are the density and molecular weight of the polyol. As polyether can form hydrogen bonds of moderate strength, a correction was made for the values as suggested in the literature (235). Table 4.XXX summarizes the δ values of hard and soft segments. It can be seen that $\Delta\delta$ for hard segment polyol pairs increases in the order PTMG > PPG > PEG.

As suggested by Tobolsky (236) components generally become incompatible if the $\Delta\delta > 2$. A large difference of $\Delta\delta$ between hard

TABLE-4.XXX

SOLUBILITY PARAMETERS OF HARD AND SOFT SEGMENTS

Component	Solubility Parameter $(Cal\ cm^{-3})^{1/2}$	$(\Delta\delta)^2$	$\Delta\delta$
Hard segment (H_{12}MDI/BD)	10.5	-	-
PTMG	8.7	3.24	1.8
PPG	9.2	1.69	1.3
PEG	11.6	1.21	1.1

and soft segments results in more incompatibility leading to phase separation. The values in the present case are however, less indicating phase mixing which in fact vary as PEG > PPG > PTMG. That is, among these three systems, relatively PEG based polymer exhibits maximum phase mixing, PTMG based system shows least while PPG shows intermediate behaviour.

Sung et al(40) have shown that polar soft segment forms strong interaction like hydrogen bonding with hard segment resulting in higher degree of phase mixing. Chang and Wilkes(174) reported that PPG which contains an extra methyl group, possesses lower dipole moment, a weaker dispersion force and a lower

tendency towards hydrogen bonding and thus relatively more incompatible with hard segment . Lockwood et al (230)also observed similar behaviour of PPG in comparison with PEG. However, in comparison with PTMG, PPG mixes more readily with the hard segment due to its amorphous nature arising from the atatic structure.

For checking the consistency of the predictions arrived from the solubility parameters, IR spectroscopic method was employed. As discussed in section 4.1.1 the ratio of hydrogen bonded -C=O group to free -C=O is considered as a measure of phase separation in polyurethanes samples. Figure 4.37 shows the expanded version of -C=O absorption region of polymers consisting of the various polyols as soft segment. In the region of 1650-1750 cm^{-1}, the absorption peak for each material split into two peaks. The bonded -C=O peak centres at 1702 cm^{-1} while the free -C=O absorbs at 1730 cm^{-1}. According to Barrow the extinction coefficient for both bonded and non-bonded -C=O bands are approximately the same (170). Based on this arugument the fraction of bonded -C=O is

$$A_{1702}/A_{1702}+A_{1730} \text{ ---------(2)}$$

As shown in the equation (2), the fraction of bonded -C=O can be approximated from the ratios of the areas of the peaks. The estimated ratios for the three polymers are shown in Table 4.XXX1

The summarized values indicate that, percent of bonded -C=O groups are more in PTMG based polyurethane and least in PEG based

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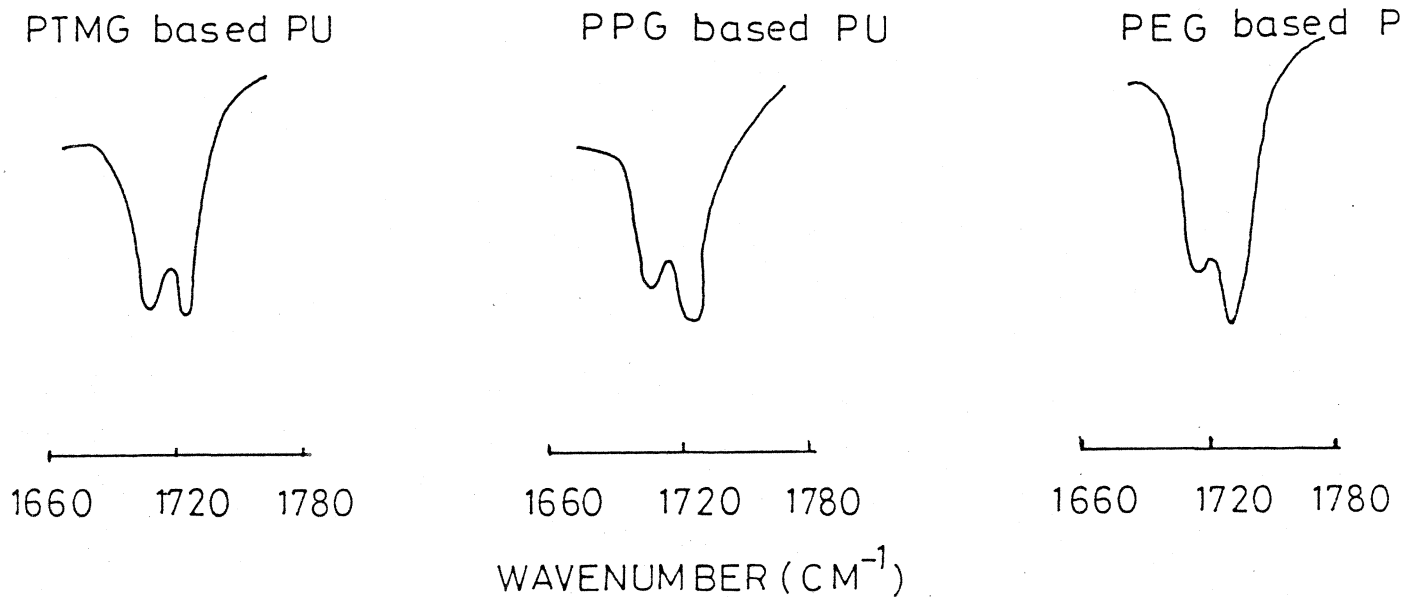


Fig.4-37. Expanded version of carbonyl absorption peaks of polyurethanes based on various polyols

material. In other words, from a relative point of view, PTMG

TABLE-4.XXX1

IR SPECTROSCOPIC DATA

Soft segment	% bonded -C=O $(A_{1702}/A_{1702}+A_{1730})X100$
PTMG	58
PPG	49
PEG	41

based polyurethane exhibits relatively more phase separation. Taking the % bonded -C=O as the index of phase separation, phase mixing seems to be in the order PTMG < PPG < PEG. The IR spectral evidences, in fact, agree well with the conclusions derived from thermodynamic aspects based on solubility parameters.

The change in absorption of the diffusants in the materials can be visualized in terms of the specific morphology of each of the materials. Depending upon the nature of polyol used, the polymer shows varied degree of phase mixing. The role of phase mixing in the absorption of the lipids has already been highlighted in section 4.2.1. The substantial degree of phase mixing in PEG based polyurethane, curtails the chain mobility in the soft segment domains to greater degree which in turns reduces the

absorption of the diffusants. In PPG based polyurethane, in comparison with PTMG based material, the extent of phase mixing is more. The reduced segmental mobility due to the dissolution of more hard segment domains, is instrumental in reducing the absorption of lipids in this material. Relatively more phase separated PTMG based polyurethane, on the other hand, absorbs more lipids.

The percent absorption of stearic acid is almost equal in PPG and PTMG based polymers. Stearic acid can move with ease due to its linear geometry through the interstices though the degree of phase mixing is different in these two polymers. It's diffusion may not be affected unless a very large difference in segmental mobility exists. The difference in the extent of absorption is, however, considerable in the case of rigid molecules like cholestrol. A graphical representation of % equilibrium absorption of cholestrol, as a typical example of bulky molecule, versus phase separation index (the IR peak ratios) is shown in figure 4.38. The variation with phase separation, in a linear fashion, evidently points out the profound influence of the morphological state on absorption which in turn reflects the considerable role of soft segment purity on the absorption. Additionally the data represented in the figure 4.38 indicates that even in a slight alteration in the segment mobility resulted by the dissolved hard segment domains, affects the absorption of rigid molecules to a considerable extent.

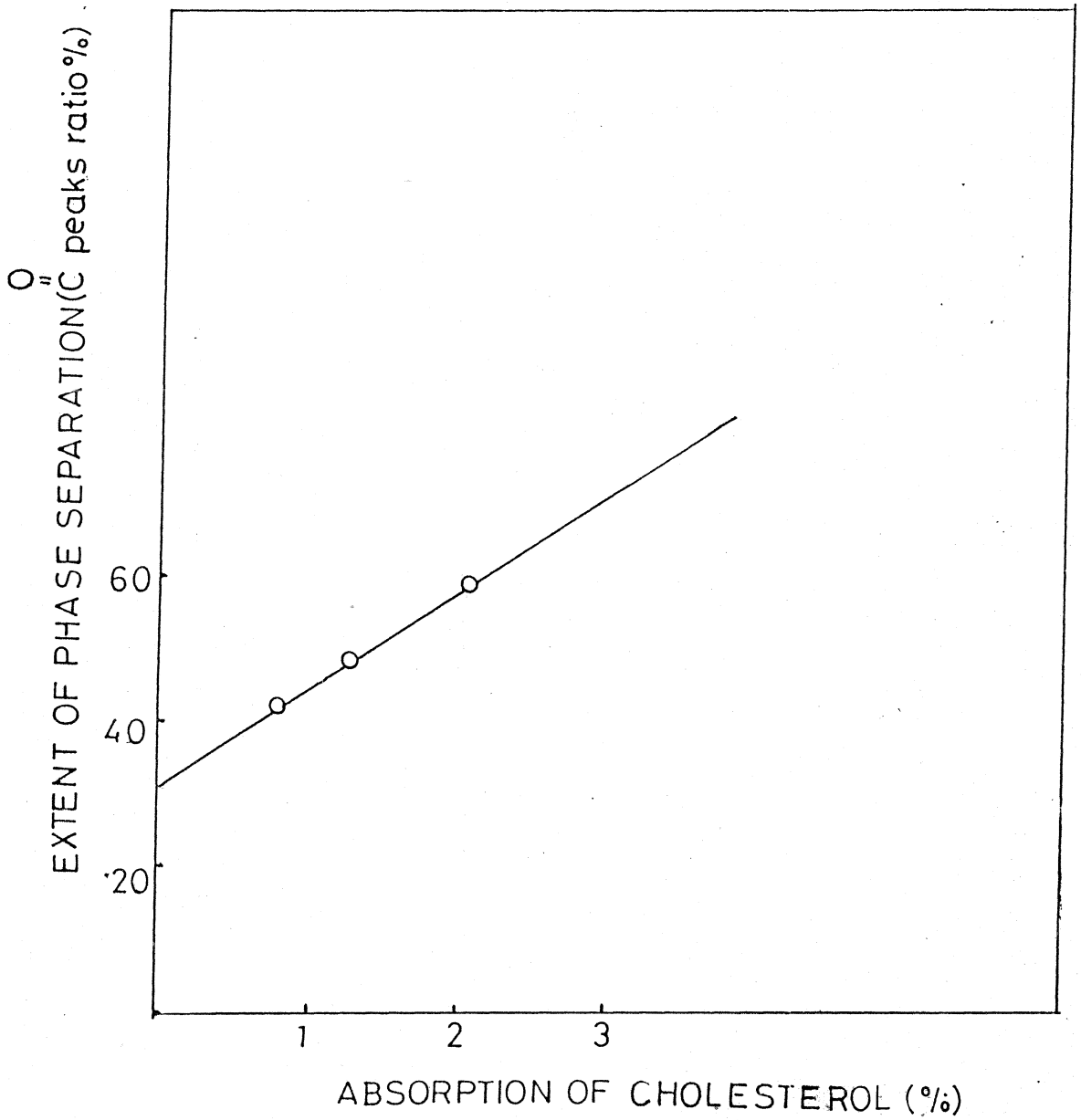


Fig. 4-38 . Influence of phase separation on the equilibrium absorption.

4.3.2. Effect of molecular weight of polyol on the absorption of lipids

Though polyurethanes can be prepared with polyols having a range of molecular weight of 500-5000, most of the biomedical polyurethanes consist of polyol soft segment having 1000-2000 molecular weight range.This could be due to a definite effect of molecular weight of polyol soft segment in the size range of 1000-1400 to give a minium cell growth and other responses as observed by Lyman et al(237). This dicussion is,therefore, limited to polymers synthesized using 1000 and 2000 polyols.

For comparing the results as in the previous case hard segment content is kept constant at 33%. The molecular weight parameters of the polymers having different polyols as soft segment are shown in Table.4.XXV111. The dispersities of the materials are nearly equal. The %equilibrium absorption of the diffusants in the materials is shown in Table.4.XXX11. The extent of absorption of all the diffusants is higher in comparison with the polymers having 1000 molecular weight polyols. The higher free volume as well as less hard segment content in the soft segment domains are the probable factors responsible for the enhanced absorption. The probability of phase separation has been shown to be more with high molecular weight polyol soft segment (41,238). Nearly complete phase separation has been demonstrated in PTMG 2000 based polurethane (239). Sung et al (41) have also

TABLE 4.XXXII

EFFECT OF MOLECULAR WEIGHT OF POLYOL ON THE ABSORPTION OF LIPIDS

Polyol	Mol. Wt.	Equilibrium Absorption (%)					
		Stearic acid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyl oleiate
PTMG	1000	3.08±0.04	2.04±0.05	1.52±0.02	1.21±0.06	0.51±0.03	0.48±0.07
	2000	3.80±0.08	2.97±0.06	1.69±0.03	1.60±0.09	0.93±0.07	0.61±0.04
PPG	1000	3.13±0.06	1.25±0.07	0.51±0.03	0.80±0.04	0.31±0.04	0.21±0.03
	2000	4.52±0.07	3.16±0.04	1.81±0.05	1.87±0.06	0.81±0.05	0.50±0.02
PEG	1000	1.32±0.02	0.75±0.05	0.16±0.02	0.30±0.05	0.15±0.02	0.09±0.01
	2000	1.80±0.04	0.82±0.02	0.26±0.01	0.51±0.02	0.26±0.03	0.19±0.02

shown that domains in PTMG 2000 based polyurethanes are better phase separated than those of PTMG 1000 based polymers. However, molecular weight alone cannot be the major factor determining phase separation. The interaction potential between the hard and soft segments has a prominent role in determining the phase separation. This aspect, in fact, has been demonstrated in PEG based polyurethanes. The inability of these material, to crystallize even under deformation is due to the significant level of phase mixing (237). This typical example substantiate the role of thermodynamic aspects in determining the morphological features like phase mixing even in polyurethane, having higher molecular weight polyols.However, based on general trend towards phase separation with the increase of molecular weight of polyol and subsequent freedom associated with soft segment chain mobility together with the increased free volume, seems to be the principal factors favouring more absorption in these materials than 1000 molecular weight polyol counterparts.

One interesting anomaly noticed in this case, is the enhanced absorption in PPG 2000 based polymer than that in the PTMG 2000 based material. This is exactly opposite to the results obtained for PPG 1000 and PTMG 1000 polyurethanes. By scrutinizing the soft segment domains in PPG 2000 and PTMG 2000 based polymers, the factors for this anomaly may be obtained.

The realization of soft segment crystallinity has been

known to increase with soft segment molecular weight. Petrovic et al(172) have shown that PTMG soft segment in polyurethane, crystallizes when its molecular weight is 2000 or more. A typical WAXD trace for PTMG 2000 based polymer is shown in figure 4.39. Several low intense, relatively sharp peaks, can be seen among which the prominent one is at 20.2 degree. The 'd' spacing corresponding to this angle is 4.40A which very well agree with the reported crystalline reflection of PTMG unit cell (182). The other two traces are free from such peaks indicating the amorphous nature. Differential calorimetric scans for the three polymers are shown in figure 4.40. PTMG 2000 based polymer shows a weak endothermic transistion around 40°C, a transistion, known as associated with the soft segment crystallinity (162). Other two materials do not show any such peaks reflecting the lack of soft segment crystallinity. Both WAXD and DSC results indicate soft segment crystallinity in PTMG 2000 based polyurethane. The lack of crystallinity in PPG 2000 and PEG 2000, as evidenced by WAXD and DSC analysis, is due to the atatic nature of PPG and the extensive degree of phase mixing in PEG based polyurethanes which rule out the crystalline ordering. Crystallities present in the soft segment of PTMG based polyurethane enhance phase separation further and also act as giant cross links reducing the chain mobility. Additionally crystallities acting as impermeable barrier could reduce the absorption further. The reversal of

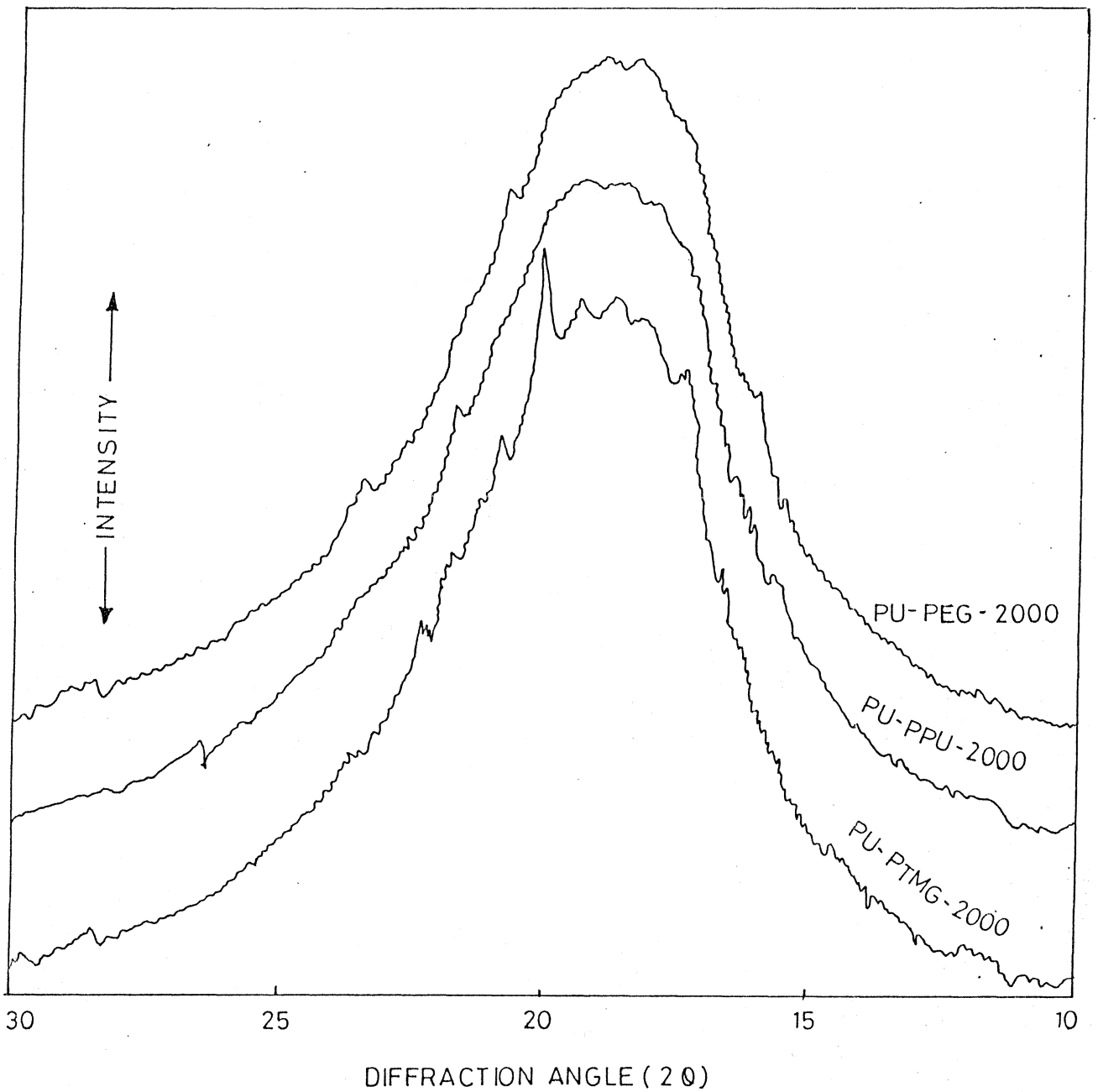


Fig.4-39. WAXD traces for polyurethanes based on various polyols.

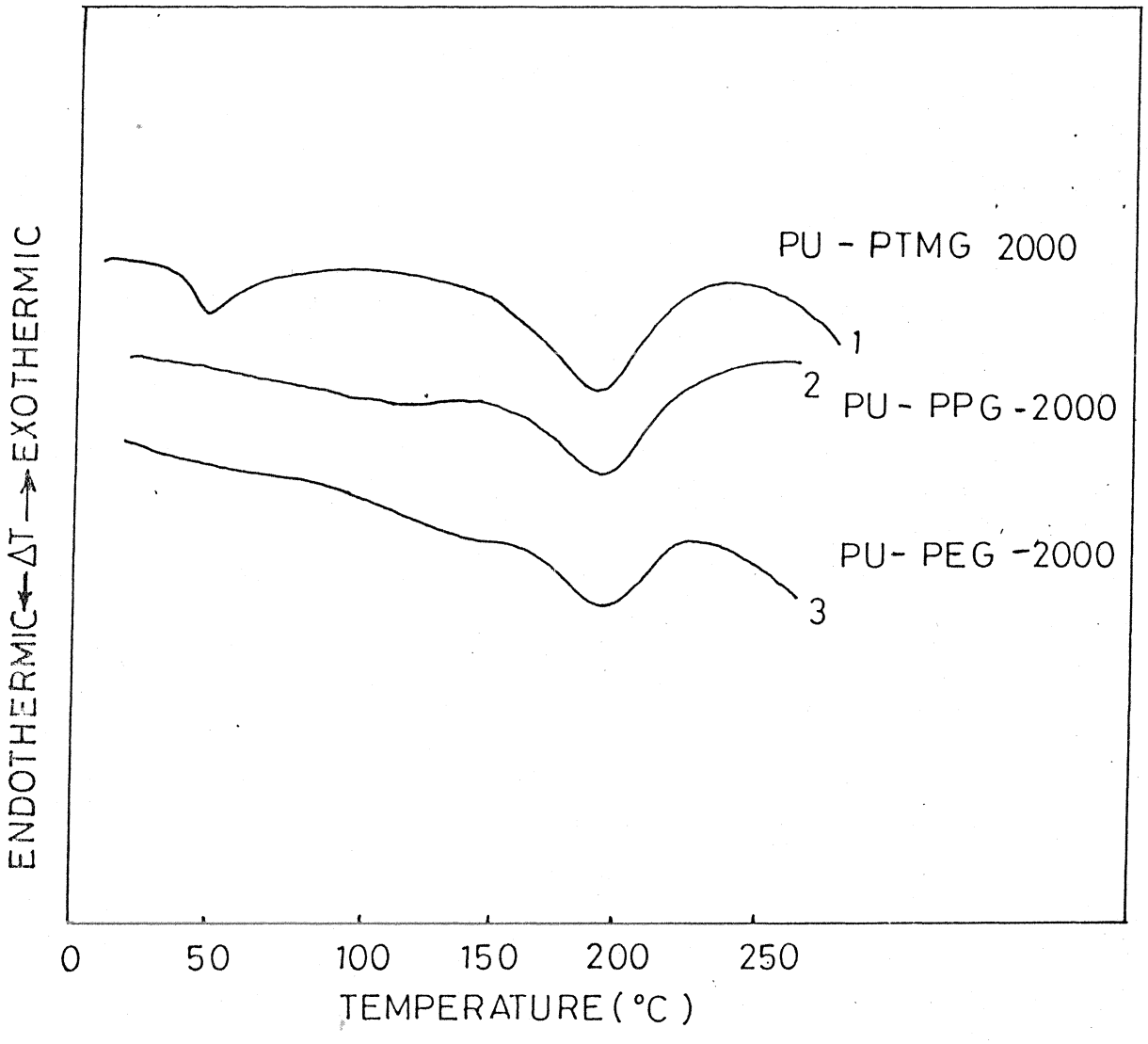


Fig . 4-40 . DSc Thermograms for polyurethanes based on different polyols

sorption trend in PTMG 2000 and PPG 2000 polymers in comparison with PTMG 1000 and PPG 1000, then could be attributed to the soft segment crystallinity in PTMG 2000 based polyurethane. Among the three 2000 molecular weight polyol used, the least absorption is again in PEG based polymer which can be assigned to the high degree of phase mixing.

SaDaCosta et al(77) have shown that PEG based polyurethanes are the least thrombogenic from a comparative study using polyurethanes based on various polyols as soft segment. These authors found negligible blood platelet retention on PEG based polyurethane surface than PPG or PTMG based polymers. Bots et al(240) have demonstrated promising results in experiments using narrow bore vascular grafts of crosslinked polymers of PEG. More recently Bamford et al(241) showed extremely low adhesion of platelets on PEG grafted polyurethanes . All these studies indicate that on the more hydrophilic PEG moieties, platelet adhesion and activation is rather low and the PEG based polyurethanes would be more advantageous in blood contact applications. The present study highlights yet another interesting aspect of PEG based polyurethanes. The lipid absorption is minimum or even negligible in these materials in comparison with the commonly used PPG or PTMG based polyurethanes.

The data obtained from the comparative study on the polymers having different polyols as soft segment can be summar-

SECTION 4.4

DIFFUSION IN GRAFT COPOLYMERS OF POLYURETHANES

The efforts expended to understand the diffusion and absorption of lipids in the graft copolymers of polyurethanes are discussed in the following sections.

4.4.1. Difffusion in hydrophilic grafts: Poly(HEMA) grafted polyurethanes.

The diffusion studies in polyurethanes led to the conclusion that the diffusion and absorption are confined to the soft segment of the polymers. The grafting of poly(HEMA) chains was found to be at the soft segment regions (Section 4.1.3) and as a result drastic changes in diffusion could be expected. The mechanical data suggest a gross reduction in flexibility which could be due to the reduction in chain mobility of the grafted soft segment domains. The additional constraints would reduce the interstitial space and affect the molecular diffusion particularly of bigger molecules to a considerable extent. The probability of creating sufficient space to enable the diffusion would be low due to the sluggishness in segment mobility.

The estimated diffusion coefficients of the diffusants in the graft copolymers are tabulated in Tables 4.XXX111, 4.XXX1V and 4.XXXV. It can be seen that 'D' decreases several fold in graft copolymers which agrees well with the above mentioned possibilities:

Pace and Datyner (210) have developed a molecular theory to explain the diffusion in polymers. According to them, the diffu-

TABLE 4.XXXIII

EFFECT OF POLY(HEMA) GRAFTING ON THE DIFFUSION COEFFICIENTS OF LIPIDS IN PU-1

Graft Yield (%)	Diffusion Coefficient (x10⁹ cm²/sec.)					
	Stearic acid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyl oleiate
0	3.41±0.03	1.62±0.02	1.35±0.03	0.73±0.05	3.13±0.05	2.01±0.03
5	2.54±0.04	1.02±0.06	0.96±0.05	0.31±0.02	2.31±0.08	1.70±0.04
16	0.94±0.06	0.42±0.01	0.26±0.03	0.11±0.06	0.77±0.06	0.51±0.06

TABLE 4.XXXIV

EFFECT OF POLY(HEMA) GRAFTING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN PU-2

Graft Yield (%)	Diffusion Coefficient ($\times 10^7$ cm^2/sec.)					
	Stearic acid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyl oleiate
0	2.37±0.04	1.16±0.04	0.72±0.03	0.56±0.04	1.77±0.02	1.62±0.01
4	1.68±0.06	0.89±0.07	0.53±0.03	0.19±0.03	1.09±0.06	0.96±0.04
11	0.68±0.02	0.26±0.03	0.14±0.05	0	0.46±0.05	0.36±0.02

TABLE 4.XXXV

EFFECT OF POLY(HEMA) GRAFTING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN PU-3

Graft yield (%)	Diffusion Coefficient ($x10^9$ $cm^2/sec.$)					
	Stearic acid	Cholesterol	Cholesteryl acetate	Triolein	Methyl palmitate	Butyl oleiate
0	2.01±0.02	0.63±0.03	0.57±0.05	0.42±0.02	1.21±0.02	0.98±0.04
3.3	1.47±0.05	0.27±0.04	0.23±0.04	0.16±0.03	0.89±0.01	0.69±0.05
6.5	0.44±0.03	0.12±0.02	0.09±0.01	0	0.39±0.04	0

sion is possible only if symmetrical chains separate sufficiently to allow transverse passage of a diffusant. In the present situation, the separation of chains to such an extent would be possible at the expense of considerable amount of energy. The difusion under constraint situation is pictured as (242)

$$D = D^*/Tb \text{ ----------(1)}$$

where D* is the diffusion coefficient in the amorphous polymer, T is the geometric impedance essentially related to the tortuosity of path arising due to the presence of impermeable region like crystalline island and "b" is the chain immobilization factor. Assuming that the equation holds good in the present case, D* may be considered as diffusion coefficient in unmodified polymer (i.e. PU). T could also be taken as an invariant considering the content of hard segment domains which are also barrier to permeants, is not changing in the graft copolymers. The change in diffusion could then be due to the variation in the immobilization factor arising from the reduction in flexibility by grafting. If this is the case, grafting of poly(HEMA) should increase the energy barrier for diffusion and 'D' should be reduced with the extent of grafting. A glance at the tables, in fact, agree well with these arguments.

The change in 'D' of the diffusants between the control and graft copolymers with low % grafting is less. However, D reduces considerably in materials having a higher content of

grafting. In materials, with a low degree of grafting, grafting is mainly confined to the surface, leaving the bulk intact, but with increased grafting, bulk also gets modified resulting in the reduction of chain mobility affecting 'D'.

It is observed that the equilibrium % absorption also decreases with the extent of grafting. The % absorption versus % grafting is illustrated in Figure 4.41. Figures 4.42 and 4.43 are the graphical representations of the same parameters in PU-2 and PU-3. These figures indicate that, the absorption of diffusants linearly decreases with % grafting. Apart from the reduction in chain mobility, the additional factor controlling the absorption, is the enhanced hydrophilicity of the polymers resulted by the grafting of hydrophilic HEMA. The increased hydrophilicity which is apparent from the contact angle data (characterization section of graft copolymers, section 4.1.3) of the graft copolymers, can restrict the absorption to certain degree by introducing thermodynamic incompatibility on the hydrophobic diffusants.

Extrapolation of the curves illustrated in figures 4.41, 4.42 and 4.43 to the abcissa provides maximum grafting needed to stop the absorption of each of the diffusants in PU-1, PU-2 and PU-3. This is possible because of the linear relationships between the % absorption and % grafting. The % grafting required to stop the absorption deduced from the figures vary from polymer to polymer. The extent of grafting needed to stop the absorption of

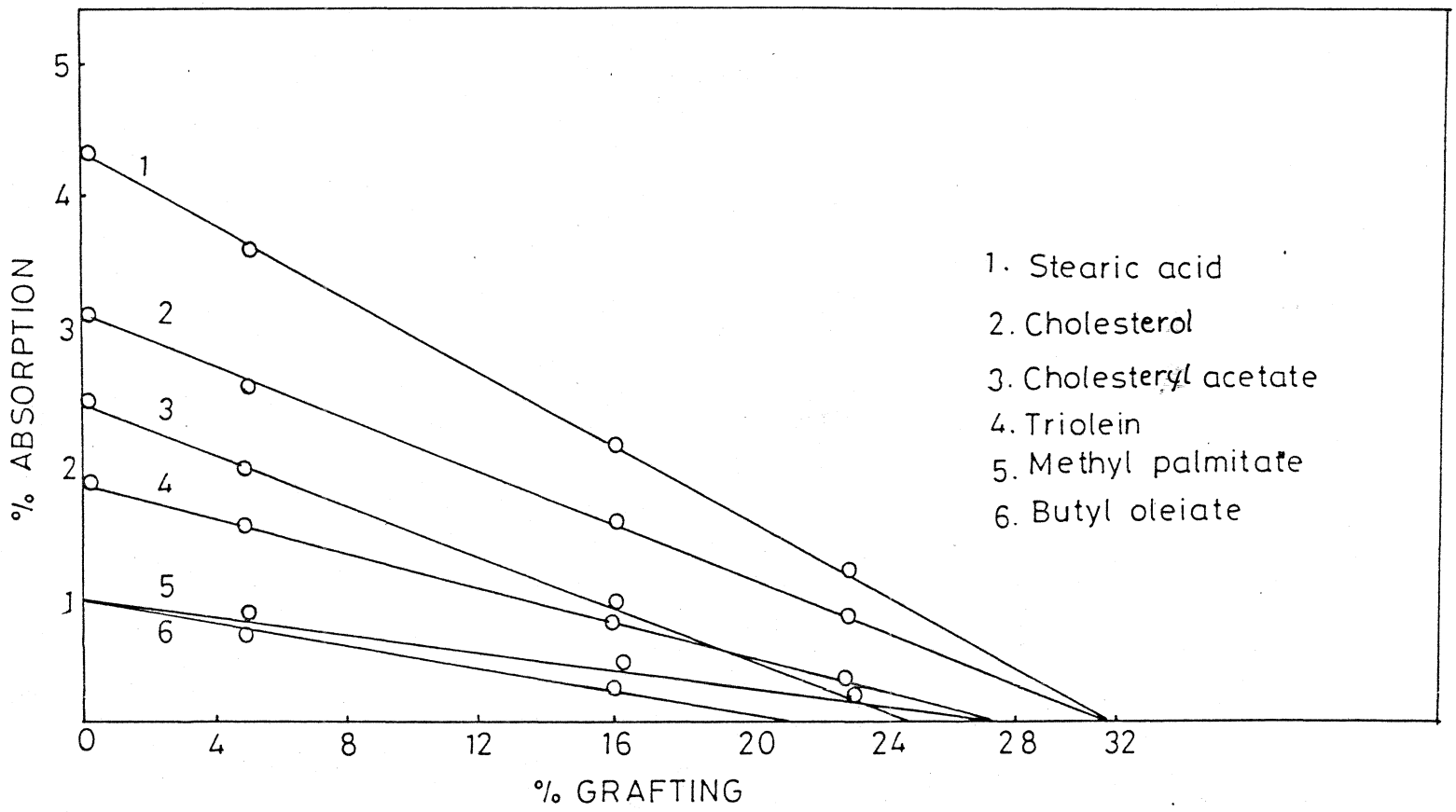


Fig-4-41 . Variation of equilibrium absorption of diffusants with extent of grafting of poly(HEMA) in PU-1

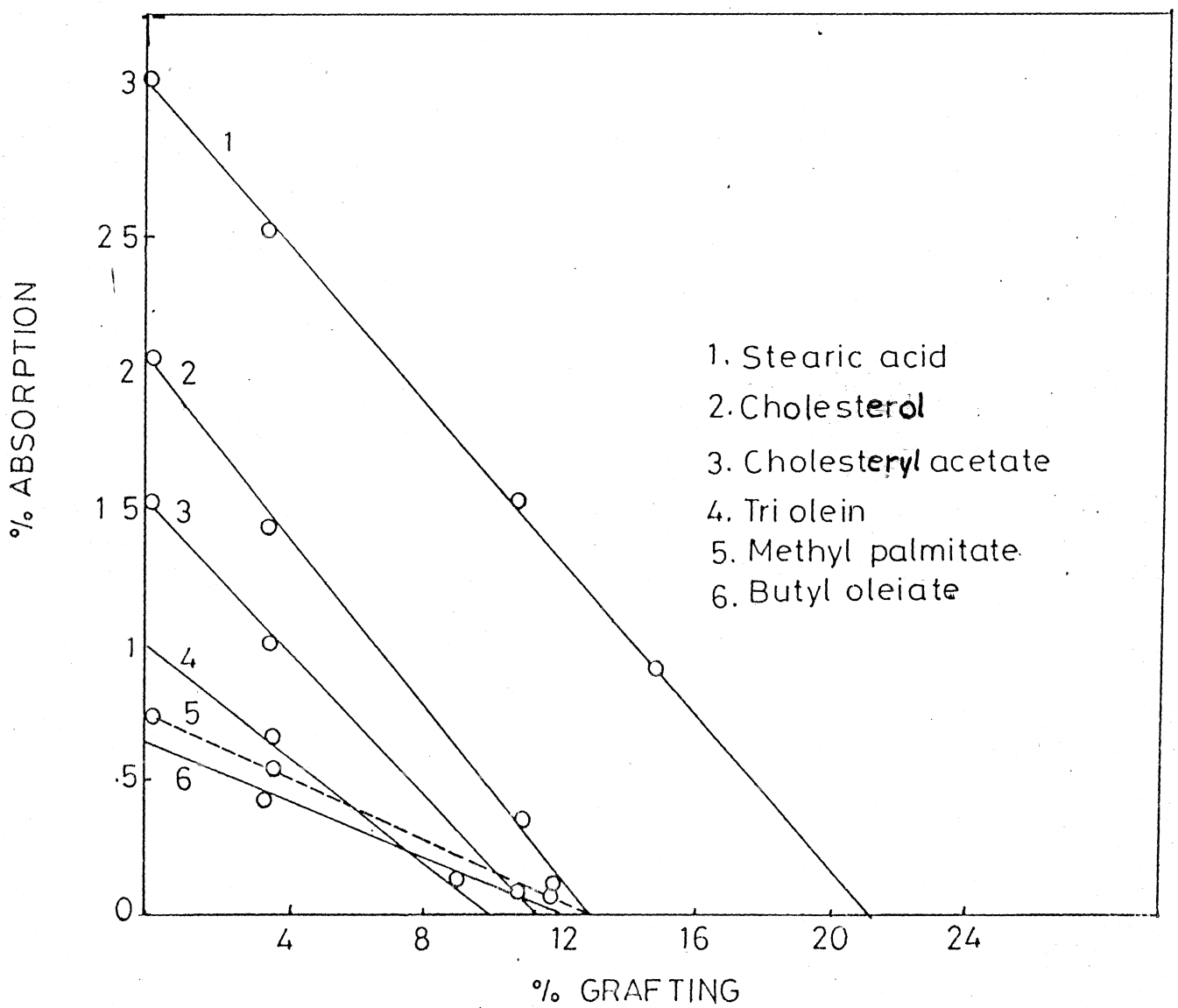


Fig. 4-42 . Variation of equilibrium absorption of diffusants with the extent of grafting of poly(HEMA) in PU-2

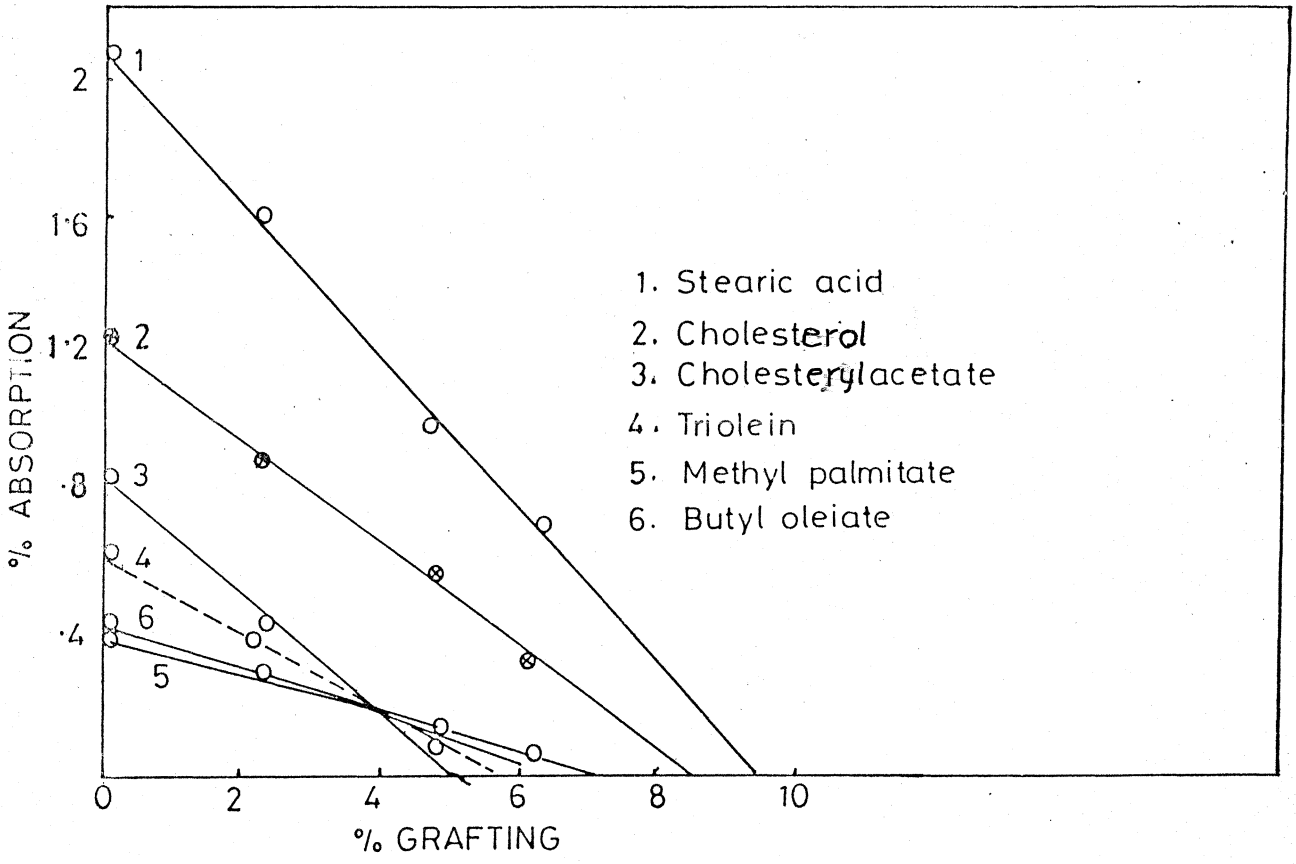


Fig.4-43. Variation of equilibrium absorption of diffusants with the extent of grafting of poly (HEMA) in PU-3

a diffusant (e.g. cholestrol) is in the order PU-1 > PU-2 > PU-3. In materials having higher hard segment content, the % grafting needed to arrest the absorption is less.This is expected in the sense that, more hard segment domains have an immobilization effect on soft segments. To check the reliability of these values obtained from the graphs, additional experiments were performed using materials having % grafting close to that of theoretical % grafting. Both theoretical values (deduced from the figures) and experimental results are shown in Table 4.XXXV1. Close agreement between the theoretical and experimental results, indicate that the absorption indeed vary linearly under the reported experimental conditions and a theoretical prediction is possible in linear polyurethanes.

The negative influence of grafted poly(HEMA) chains on the absorption could be gauged from the infrared spectrum (figure 4.44) of cholesterol extracted from poly(HEMA) grafted polyurethane(PU-2), containing grafted poly(HEMA) to different proportions. The absorption of cholesterol gradually decreases as the % grafting increases.

It can be seen that, grafting of poly(HEMA) profoundly affect the diffusion of bigger molecules having rigid ring structure, though it influences the linear molecules also. However, more grafting is needed to arrest the diffusion of linear molecules like stearic acid. The values summarised in Table

TABLE 4.XXXVI

EXTENT OF POLY(HEMA) GRAFTING REQUIRED TO ARREST THE DIFFUSION OF LIPIDS IN POLYURETHANE

Component	PU-1		PU-2		PU-3	
	Theoretical	Experimental	Theoretical	Experimental	Theoretical	Experimental
Stearic acid	31.0	34.0	21.4	26.0	9.5	11.0
Cholesterol	30.4	33.0	13.0	14.5	8.5	11.0
Cholesteryl acetate	25.0	30.0	11.4	14.5	5.0	6.5
Triolein	28.0	30.0	10.0	11.0	5.5	6.5
Methyl palmitate	27.0	34.0	12.6	14.5	7.2	11.0
Butyl oleiate	21.0	30.0	13.0	14.5	6.1	6.5

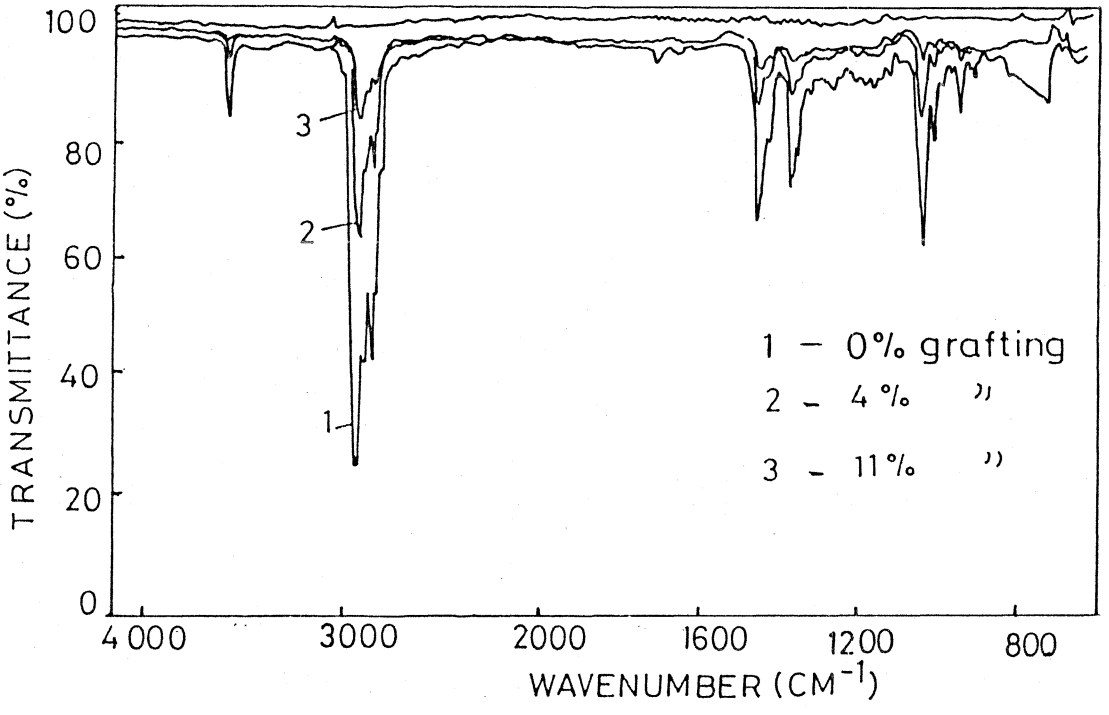


Fig.4-44 . Variation in the equilibrium absorption of cholesterol with the extent of grafting of poly (HEMA) in PU-2.

4.XXXV1 in fact, very well reflect this aspect. The extent of grafting required to stop the absorption of stearic acid can prevent the absorption of other diffusants too. Interestingly this parameter (G) vary in the order PU-1 > PU-2 > PU-3) depending upon the hard segment content. The variation in G with hard segment content is illustrated in figure 4.45. The curve can fit into an exponential equation of the form.

$$G = Goe^{-a*} \text{ ----------(1)}$$

where Go and 'a' are constants depending on the nature of the graft and x is the % hard segment content. This simple equation opens up an alternate way to predict the % grafting to arrest the absorption of lipids in polyurethanes.

Effect of PVP grafting:

The effect of grafting hydrophilic species onto polyurethanes in altering the absorption of lipids is further illustrated using PVP. PVP also as Poly(HEMA),is highly hydrophilic. The influence of grafted PVP chains on the diffusion coefficient of stearic acid and cholesterol, representatives of linear and rigid diffusants, is shown in Table 4.XXXV11. As in the case of poly(HEMA) grafts, here also the effect of grafting is considerable on the diffusion of cholestrol due to its bulky geometry.

The variation of % equilibrium absorption of stearic acid and cholesterol with the extent of grafting of PVP, is shown in

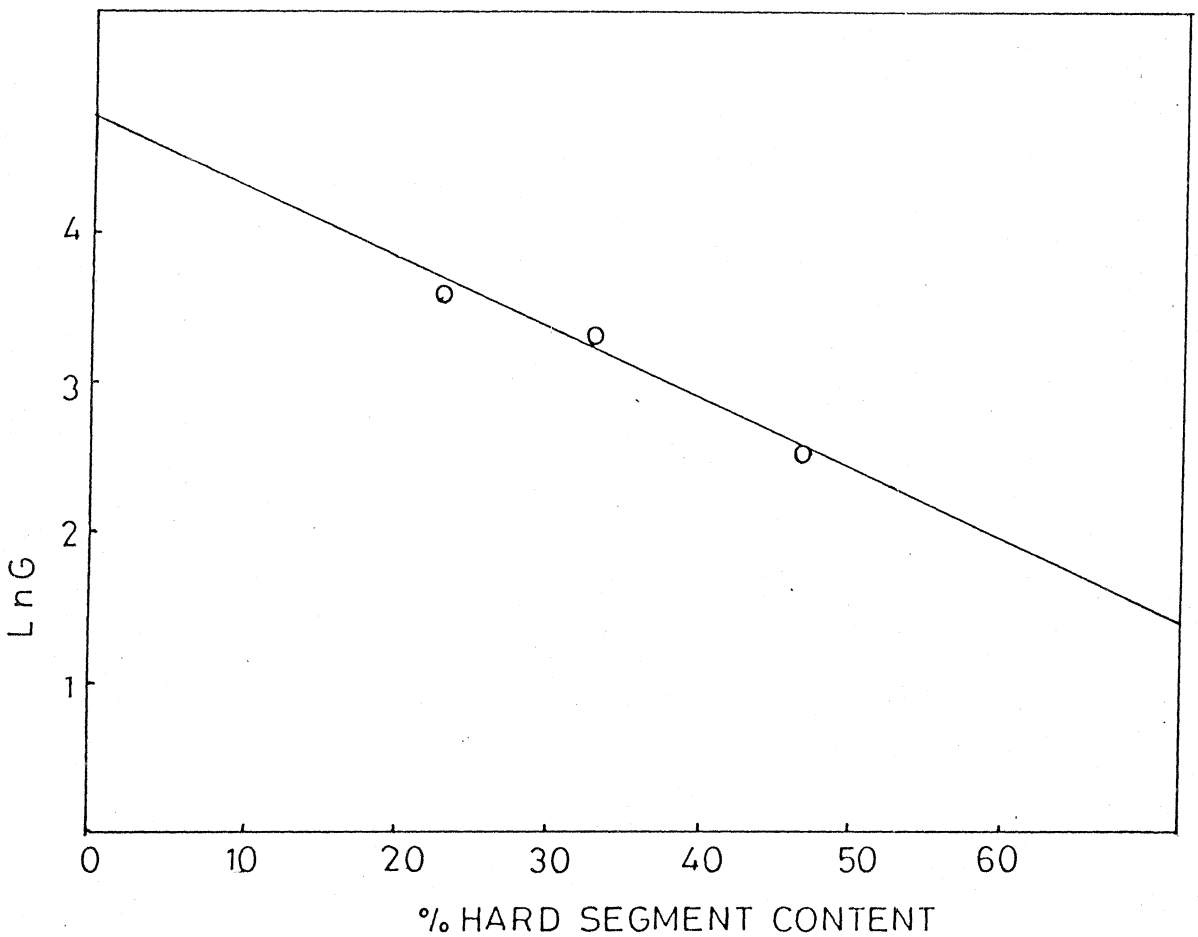


Fig.4-45. A graphical representation of % grafting required to stop the absorption of diffusants versus % hard segment

TABLE 4.XXXVII

EFFECT OF POLY(NVP) GRAFTING ON DIFFUSION COEFFICIENT OF LIPIDS IN POLYURETHANE

Polymer	Graft yield (%)	Diffusion coefficient ($\times 10^7$ cm^2/sec.)	
		Stearic Acid	Cholesterol
PU-1	0	3.41±0.03	1.62±0.02
	10	1.64±0.06	1.06±0.05
	29	0.84±0.11	0.57±0.03
PU-2	0	2.30±0.04	1.16±0.04
	8	1.26±0.02	0.46±0.06
	19	0.72±0.04	0.16±0.02
PU-3	0	2.01±0.02	0.63±0.03
	6	0.82±0.03	0.39±0.01
	18	0.34±0.06	0.12±0.02

figures 4.46, 4.47 and 4.48. The linear variation in absorption with the % grafting indicates that the extrapolation of the arguments raised in the case of poly(HEMA) grafts is possible in this case also. That is, by extending the plots as shown in the figures, the theoritical % grafting of PVP needed to arrest the diffusion of lipids can be obtained. The theoretical % grafting, obtained from the graphs together with the experimental results are tabulated in Table 4.XXXV111.

TABLE.4.XXXV111

% GRAFTING OF PVP REQUIRED TO STOP THE ABSORPTION OF LIPIDS

Diffusant	PU-1		PU-2		PU-3	
	Cal.	Expt.	Cal.	Expt.	Cal.	Expt.
Stearic acid	50	56	35.5	40	17.6	22
Cholesterol	38	44	26.5	32	15	20

The stabilization of PVP grafted polyurethanes, by forming additional hydrogen bonds involving -C=O groups of PVP chains has been shown by Egboh et al(121) in explaining the enhanced thermal stability of PVP grafted polyurethane. Improved chain interaction, presumably, through hydrogen bonds results in the reduction of segmental mobility. The hydrophilicity of the polymers increases by the introduction of PVP chains through grafting. The

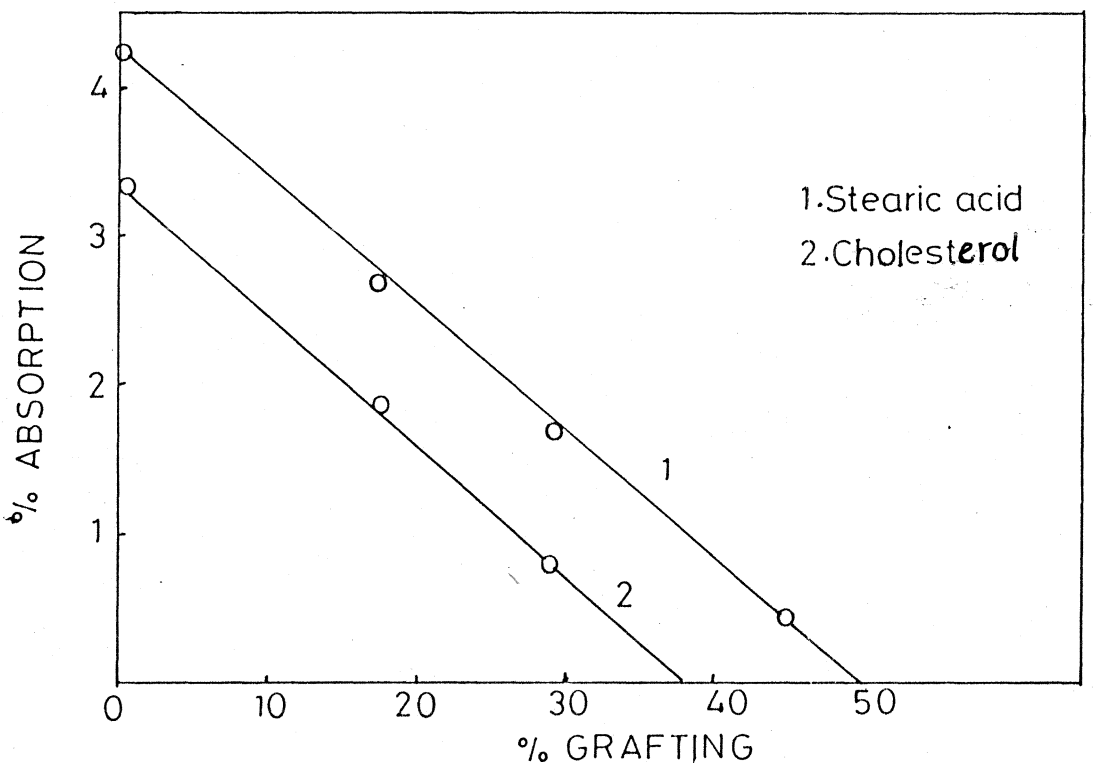


Fig. 4-46 .Variation of the equilibrium absorption of lipids with the % grafting of PVP in PU-1

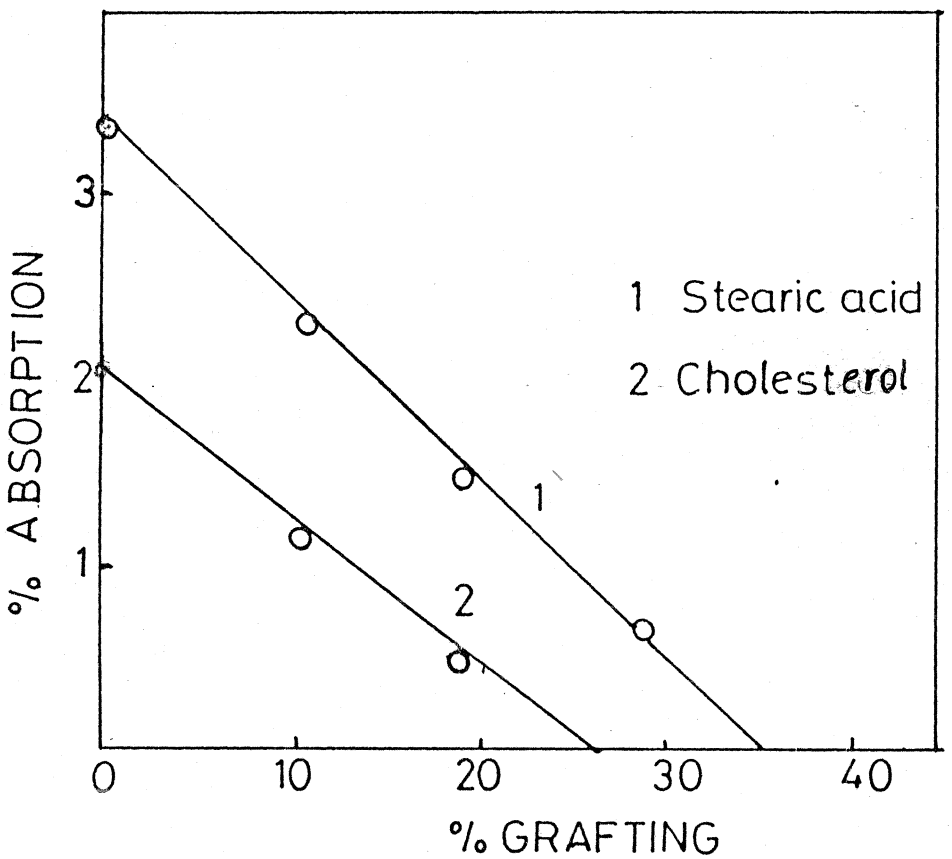


Fig. 4-47 . Variation of equlibrium absorption of lipids with the % grafting of PVP in PU-2

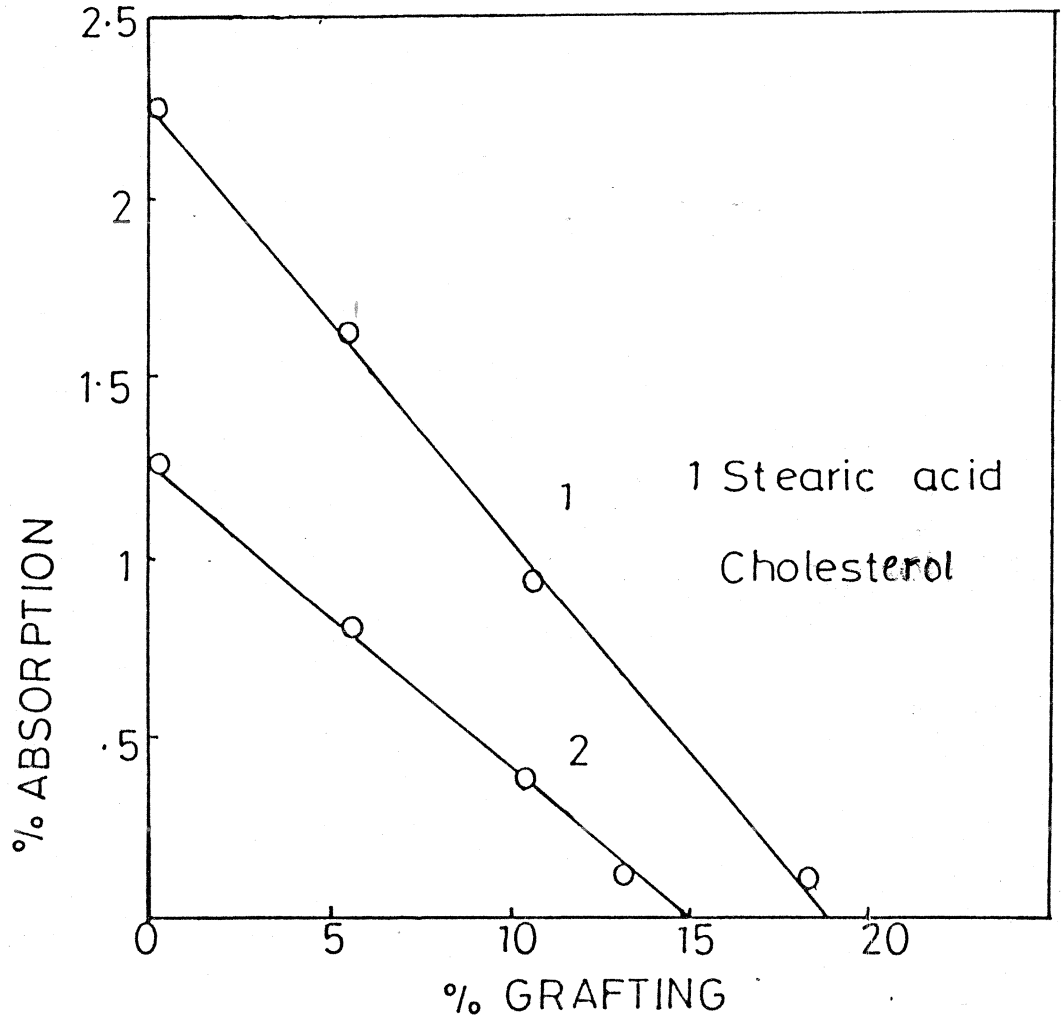


Fig.4-48. Variation of equilibrium absorption of lipids with % grafting of PVP in PU-3

reduced segmental mobility together with the increased hydrophilicity seems to be operative in reducing the absorption of lipids.

Both theoretical and experimental % grafting required to arrest the absorption of lipid, are, however, higher than those obtained for poly(HEMA) grafts. The rings in PVP moieties may be interfering the close packing of the chains leaving considerable interstitial space which permit a higer rate of diffusion.

Effect of grafting of binary species.(HEMA+BA)

This section deals with the diffusion and absorption of lipids in mixed grafts. The graft consists of PBA,a hydrophobic and flexible unit and poly(HEMA), a hydrophilic entity. The estimated diffusion coefficients for stearic acid and cholestrol in the copolymers are shown in Table 4.XXX1X. Considerable reduction of 'D' is observed only in polymers with higher content of grafted species. This contradiction, when compared with poly(HEMA) grafted polymers, can be traced to the morphology of the grafts. When grafting is carried out from the mixture, as shown in section 4.1.3, HEMA prefers the surface and PBA the bulk. The PBA chains could mix with the soft segment of the polyurethane and forms nearly a homogeneous phase due to the closeness of the solubility parameters of grafted chains of PBA [8.8{ $Cal/cm^3\}^{1/2}$] and soft segment [8.7{ $Cal/cm^3\}^{1/2}$]. The introduction of highly flexible PBA chins (Tg of PBA is -54 ° C) to

TABLE 4.XXXIX

VARIATION OF DIFFUSION COEFFICIENT IN MIXED GRAFT WITH THE PERCENTAGE GRAFTING

Polymer	Graft yield (%)	Diffusion coefficient ($x10^7$ $cm^2/sec.$)	
		Stearic Acid	Cholesterol
PU-1	0	3.41±0.03	1.62±0.02
	15	1.75±0.03	0.76±0.02
	34	0.72±0.05	0.31±0.06
PU-2	0	2.37±0.04	1.16±0.04
	10	1.46±0.03	0.61±0.05
	25	0.36±0.06	0.19±0.05
PU-3	0	2.01±0.02	0.63±0.03
	6.4	0.83±0.03	0.39±0.04
	10	0.34±0.02	0.13±0.03

the polymer backbone do not introduce any additional rigidity. In such cases large distrubance in free volume cannot be expected so as diffusion coefficients of the diffusing species (243). However, as the % grafting increases, the surface is completely covered with poly(HEMA) in addition to the modification of bulk. The enhanced hydrophilicity of the surface together with the modified bulk then begins to unfavour the diffusion of lipids. Visibly high reduction in diffusion in grafts having high extent of grafting, apparently favour the above mentioned alteration in the polymers.

The morphological changes resulted by grafting and the degree of grafting have a more pronounced effect on the absorption of the lipids. The absorption profile with extent of grafting in PU-1, PU-2,and PU-3 are depicted in figures 4.49-4.51. Though the materials contain flexible PBA,the absorption curves resemble with that of poly(HEMA) grafts reflecting,poly(HEMA) is controlling the absorption of lipids in the mixed grafts. The linear variation of absorption with the extent of grafting facilitate the determination of theoritical % grafting needed to stop the absorption by extrapolating the curves as shown in figures. The theoretical % grafting and experimental results are tabulated in Table 4.XXXX.

Comparing to the experimental values to stop the absorption in poly(HEMA) grafts, in mixed grafts, a higher % grafting is

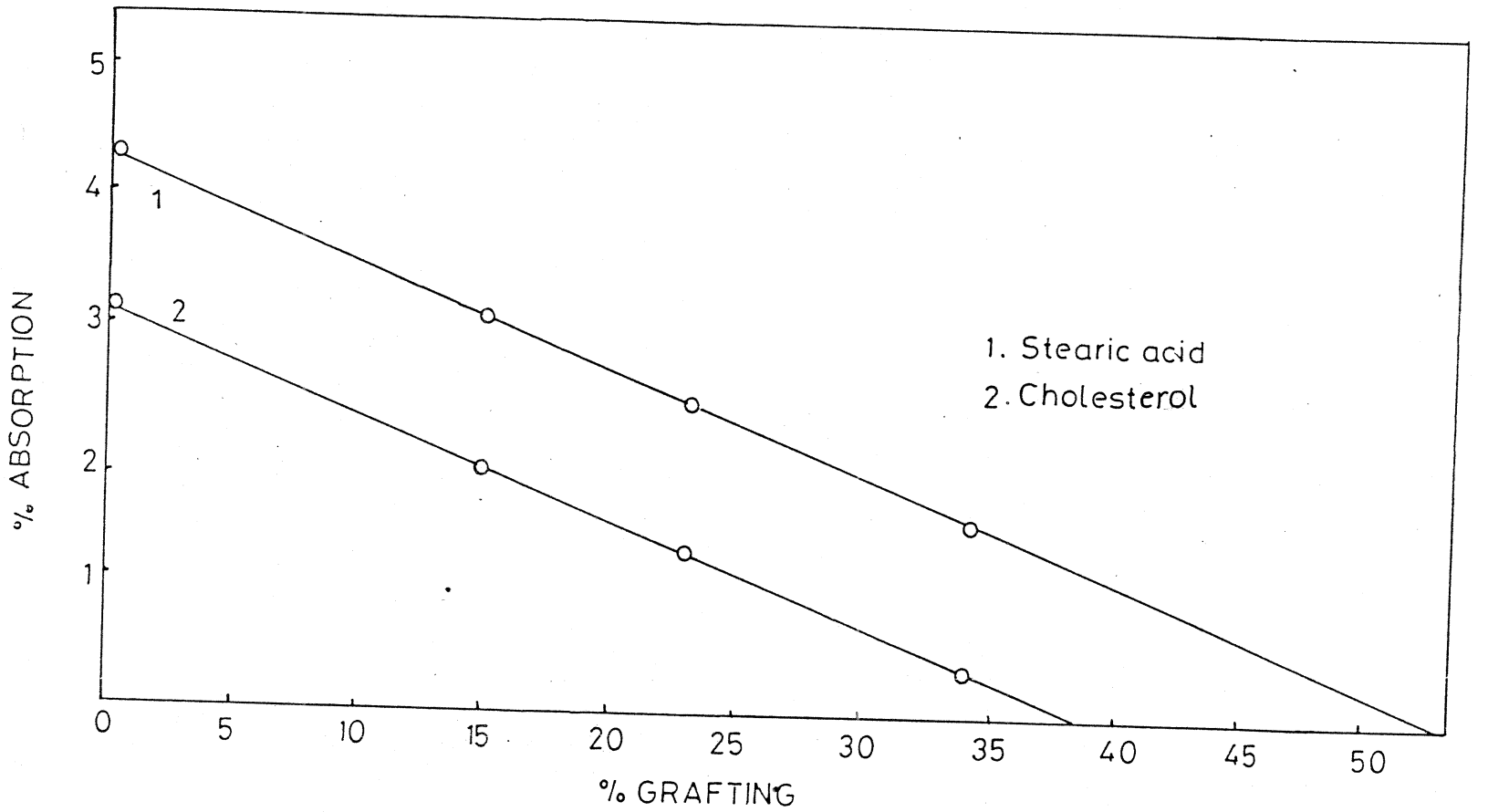


Fig. 4-49 : Variation of equilibrium absorption of diffusants with extent of grafting of poly (HEMA) and poly butyl acrylate in PU-1

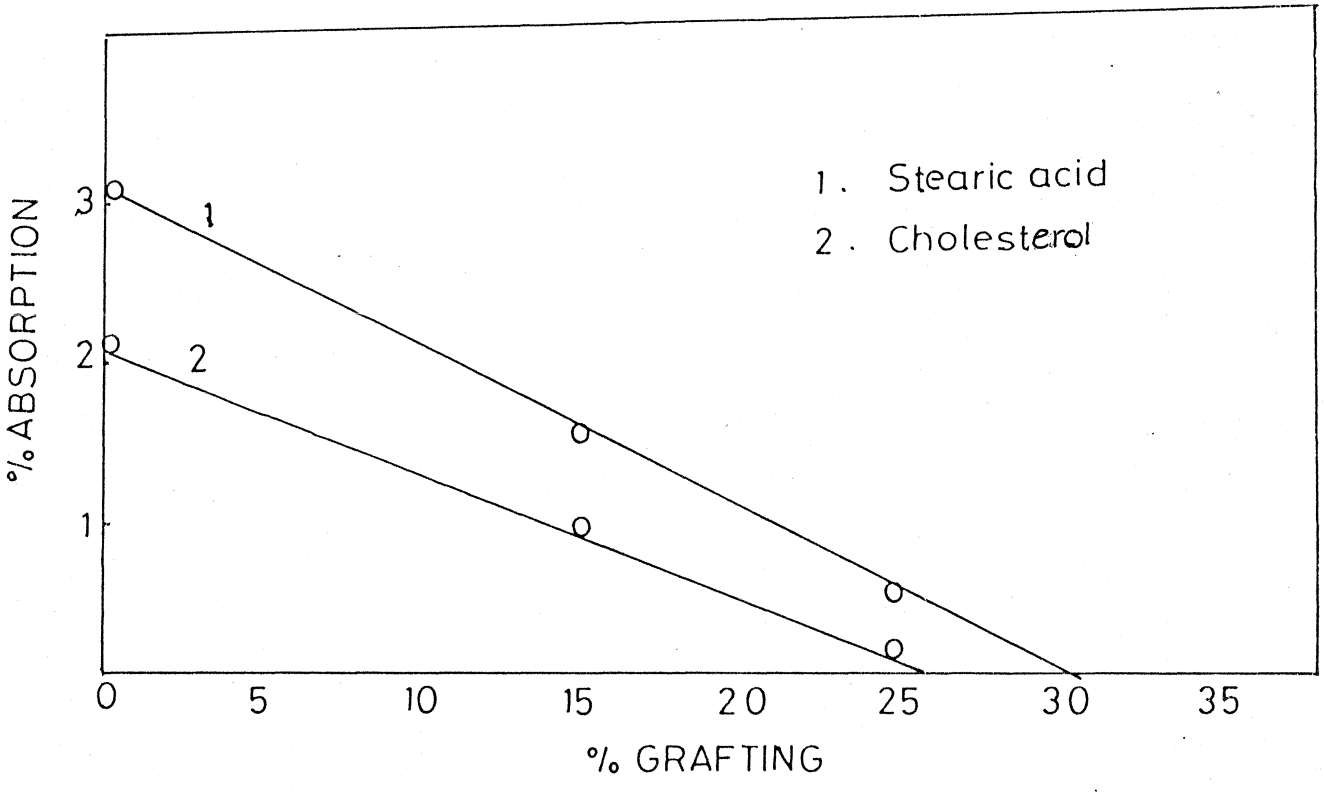


Fig. 4-50. Variation of equilibrium absorption of diffusant with the extent of grafting of poly(HEMA) and poly butyl acrylate in PU-2

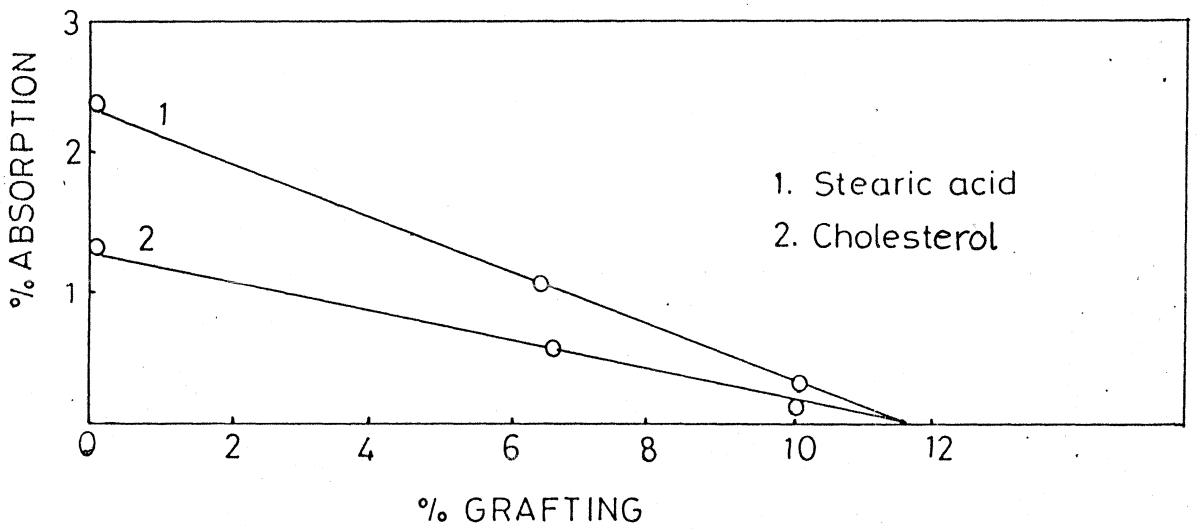


Fig. 4-51. Variation of equilibrium absorption of diffusants with the extent of grafting of poly(HEMA) and poly butyl acrylate in PU-3

needed to get the same effect of stopping the absoprtion. This is probably due to the presence of hydrophobic and flexible PBA chain in the graft which could facilitate the absorption.

Effect of PMMA grafting on the absorption of lipids:

Grafting of a relatively hydrophobic entity like PMMA, could in principle, increase the diffusion and absorption of hydrophobic lipids.

TABLE.4.XXXX

EXTENT OF GRAFTING OF MIXED MONOMERS NEEDED TO STOP THE ABSORPTION

Lipid	PU-1		PU-2		PU-3	
	Cal.	Expt.	Cal.	Expt.	Cal.	Expt.
Stearic acid	53	63	30	36	12	14
Cholesterol	37.3	41	25	30	11	14

The diffusion coefficients, estimated for stearic acid and cholestrol are shown in Table 4.XXXX1. These parameters decreases with the increase of grafting of PMMA.

By knowing, the structural alteration induced by grafting, the factors responsible for reducing the diffusion coefficients may be traced. The solubility parameters of PMMA is

TABLE 4.XXXXI

EFFECT OF GRAFTING OF PMMA ON DIFFUSION COEFFICIENT OF LIPIDS IN POLYURETHANE

Polymer	Graft yield (%)	Diffusion coefficient ($x10^9$ $cm^2/sec.$)	
		Stearic acid	Cholesterol
PU-1	0	3.41±0.03	1.62±0.02
	34	2.16±0.01	0.81±0.04
	74	1.82±0.06	0.62±0.03
PU-2	0	2.37±0.04	1.16±0.04
	15	1.68±0.08	1.02±0/06
	40	0.96±0.04	0.51±0.05
PU-3	0	2.01±0.02	0.63±0.03
	5.5	1.62±0.04	0.58±0.02
	15	0.59±0.06	0.23±0.05

9.1[Cal/cm^3]$^{1/2}$ and that of soft segment is 8.7[cal/cm^3]$^{1/2}$. According to Tobolsky (236) the chance of mixing of two components is more if their solubility parameter difference is < 2 and a thorough mixing can be expected here as difference is only 0.4. The Tg of PMMA is higher (105°C) and the polymer behaves as glass at experimental temperature. The incorporation of PMMA chains to the soft segment of polyurethanes could result in increased rigidity. The graft copolymer, having an altered morphology gained by the mixing of the soft segment and grafted chains along with the enhanced rigidity could grossly reduce the interstitial volume or free volume reducing the diffusion.

The variation of absorption of the lipids with increased PMMA grafting is shown in figures 4.52-4.54. The linear plots indicate that, PMMA grafts also behave somewhat similarly with the hydrophilic grafts discussed earlier. At high % grafting, the polymer behaves as a glassy PMMA matrix. The increased hydrophobicity, resulted by grafting of PMMA, should in fact increase the absorption of lipids. In contrast, it is observed that the absorption comes down and approaches zero at high degree of grafting. This observation lead to the conclusion that chain mobility is the major factor deciding the absorption.

Permeation and diffusion of gases has been shown in PMMA through the existing molecular pores (244). Such possibility is ruled out here due to the bulkiness of the diffusants. Diffusion

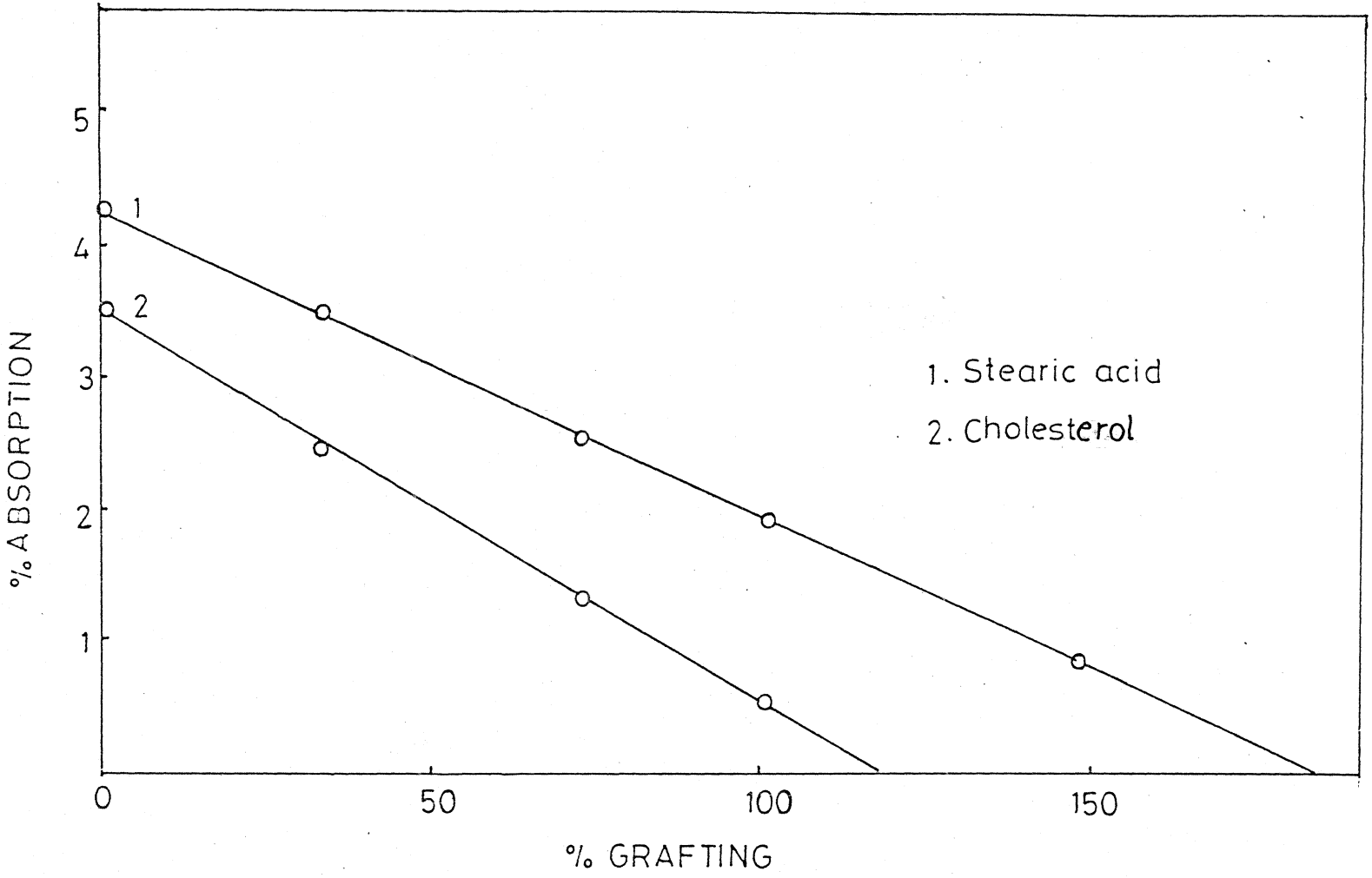


Fig.4-52. Variation of equilibrium absorption of diffusants with the % grafting of PMMA in PU-1

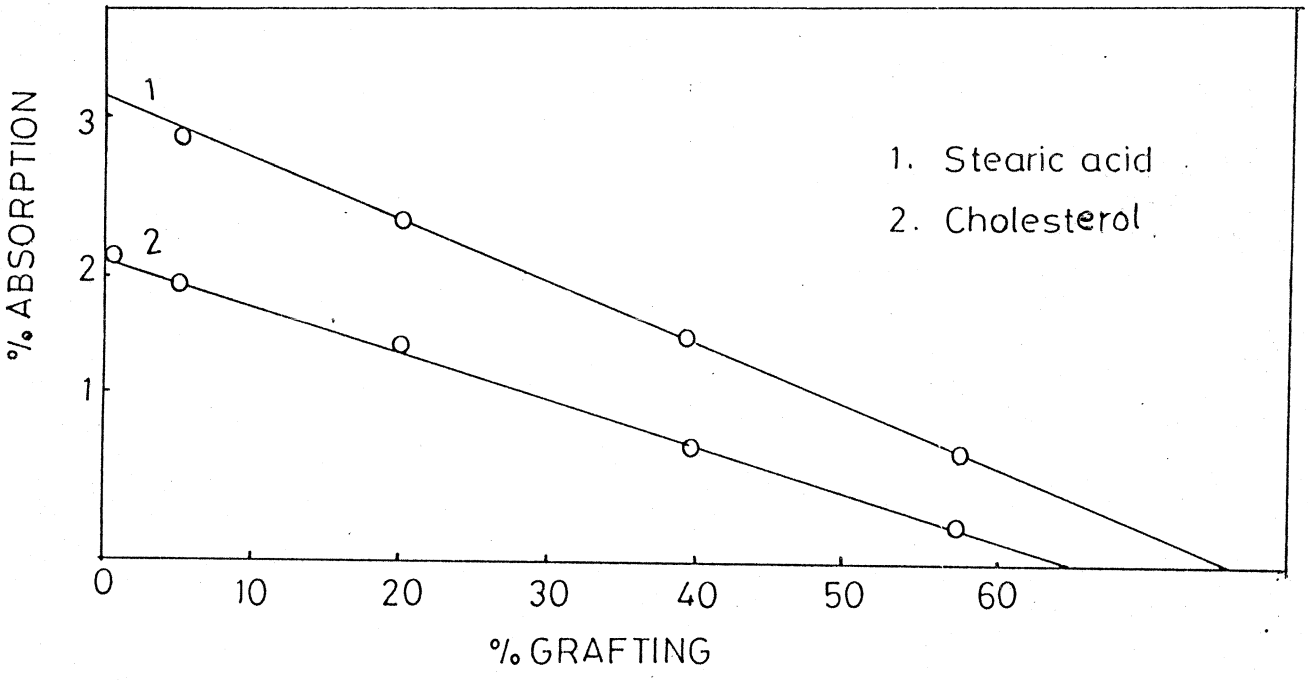
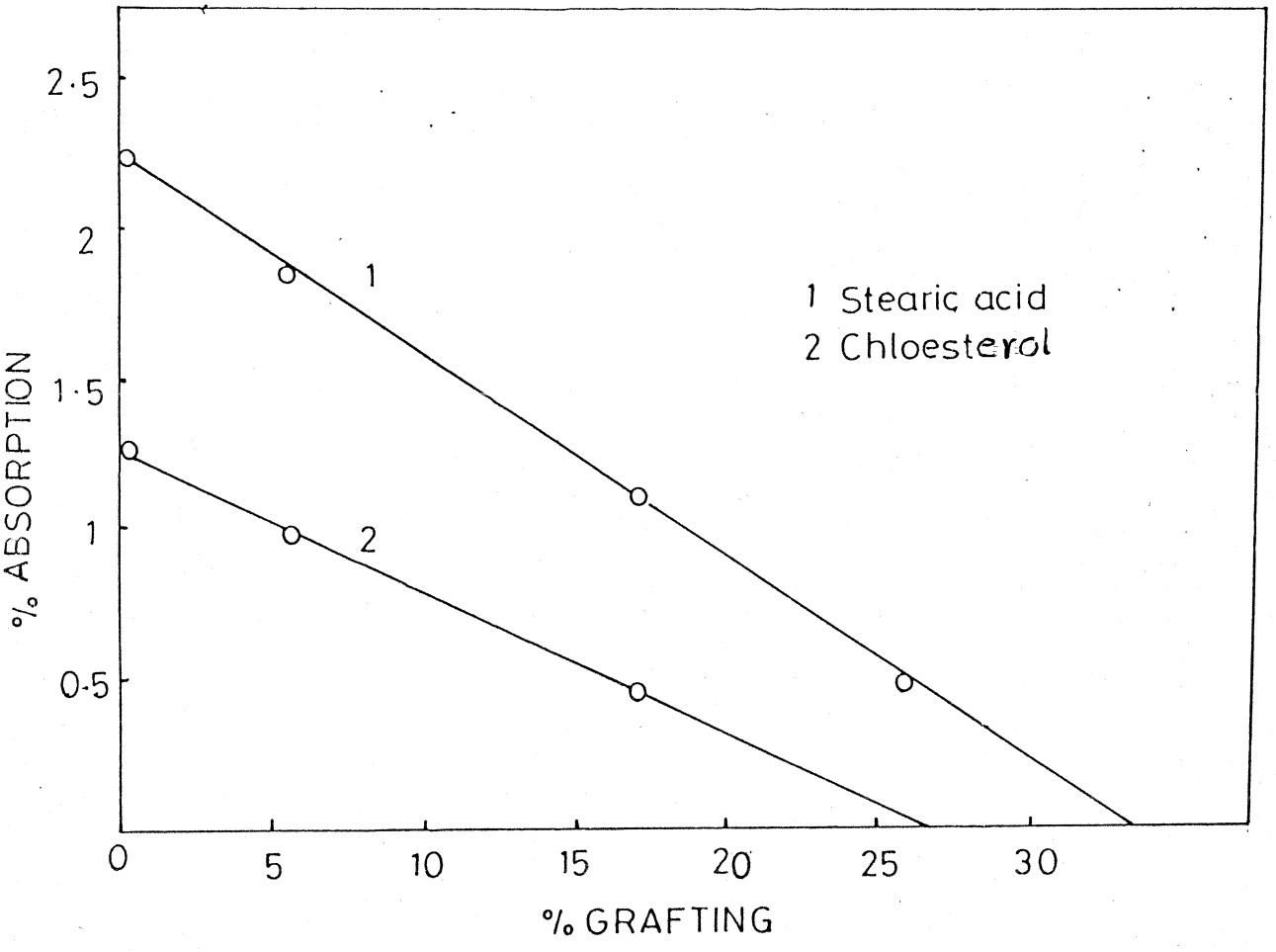


Fig. 4-53. Variation of equilibrium absorption of diffusants with the % grafting of PMMA in PU-2



Fig·4-54· . Variation of equilibrium absorption of diffusants with % grafting of PMMA in PU-3.

of these types of molecules would be possible if the coalition of few voids to form a space of adequate size which is possible only if the chain mobility is permitted to considerable degree and this process need more energy.

Theoretical % grafting to arrest the absorption of the lipids can be obtained by extrapolating the linear plots (Figures 4.52-4.54)to the abcissa. These values are grouped along with experimental results in Table 4.XXXX11.

These data shows that lipid absorption in polyurethanes could be controlled by grafting PMMA though it is hydrophobic in-comparison with PHEMA or PVP.

Effect of PBA grafting on the absorption:

To probe further the effect of hydrophobic nature of the grafted chains on diffusion/absorption and also on the role of chain mobility, the studies are extented using PBA grafted polyurethanes.

The diffusion coefficients of stearic acid and cholesterol, in the PBA grafts are shown in Table 4.XXXX111. A striking difference observed here, is the variation in diffusion coeifficient.It decreases initially in all the three polyurethanes grafted with PBA and then begins to increase along with the increase of % grafting. This strange behaviour is indeed different from the previous cases of hydrophilic grafts and can be traced to the morphological changes induced by grafting.

TABLE 4.XXXXIII

EFFECT OF POLY(BA) GRAFTING ON DIFFUSION COEFFICIENT OF LIPIDS IN POLYURETHANE

Polymer	Graft yield (%)	Diffusion coefficient ($x10^9$ $cm^2/sec.$)	
		Stearic acid	Cholesterol
PU-1	0	3.41±0.03	1.62±0.02
	16	1.84±0.04	0.94±0.03
	36	2.11±0.06	1.35±0.05
PU-2	0	2.37±0.04	1.16±0.04
	6	1.62±0.06	0.87±0.03
	12	1.81±0.02	1.06±0.01
PU-3	0	2.01±0.02	0.63±0.03
	4	1.48±0.03	0.49±0.04
	10	1.53±0.02	0.53±0.01

TABLE-4.XXXX11

EXTENT OF PMMA GRAFTING REQUIRED TO STOP THE ABSORPTION

Lipid	PU-1		PU-2		PU-3	
	Cal.	Expt.	Cal.	Expt.	Cal.	Expt.
Stearic acid	184	210	75	89	38	45
Cholesterol	118	132	65	73	25	34

Chiou and Paul (245) have observed increase in diffusion in blends which they successfully traced to the specific morphlogical features. A thorough mixing of the grafted PBA chains and soft segments could be expected due to the nearly identical solubility parameters of PBA [8.8(cal/cm^3)$^{1/2}$] and soft segment [8.7(cal/cm^3)$^{1/2}$]. The inherent chain mobility at soft segment domains does deviate substantially by the introduction of PBA due to its high flexibility (T_g =-54°C). Using Fox's equ(246), the T_g of the graft copolymer consisting of varied content of PBA may be calcuated. Data of a model calcuation using PU-1 as trunk polymer is shown in Table.4.XXXX1V. The T_g of the graft coplymer having even 90% of grafted PBA, is close to that of soft segment. Taking T_g as reflection of segmental mobility, the graft copolymers possesses almost the same extent of chain mobility as that of soft segment in polyurethane. By introducing PBA to polyurethane

TABLE.4.XXXX1V

Tg OF POLY(URETHANE-g-BA)

%grafting of PBA	Tg(°C)
0	-53
10	-53.1
50	-53.5
90	-53.9

diffusion and absorption, therefore, could not be expected to deviate from that of polyurethane itself. However, in all the three graft polymers 'D' decreases to various extent initially. The mixing process of PBA with soft segments leading to restructuring of the segments and probably pushes the hard segment domains to the surface. This type of morphological alteration could be visualized in terms of contact angle parameters.(section 4.1.3 dealing with the characterization of the PBA grafts). The increased hard segment domains is naturally expected to reduce the diffusion of the diffusants due to their impermeable nature. The formation of mobile, hydrophobic patches on the surface as the % grafting increases begins to favour the diffusion and as a consequence 'D' slowly increases.

Variation in equilibrium absorption with % grafting of stearic acid and cholesterol, are shown in figures 4.55-4.57. Similiar to the diffusion coefficients, % absorption initially

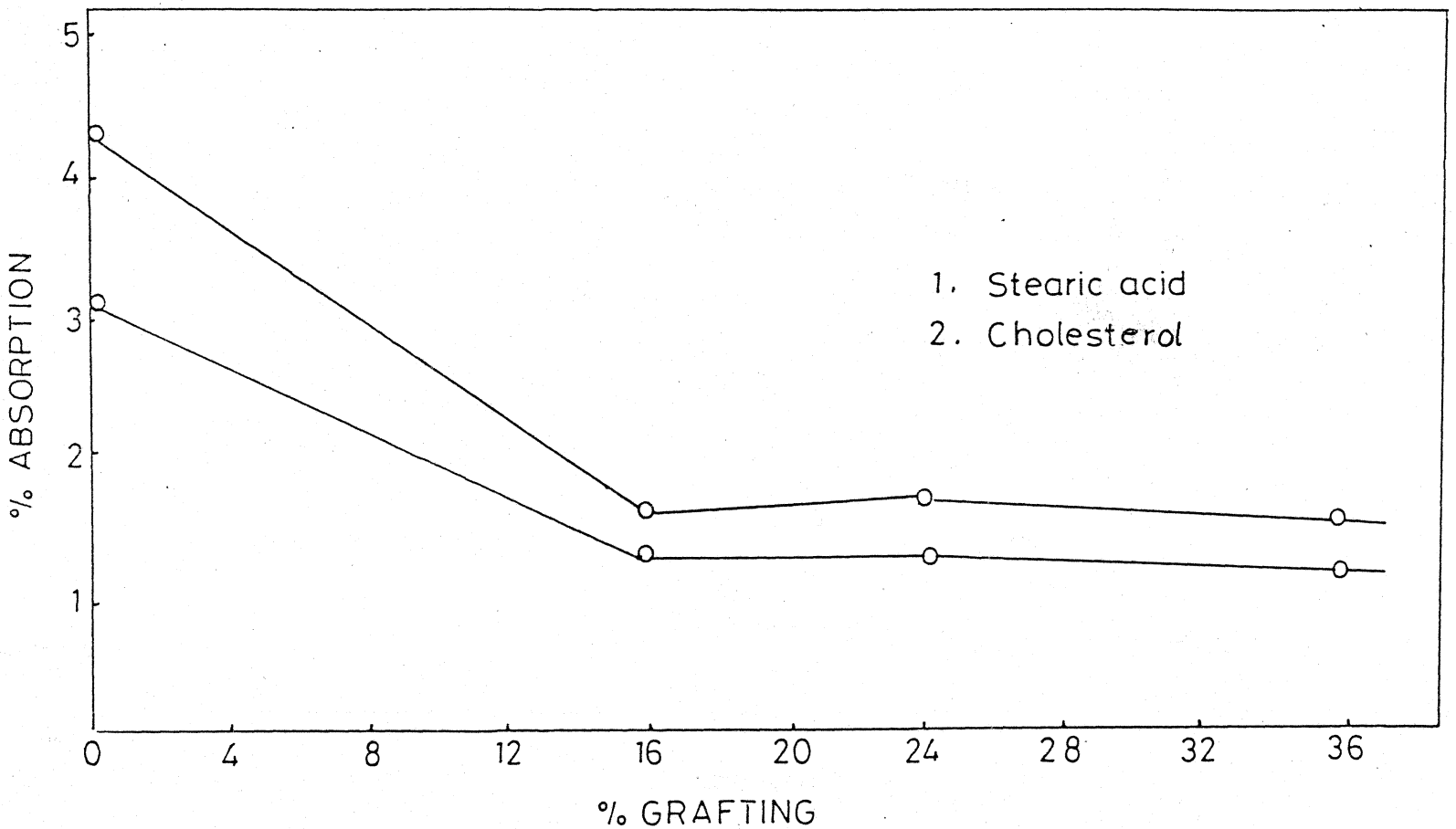


Fig.4-55. Variation in the equilibrium absorption of diffusants with the extent of grafting of PBA in PU-1.

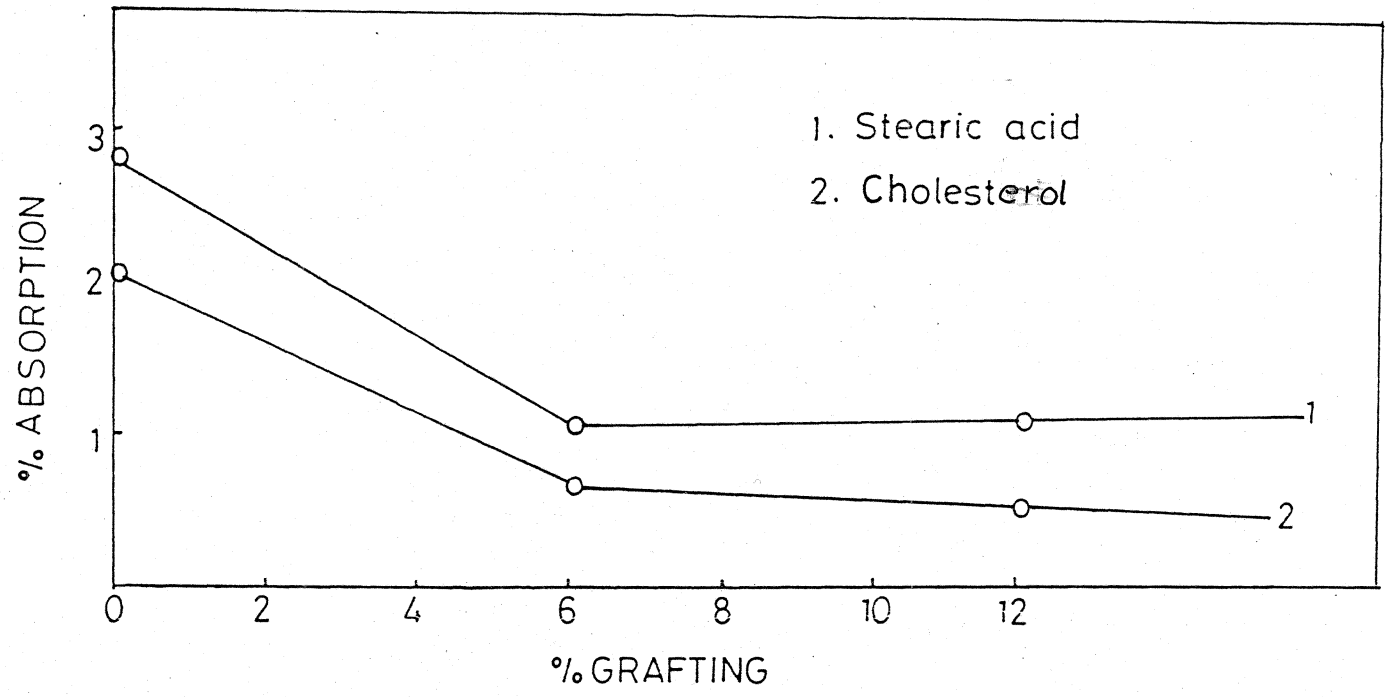


Fig . 4. 56. Variation of equilibrium absorption of diffusants with the extent of grafting of PBA in PU-2 .

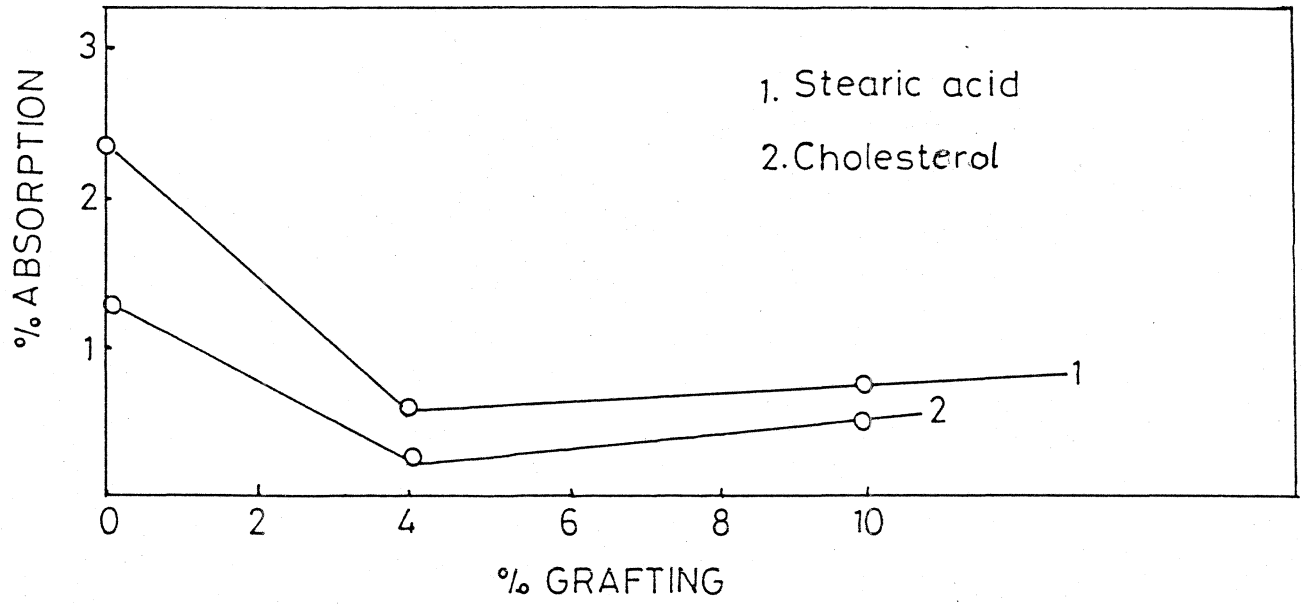


Fig. 4-57. Variation of equilibrium absorption of diffusant with the extent of grafting of PBA in PU-3.

decreases and then slowly increases with the extent of grafting. The factors, as explained above, for the non-linear variation of diffusion coefficients can also be responsible for the typicial absorption behaviour. The enhanced hydrophobicity of the grafts which catalyse the absorption of hydrophobic lipids could also be an additional factor for the increase in absorption with the increase in grafting.

Effect of PMA grafting.

To gain further understanding on the role of flexibility of the grafts on the diffusion of lipids, the studies are extended using PMA grafted polyurethanes. The Tg of PMA is 8°C and the incorporation of the same to the polyurethane expected to raise the Tg of soft segment to certain extent. Again using Fox's equation the calculated Tg of PMA grafts of PU-1 is shown in Table. 4.XXXXV. The summarized data shows that Tg progressively increases to higher scale with the % grafting of PMA. However, it can be inferred that, the graft copolymers also possess considerable degree of segmental mobility since the Tgs are still far below the experimental temperature(37°C). The solubility parameter of PMA is 10.1$(cal/cm^3)^{1/2}$ which probably does not favour a thorough mixing of soft segment and grafted PMA chains as in the PBA grafts.

The diffusion coefficients of two representative lipids are shown in Table.4.XXXXV1. The variation of absorption of these diffusants with % grafting are illustrated in figures 4.58-4.60. Both diffusion coefficients and absorption parameters point out

TABLE 4.XXXXVI

EFFECT OF POLY(MA) GRAFTING ON THE DIFFUSION COEFFICIENT OF LIPIDS IN POLYURETHANE

Polymer	Graft yield (%)	Diffusion coefficient ($x10^7$ $cm^2/sec.$)	
		Stearic acid	Cholesterol
PU-1	0	3.41±0.03	1.62±0.02
	19	2.84±0.04	1.11±0.06
	46	3.34±0.10	1.47±0.09
PU-2	0	2.37±0.04	1.16±0.04
	17	1.47±0.05	0.84±0.06
	39	1.87±0.07	1.08±0.03
PU-3	0	2.01±0.02	0.63±0.03
	15	1.31±0.03	0.47±0.05
	32	1.46±0.04	0.56±0.06

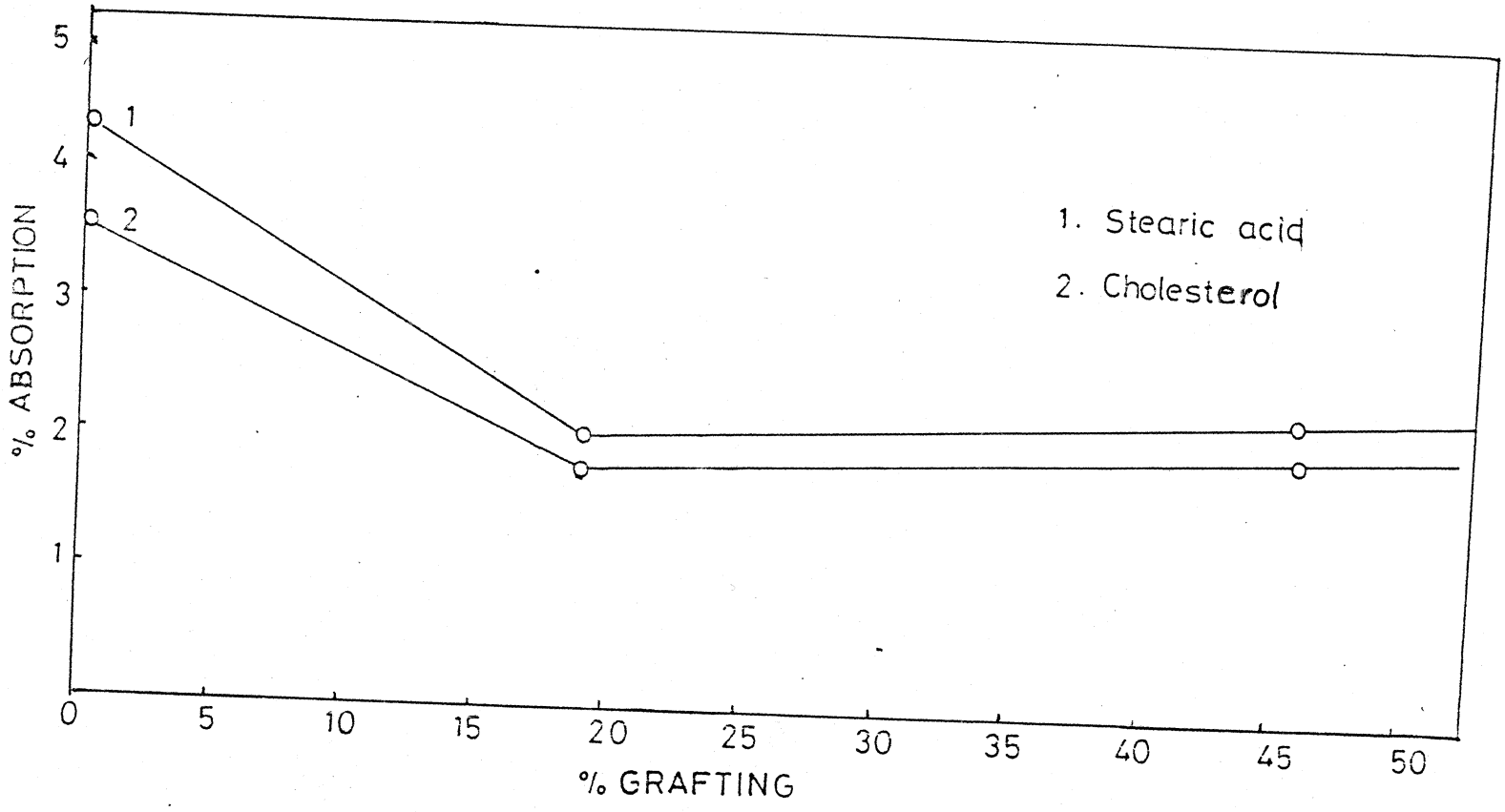


Fig. 4-58. Variation in the equilibrium absorption of diffusants with the extent of grafting of PMA in PU-1

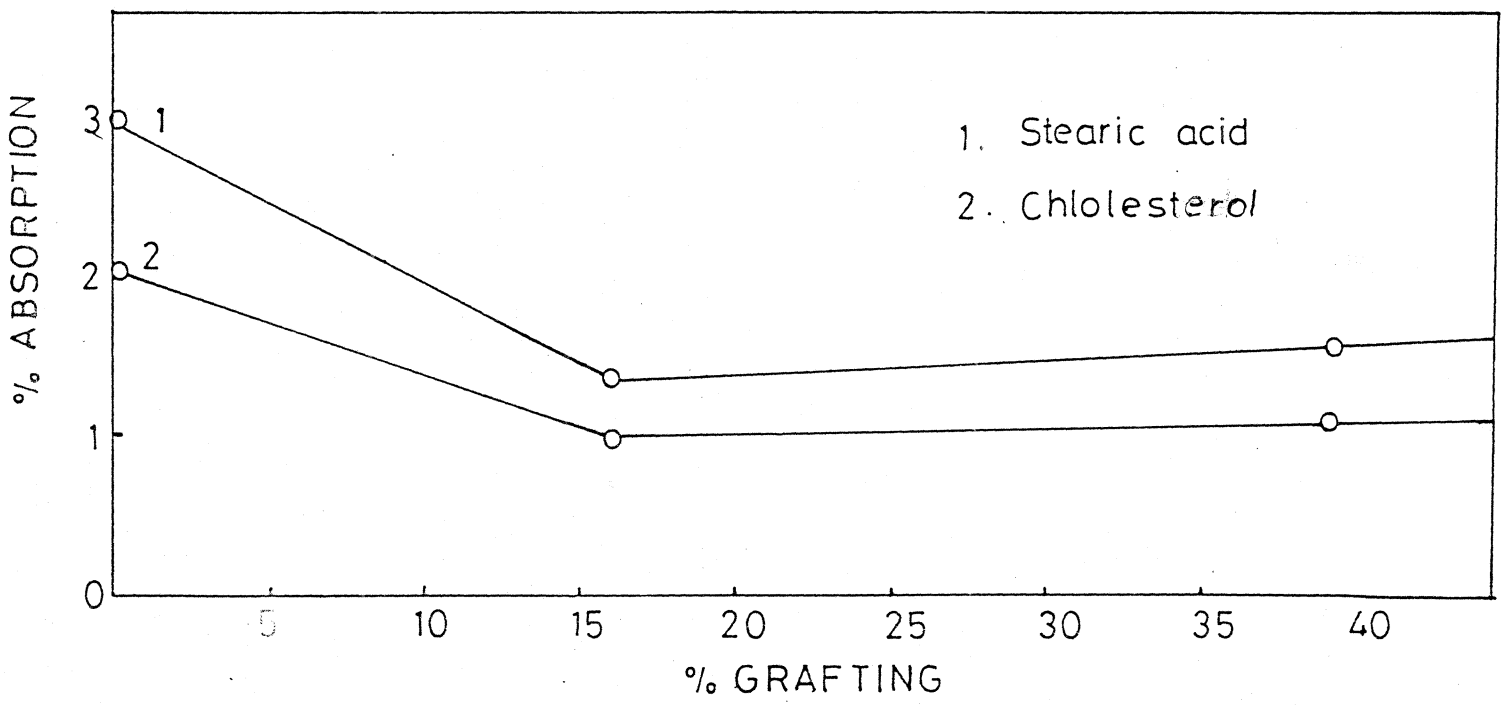


Fig. 4-59. Variation in the equilibrium absorption of diffusants with the extent of grafting of PMA in PU-2

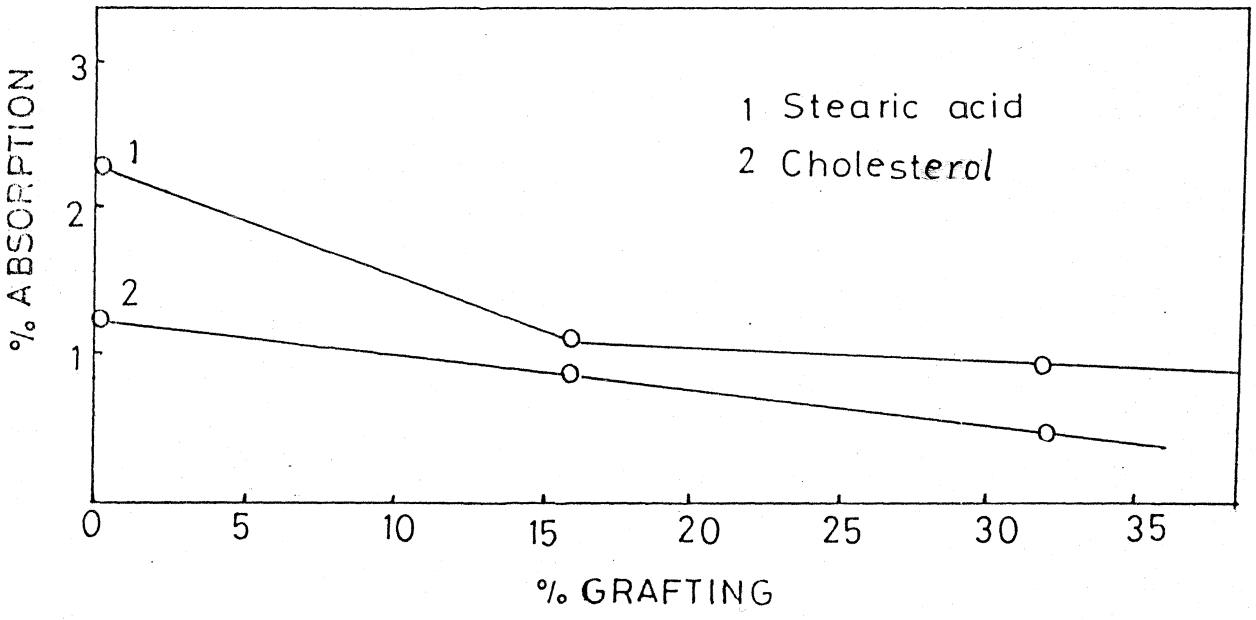


Fig. 4-60. Variation in the equilibrium absorption of diffusants with the extent of grafting of PMA in PU-3.

TABLE.4.XXXXV

Tg OF POLY(URETHANE-g-BA)

% grafting of PMA	Tg(°C)
0	-53
10	-48.1
50	-26.2
90	4.2

that diffusion process is more or less comparable to that of PBA grafts. The noticeable difference is in the absorption profile. The initial reduction in absorption is rather less compared to that of PBA grafts.This is expected due to the less mixing of grafted chains with the soft segment phase as mentioned in the preceeding paragraph. The increase in lipid absorption with % grafting is also apparent in these materials which could be due to, as stated in the case of PBA grafts, to the chain mobility and increased hydrophobicity.

The influence of the characteristics of the grafted chains is apparent from these studies.Few of the funtamental aspects observed during these studies are summarized below.

Hydrophilic grafted species reduce linearly both the diffusion and absorption in polyurethanes. Rigidity of the grafted chains and the increased hydrophilicity are seems to be the factors operative in reducing diffusion and absorption. In the mixed graft,the absorption process is governed by the grafted hydrophilic

lic moieties. The data obtained from the hydrophobic grafts further help to define the mechanism of the diffusion and absorption. The linear variation of absorption of the diffusants with grafting in PMMA grafts conclusively point out that diffusion and absorption is essentially controlled by the segmental mobility rather than the hydrophobic nature of the grafts.The data obtained from the studies using PBA and PMA grafts further confirm the role of chain mobility in lipid absorption.The increased absorption in these materials with the increase of % grafting,however,indicates hydrophobicity could also have a role in determining the extent of absorption.Comparing the results of PMMA, PBA and PMA grafts one can draw the conclusion that, segmental mobility plays the major role while hydrophobicity has only a secondary role in determining the absorption of lipids.

The relationship proposed between G(% grafting required to stop the absorption of stearic acid in PHEMA grafts) and hard segment content seems to be applicable in PVP grafts, mixed grafts and PMMA grafts due to the simple reason that,in these materials also,the absorption vary linearly as well as the theoretical G values depend on the hard segment contents(Tables 4.XXXV111, 4.XXXX and 4.XXX11X). In other words, theoretical predictions are possible in all grafts where a linear relationships between % absorption and % grafting exist.

The process of diffusion of lipids in the graft copolymers,excpet PBA and PMA grafts, points out that the absorption of lipids can be controlled or stopped by grafting these

species which all have a long history of safe usage as biomaterials.

SECTION 4.5

ABSORPTION FROM MIXTURE

The preceeding sections highlight the diffusion and absorption of the individual lipids in polyurethanes. Though these data are helpful in defining various aspects of diffusion in terms of both the characteristics of polymers and diffusants, to get a deeper understanding on the absorption of lipids particularly in the in vivo situation, in which lipids are existing as complex mixture, further studies using lipids mixture are needed. The following sections deals with the intricacies of absorption from a mixture of the components existing in separate media.

4.5.1. Absorption from the silicone oil solution of lipids:

Table 4.XXXXV11 summaries the % absorption of the polymers having varied hard and soft segment content. One noticeable difference is the enhanced absorption in all the materials especially in the case of PU-4 (66% HS). In this material, when the absorption studies are carried out, using individual components only stearic acid was absorbed to nearly 0.85%. From the mixture, the polymer absorbed over 2%. A chromatographic procedure has been developed to separate the lipids and thus to visualise the absorption of lipids from the mixtures.

100 micro litre volume of a standard solution of lipids, prepared by dissolving all the six lipids used in the studies, was injected onto the column. Figure 4.61 shows the chromatographic profile of the lipids. It is apparent that all the lipids are separated well. The analysis time, as evident from the figure, is about 10 min indicating the rapidity of the method. Figure 4.62 shows the chromatogram of the extract of a control polymer sample

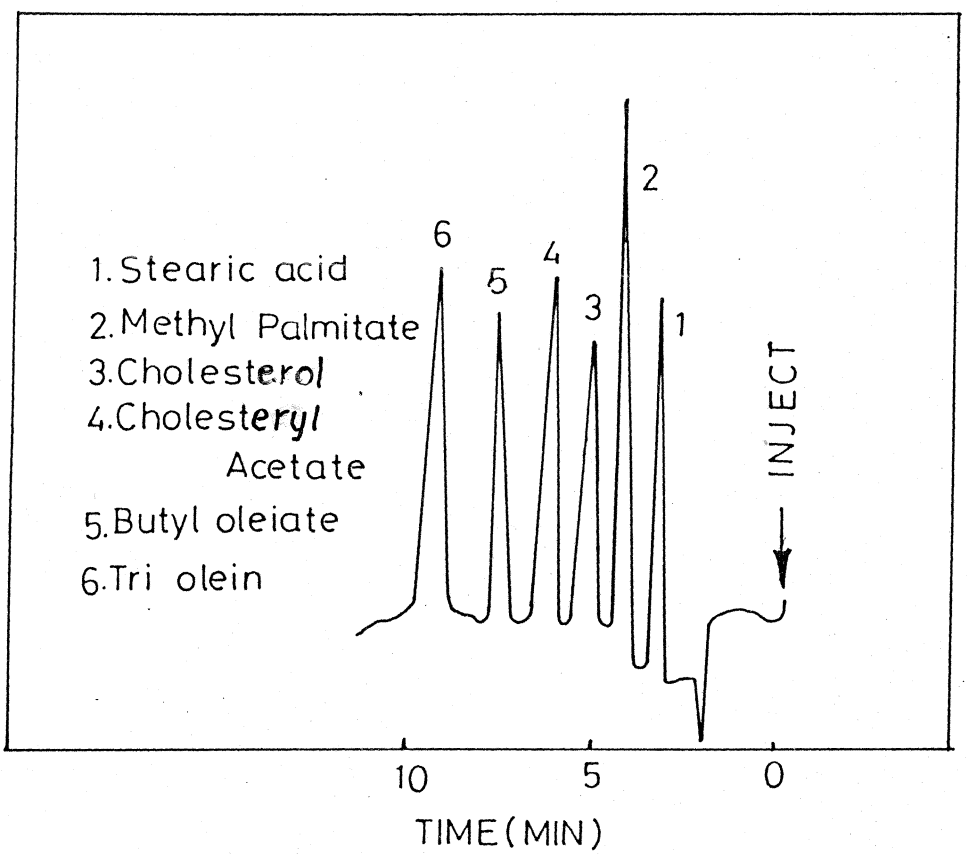


Fig. 4-61. Chromato gram of the mixture of lipids.
Column-μ Bondapak C_{18}
Mobile phase - Methyl alchol: Acetone
(60: 40 V/V)

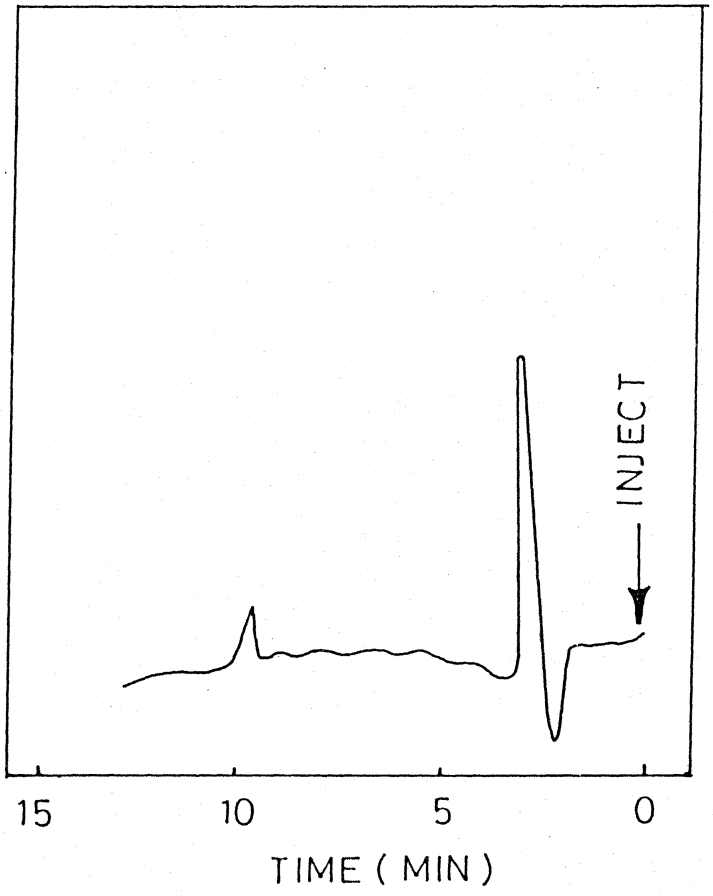


Fig. 4-62. Chromatogram of the extract of a polyurethane sample

The chromatogram shows two peaks at 3 and 9.2 min respectively. These peaks could be assigned to species, presumably, oligomers extracted from the polymer. Typical absorption profile of the polymer from the silicone oil solution of the lipids, in terms of the individual components, is illustrated in figure 4.63 in the form of a chromatogram. The chromatogram shows that the polymers absorb all the six lipids from the mixture. The absorbed components, can have a plasticizing effect, enhancing the chain mobility to create more space enabling further diffusion. The

TABLE 4-XXXXV11

EXTENT OF ABSORPTION FROM MIXTURE OF THE COMPONENTS:EFFECT OF HARD SEGMENT CONTENT.

% Hard Segment	% Absorption from		
	Silicione oil Solution	Aqueous Dispersion	Blood
0	8.12±0.13	4.78±0.09	*
23	5.89±0.16	3.86±0.04	4.73±0.12
33	3.84±0.05	2.61±0.10	3.67±0.14
47	3.15±0.11	2.16±0.01	2.91±0.07
66	2.17±0.03	0.62±0.05	1.36±0.03
100	0	0	0

* Polymer degraded.

plasticizing effect of one of the component and the subsequent

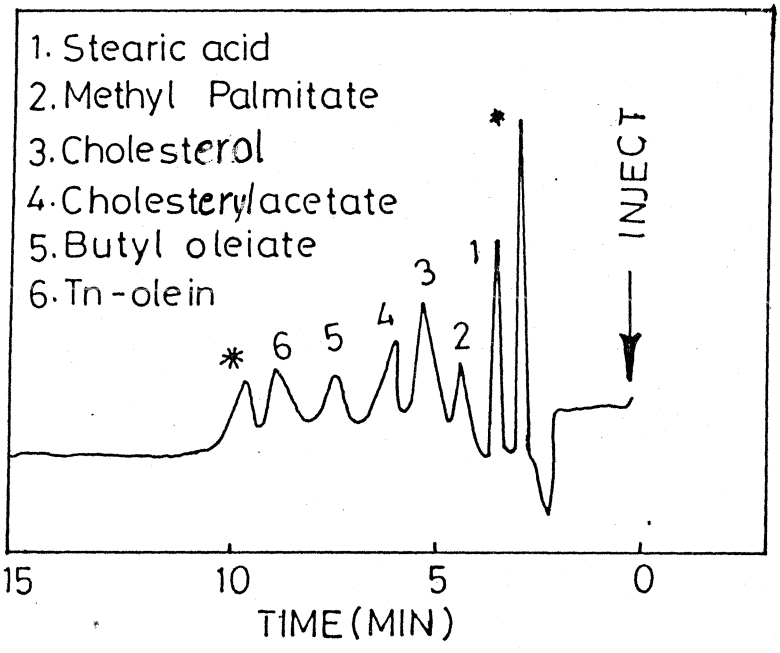


Fig . 4 - 63 . Chromatographic profile of the extract of polyurethane sample kept in silicone oil solution of lipids

* Peaks derived from polymer

effect on the enhanced solubility and permeation has been documented in the diffusion of gaseous mixture in polymers(247,248). Depending upon the hard segment content, the % absorption vary from 8.15 to 2.17%.

4.5.2. Absorption of lipids from aqueous dispersion (Phosphate buffer).

The extent of absorption from the phosphate buffer dispersion of the lipids is also shown in Table 4.XXXXV11. The % asorption is lesser than the extent of absorption from silicone oil solution. In aqueous media, due to the thermodynamic incompatibility, the lipids aggregates. The lessened contact of the lipids with the polymers and reduced probability of diffusion due to aggregation, may be the responsible factors for the reduced absorption.

Figure 4.64 illustrates the chromatographic profile of the absorbed species extracted from the polymer. Interestingly here, the % absorption of methyl palmitate is comparable to that of stearic acid. This is in contrast to what is observed from silicone oil mixture in which the absorption of methyl palmitate, being the smaller molecule among the lipids studied, is extremely low. This anomaly is explained in terms of thermodynamic consideration in section 4.2.1. The chromatographic profile indicates, that thermodynamic aspects do have a role in controlling the absorption process.

4.5.3. Absorption from blood:

Table 4.XXXXV11 summarizes, the absorption from blood by

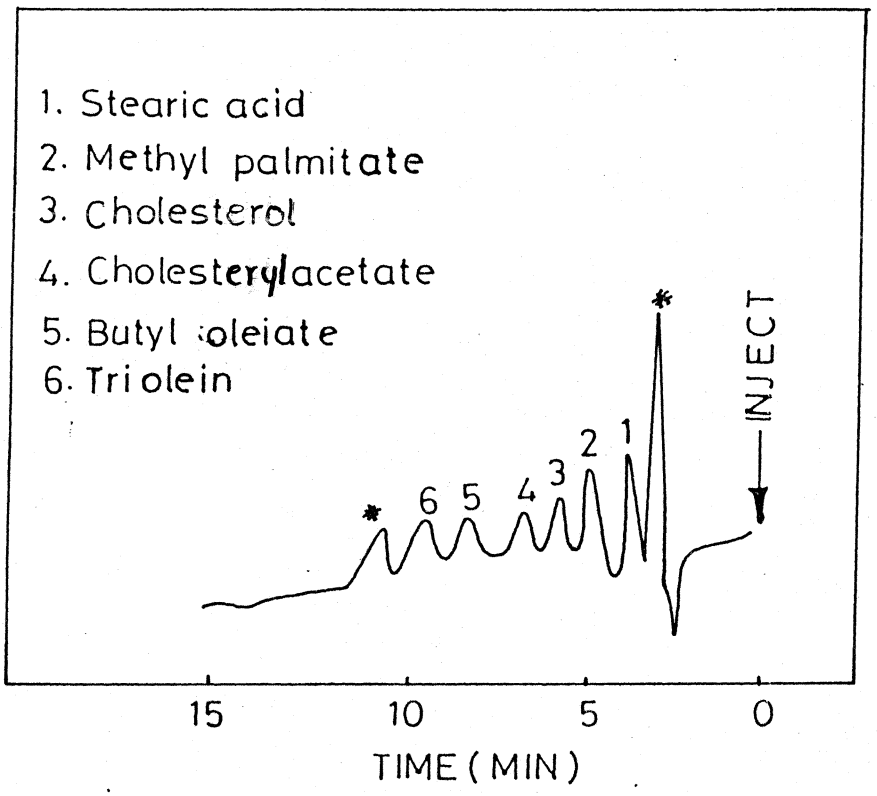


Fig. 4-64. Chromatographic profile of the extract of polyurethane sample kept in phosphate buffer dispersion of lipids

*Peaks derived from polymer

the polymers. The extent of absorption is in between that of silicone oil solution and aqueous disperson. Figure 4.65 traces the chromatographic profile of the components extracted from the materials. Though the figure speaks out the complexity of the absorption, it cannot be used, for assigning the identity of the components with reference to the chromatogram of the standard mixture, due to the possibility of coelution of components having similar characteristics . However, the chromatogram apparantly indicate the absorption of the lipids by the polymer. Figure. 4.66 illustrates the IR spectrum of carbon tetrachloride extract of polymer (PU-1) kept in blood. The spectrum shows several absorption peaks centered around 3400 cm^{-1}, 1750 cm^{-1}, 1200 cm^{-1} etc. characteristics of a typical lipids mixture.

The lipids dispersed in aqueous phase exist as aggregates or more specifically the disperson could be treated as a micellar solution. A micelle in aqueous phase is sphere-shaped aggregates of molecules. The aggregates contain a large fraction of hydrophobic molecules with a minium molecules having hydrophilic and hydrophobic moieties. The aggregates are organized in such way so that the hydrophobic fraction is surrounded by hydrophilic entities orient towards the aqueous phase. When the micelles contact with the polymer having hydrophobic domains, they disrupt and the lipids distribute individually at the surface. The lipids further diffuse into the bulk driven by the concentration gradient if the polymer chains have adequate mobility to create space for the diffusing species. The absorption of lipids from aqueous

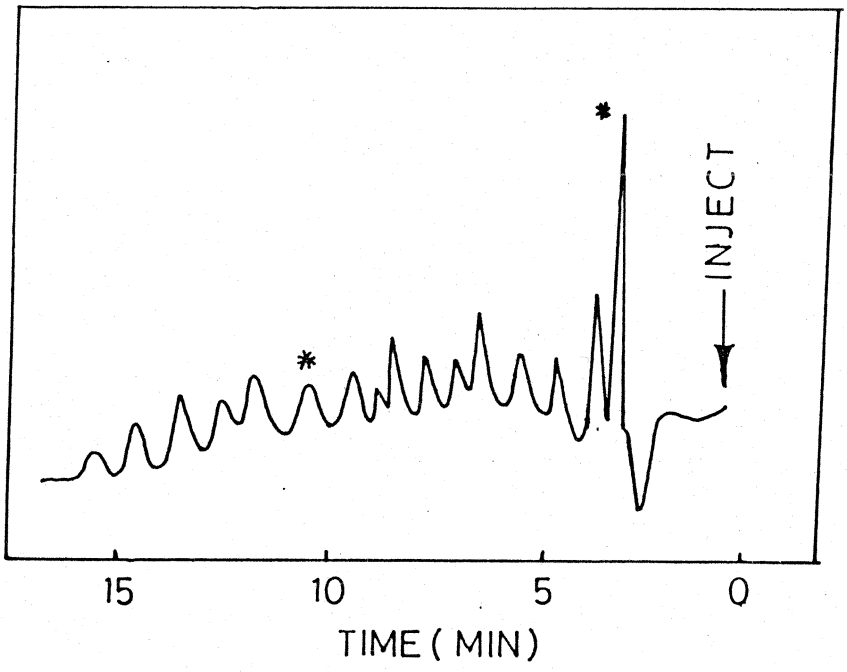


Fig. 4-65. Chromatographic profile of the extract of a polyurethane sample kept in sheep's blood.

* Peaks derived from polymer

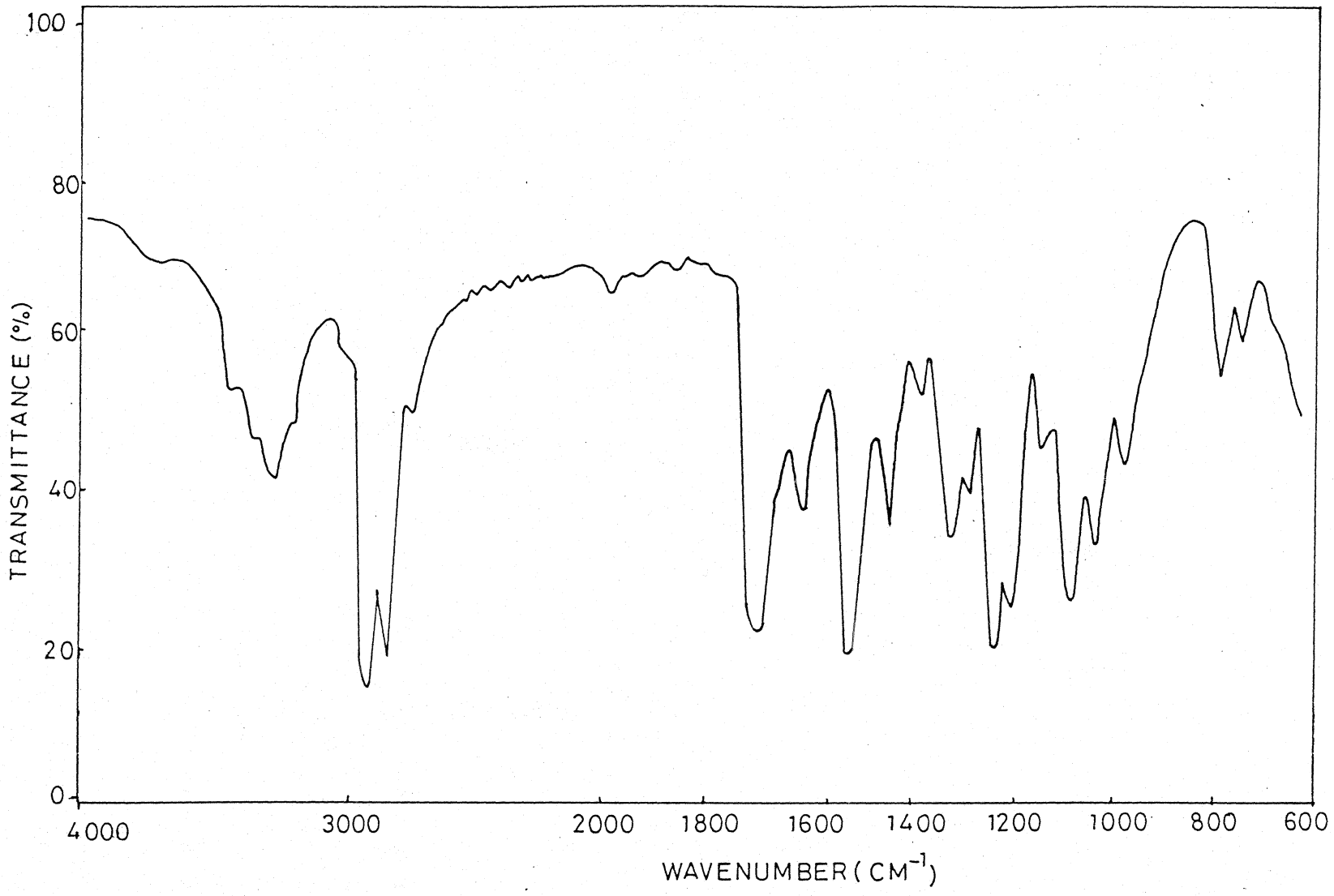


Fig. 4-66 IR spectrum of CCl_4 extract of PU-1 immersed in blood for 30 days.

phase could be visualised in terms of this mechanism. Blood contain several components and it is certainly a different entity in comparsion with the phosphate buffer in which only a limited number of lipids are dispered. It seems, however, that the absorption from blood could also be governed by the same mechanism depicted above.

The absorption data, from these three entirely different media, namely silicone oil, phosphate buffer and blood, suggest that lipids diffuse to the polymers. The absorption, however, is determined by characteristics of diffusing species, and the media in which they are present.

4.5.4. Absorption behaviour of graft copolymers:

Hydrophilic grafts:

Figures 4.67, 4.68 and 4.69 depict the graphical representation of the absorption behaviour of Poly(HEMA), PVP and the binary grafts [Poly(HEMA)+PBA] from different media, namely silicone oil solution of lipids, phosphate buffer dispersion of lipids and sheep's blood, with % grafting. In all the three cases, the absorption from silicone oil solution vary linearly with % grafting similar to that of the absorption behaviour from the solution of individual lipids. The only visible change is the substantially high % grafting required to reduce the absorption to zero. This could be attributed to the plasticizing effect of the absorbed lipids facilitating further absorption.

The absorption profile, from phosphate buffer and blood, however, decrease exponentially with % grafting. The hydrophilic

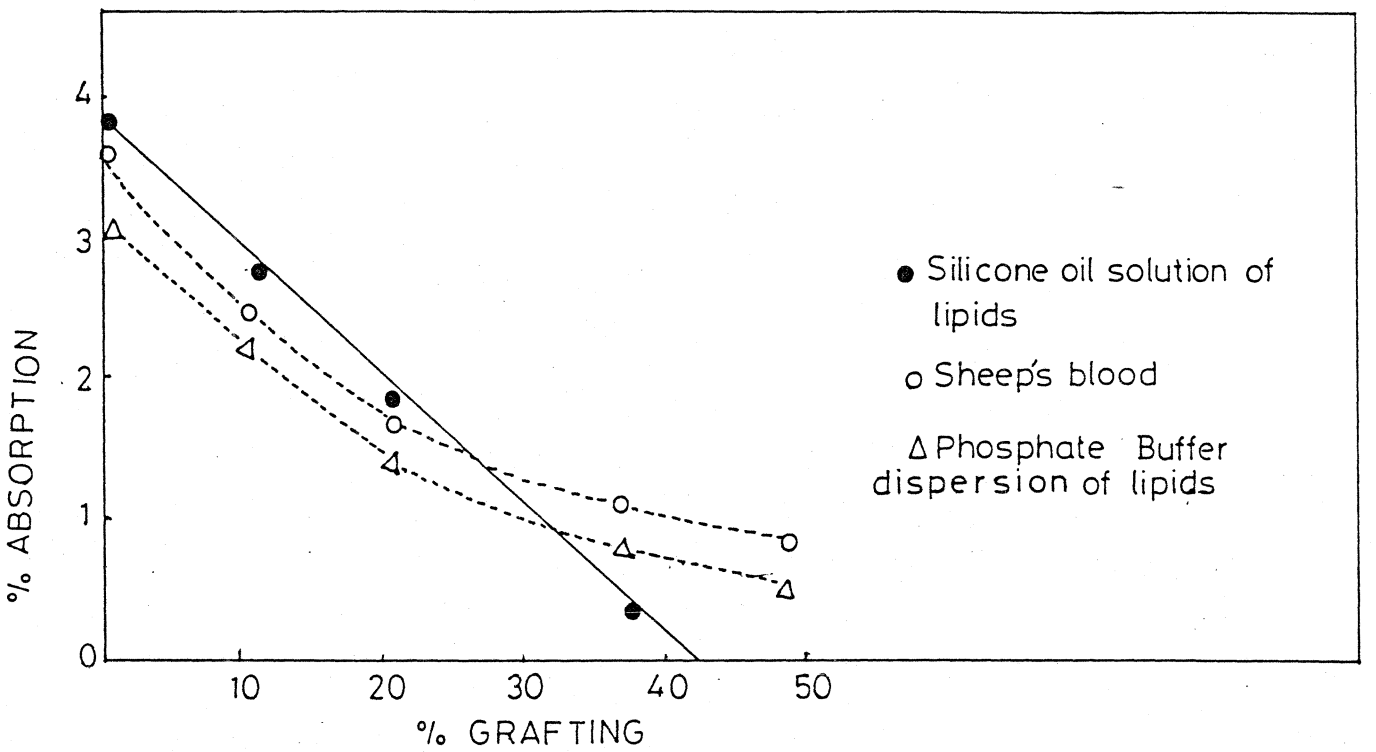


Fig. 4-67. Effect of PHEMA grafting on the absorption of lipids from various media

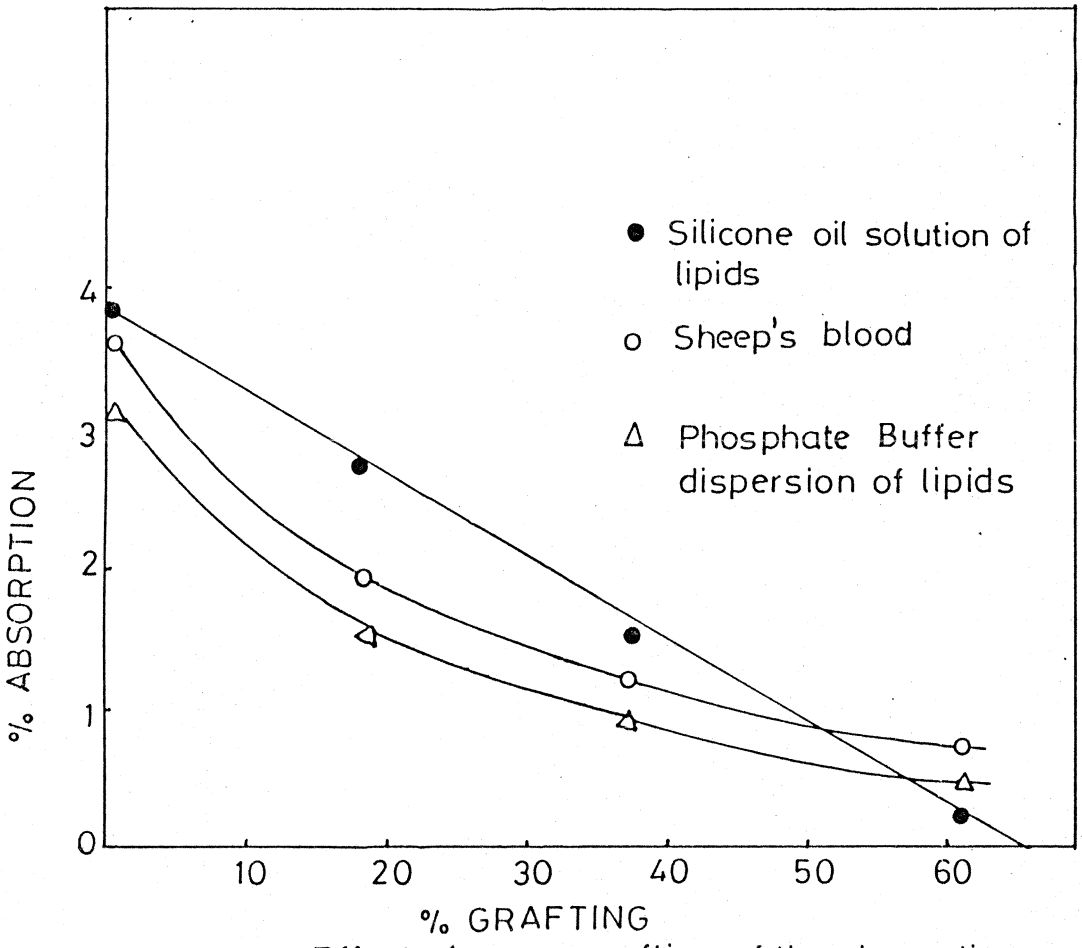


Fig. 4-68. Effect of PVP grafting of the absorption of lipids from various media

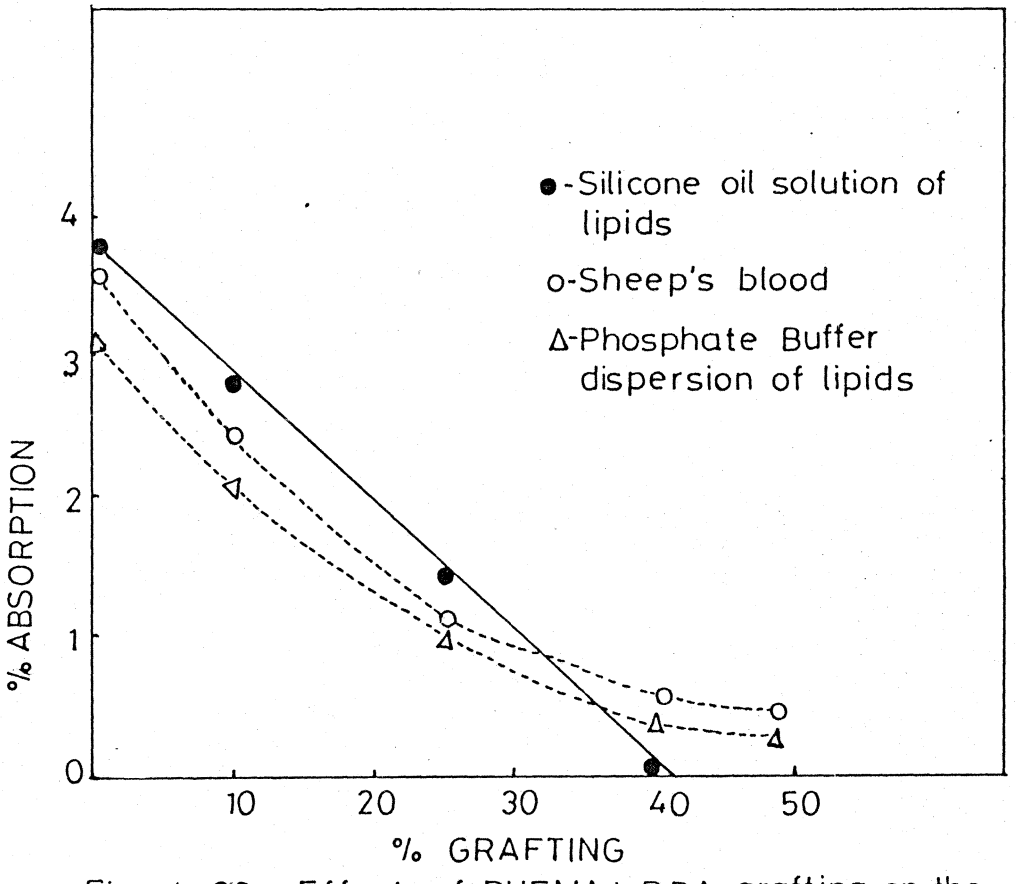


Fig. 4-69. Effect of PHEMA+PBA grafting on the absorption of lipids from various media

grafts absorb water from aqueous phase (phosphate buffer and blood)and swell. The micelles that contact with the swollen polymer find water in the polymer and water in the media alike. The aggregates distributed at the interface then could move into the bulk if interstitial space is available. The increased flexibility of the water swollen grafts and associated segment mobility makes the diffusion possible. Increased water absorption could be expected with a higher percentage of grafting. Subsequently more segmental mobility and enhanced absorption should be expected. However, the absorption rather decreases with grafting, though not linearly.With increased grafting, the hydrophilicity of the materials enhances and the accociated thermodynamic incompatibilty opposes the diffusion of the hydrophobic diffusants. These two opposing factors, the increased hydrophililicity and enhanced chain flexibility, could be attributed to the exponential nature of the absorption profile.

Hydrophobic grafts:

The absorption behaviours of PMMA, PBA and PMA grafts from silicone oil solution, phosphate buffer and blood, with % grafting are illustrated in figures 4.70, 4.71 and 4.72 respectively. The extent of absorption from the three media, vary linearly with % grafting in PMMA graft. The micelles could stablize more easily at the hydrophobic surface of PMMA grafts. Further movement of these molecules to the bulk, however, is impeded by the reduced segmental mobility of the grafts. This propably causes the linear reduction of absorption with the % grafting. The results further

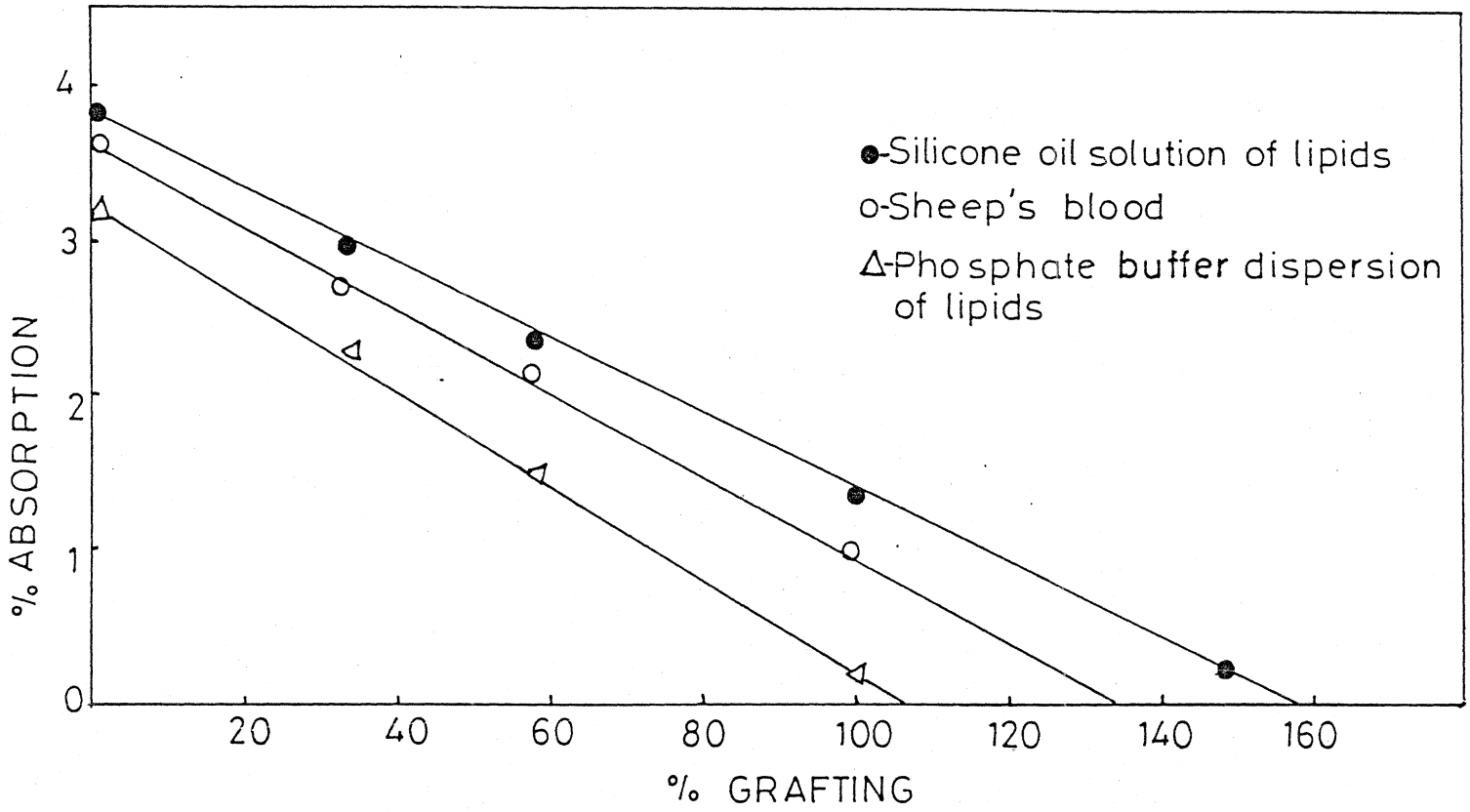


Fig. 4-70. Effect of PMMA grafting on the absorption of lipids from various media

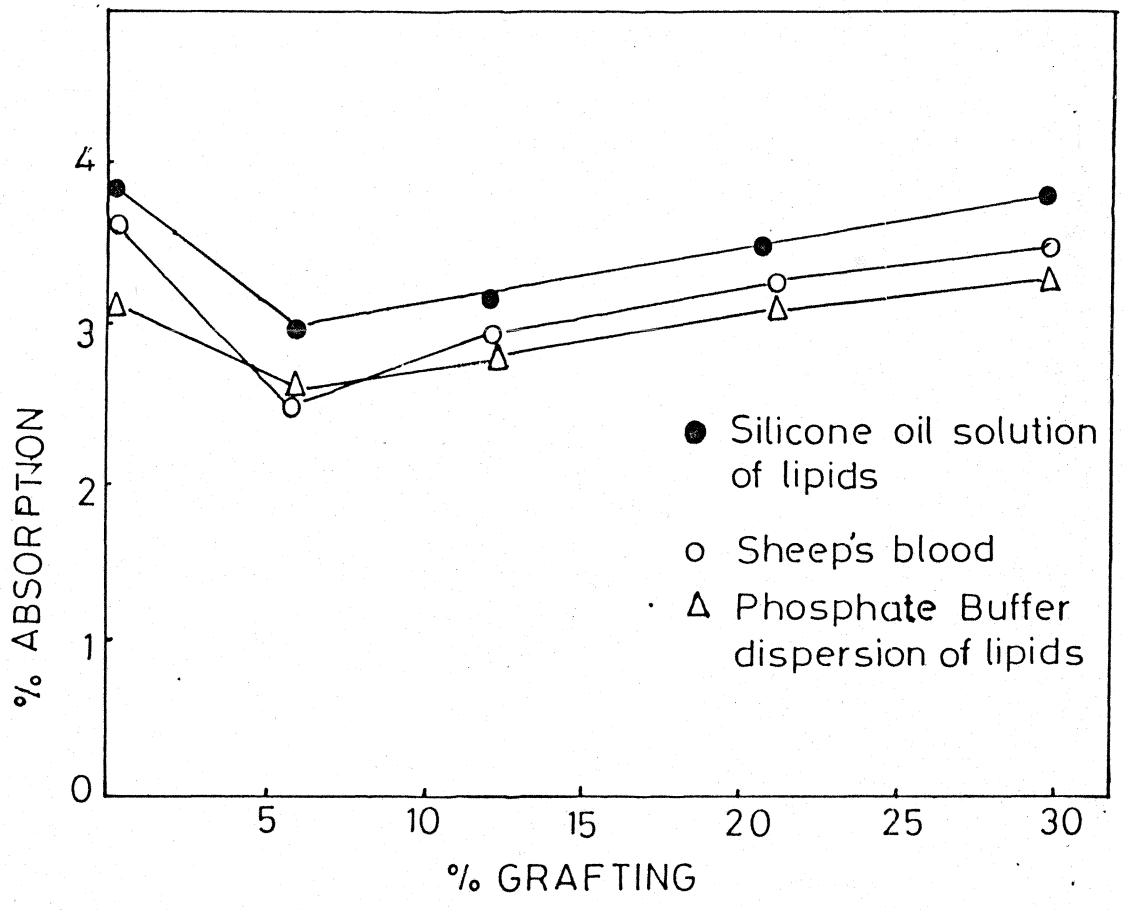


Fig. 4-71. Effect of PBA grafting on the absorption of lipids from various media

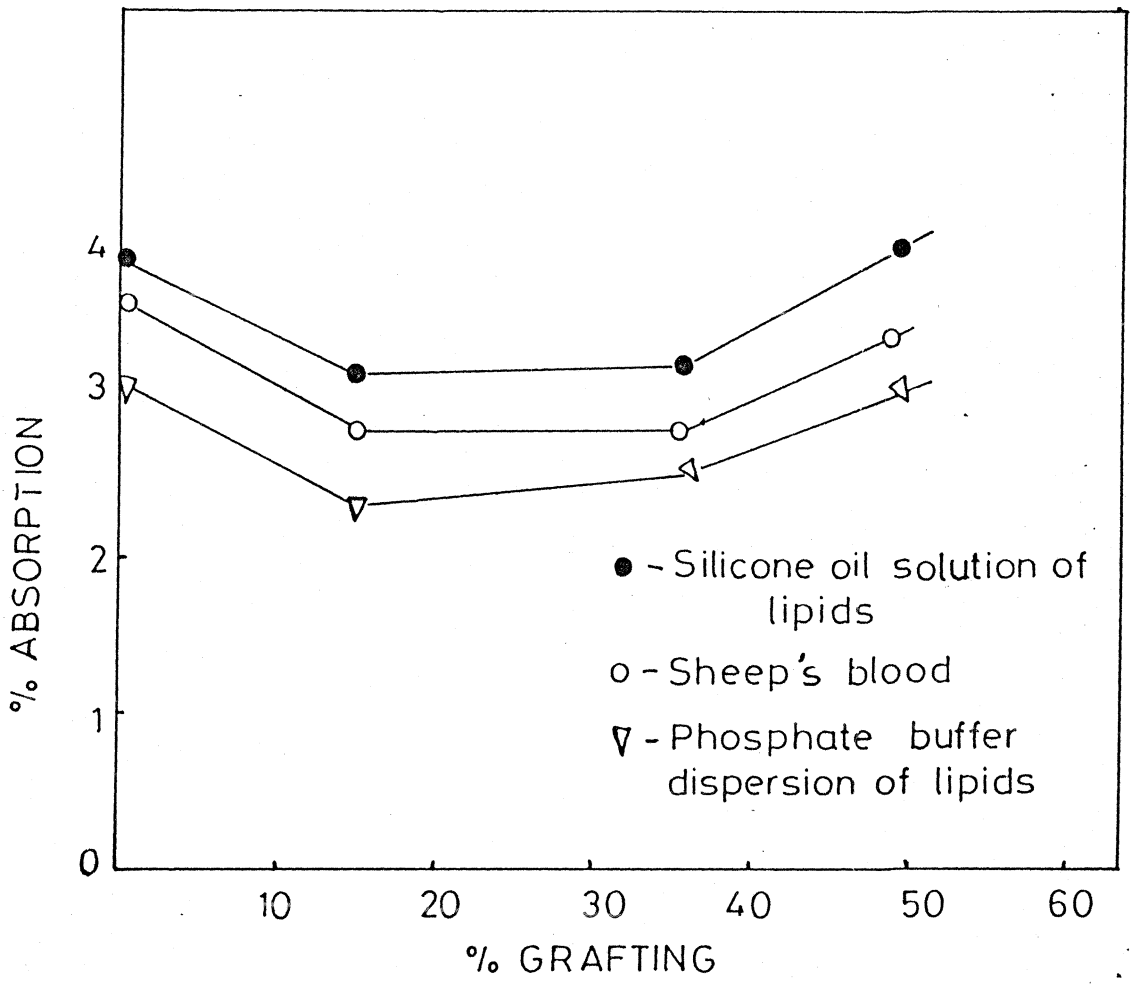


Fig. 4-72. Effect of PMA grafting on the absorption of lipids from various media

further highlight the specific role of chain mobility on the absorption of lipids.

In contrary, the absorption in PBA and PMA grafts show some interesting aspects. The absorption from all the three media decreases initially and then increases with the increase of % grafting. These grafts show the same behaviour when studies were carried out using individual lipids (section 4.4). The initial reduction with grafting could be traced to morphological alteration and subsequent redistribution in free volume. The increased % grafting of these species lead to the formation highly flexible localized regions which catalyse the diffusion of the lipids.

By analysing the absorption behaviour of the different graft copolymers from varied media, it seems that, the degree of chain mobility of the polymers is the governing factor determining the absorption while hydrophilicity or hydrophobicity plays only a secondary role.

CHAPTER 5

SUMMARY, CONCLUSIONS AND FUTURE PROSPECTS

CHAPTER-5

The endeavour to probe into the fundamentals of diffusion and absorbtion of lipids in linear segmented polyurethanes and graft copolymers of polyurethanes has paved the way towards a more perfect understanding of this problem.

The linear segmented polyurethanes synthesized with varied hard and soft segment content are characterized using different techniques. The analytical data provide a detailed picture on the state-of-art of the materials. Though the polymers have a two phase morphology, the extent of phase mxing is found to increase with % hard segment content. Both IR and DSC results confirmed this trend. WAXD data, though rule out the crystallinity, indicate short range ordering in these materials.

The studies, using individual lipids in polyurethanes with varied hard segment content, proved the profound influence of both material characteristics and the diffusing species on the diffusion and absorption. Hard domains are found to be impermeable to the diffusants. By analysing the absorption data in materials having varied hard and soft segment content including 100% soft and 100% hard segment materials, it is observed that the absorption is confined to the soft segment. The absorption values are found to vary exponentially with soft segment content rather than linearly. This is due to phase mixing and subsequent restriction to the mobility of soft segment chains resulting in the reduction of the diffusion.

The diffusion process is found to be Fickian. The diffusion

coefficient of a given lipid is found to decrease with the increase of hard segment content. Activation energy is also found to be more in materials with increased hard segment content. The hard segment domains acting as giant physical crosslinks, reduce the chain movement and increase the activation energy.

From the impermeability of hard domains and the reduction in absorption along with the increase of hard segment content, it appears that, segmental mobility and phase purity are the determining factors for the diffusion. The solubility parameter of soft segments is comparable to that of the diffusing species which additionally favours the absorption to the soft segment. The study further led to propose an empirical equation between % absorption and soft segment content. The equation, $S=S_0(1-e^{-x})^2$, where S is % equilibrium absorption, S_0 is equilibrium absorption in 100% soft segment polyurethane and x is the fraction soft segment, is simple and enables a theoritical prediction of absorption of lipids in polyurethanes.

The studies on the room temperature-stretched materials show orientation in soft segment even after removing the stress and also point out more phase mixing in the stretched samples. Both absorption and diffusion coefficients are found to decrease in stretched polymers. The reduction in % absorption is more visible in material having higher hard segment content. Normally the extent of diffusion reduces to 10-15% in drawn materials. Interestingly here, depending upon the hard segment content, reduction in absorption is as high as 80%, for the bigger diffus-

ants which presumably arises by the enhanced phase mixing. The results emerged from the studies on stretched materials, further support that segmental mobility and phase mixing are the prime factors deciding the absorption.

The data on the graft copolymers provide some interesting findings. In polyurethane grafted with HEMA and NVP, the absorption from silicone oil solution is found to decrease linearly with the increase of % grafting. The altered morphology resulted by grafting and subsequent reduction in chain mobility together with the enhanced hydrophilicity could probably be the reasons for reduction of the absorption. The reduced diffusion in grafts could also be due to the increased tortuosity and chain immobilization factors.

The role of segmental mobility as the major factor deciding the absorption is further reflected in PMMA-grafted samples. The grafting of this monomer, due to its hydrophobicity, should increase the absorption. In contrary, the absorption decreased with the increase of % grafting.The grafting of glassy rigid PMMA presumably reduces the inherent mobility of polyurethane soft segment resulting in a reduction of absorption.

PBA and PMA grafts show interesting results. The absorption initially reduces and begins to increase along with the increase of % grafting. The initial reduction could be due to restructuring of the polyurethane grafts in comparison with that of homo polyurethane. The increase in absorption with subsequent grafting could be traced to two factors, namely the increased

chain mobility, and the formation of more hydrophobic region having chain mobility.

The grafts having binary species, namely PBA and Poly(HEMA), however, show the behaviour of Poly(HEMA) grafts. In comparsion with Poly(HEMA) grafts, the extent of absorption for the binary graft, at a particular % grafting is slightly more which is probably due to the presence of flexible, hydrophobic PBA in the binary graft.

The absorption data obtained from graft polymers, strongly suggest that the important factor influencing the absorption is the chain mobility. The effect of grafting on the absorption led to propose a relationship between the % grafting needed to stop the absorption(G) in polyurethanes and the hard segment content(x). The equation, $G=G_0 e^{-**}$, could be used to predict the extent of grafting needed to arrest the absorption of a given lipid in polyurethane of known hard segment content.

The studies using mixture of the lipids dissolved in-silicone oil show enhanced absorption in polyurethanes.This could be attributed to the plasticizing effect. The absorbed lipids could have a plasticizing effect enhancing the segmental mobility. The absorption from aqueous dispersion is less which can be traced to the less contact of the lipids with the polymer due to the formation of aggregates in aqueous medium. The hydrophilic graft copolymers show an exponential decrease of absorption with the extent of grafting. The hydrophilic species can absorb water loosing rigidity and can have more chain mobility

permitting the diffusion. The enhanced hydrophilicity, however, reduces the absorption of the hydrophobic species. The exponential decrease could probably be due to these two opposing factors. PMMA graft, however, shows a linear reduction in absorption with the increase of % grafting. PBA and PMA grafts show same behaviour observed in the case of silicone oil solution. The absorption characteristics from blood also show similar trend of aqueous dispersion. The extent of absorption is, however, slightly more than that from aqueous dispersion . The increased absorption could be due to the better contact of the components with the polymer and the presence of more components in blood. The chromatograms of the extract of polymers from blood show several peaks indicating diffusion of the lipids. The IR spectrum shows characteristics of lipids, further confirming the chromatographic results.

The affinity of lipids to polyurethanes irrespective of the media in which they are present is more apparent from these studies.

FUTURE EFFORTS:

1. Evaluation of structural changes resulted by lipid absorption.

Lipid absorption is known to affect the mechanical properties of polyurethanes. Efforts will be directed to understand the mechanism of this aspect.

2. Lipid absorption and calcification:

Lipid absorption has been hyphothesized as one of the

several factors leading to the minierlization of blood contacting polyurethane surfaces. A detailed investigation to define the role of lipids in the deposition of calcium salts on the polyurethane surfaces particularly with an aim to understand the fundamental aspects associated with the process will be carried out.

3. On the possible role of lipids on the destabilization of polyurethanes:

Lipid absorption has also been listed among the causatives in degrading polyurethane implant though it has not been proved conclusively. Other routes of degradation, namely, enzymatic, oxidative and hydrolytic, have been subjected to widespread attention. In a similar fashion, the influence of lipids in polyurethane degradation will be investigated

4. Use of diffusion as a probe to understand structural features of polyurethanes:

Diffusion of molecules particularly those scale with the microdomains of polymers has been known to give further insight on the microstructure of the polymers. Variation of diffusional data, in the present work, has been well correlated with the morphological features of polyurethanes like phase mixing. By choosing appropriate molecules as diffusants, it may be possible to define the microstructural parameters of polyurethanes which are inaccessible to conventional techniques.

5. Synthesis of multispecies grafted polyurethanes:

An ideal biomaterial with the mechanical properties of

polyurethanes simultaneously devoid of the undeseriable factors of polyurethanes has yet to emerged. During the course of the present study, polyurethane grafted with a hydrophobic and hydrophilic species simultaneously from a binary mixture has been synthesized to know the absorption profile of lipids in this materials. This material consisting of functionally different species found to have better mechanical properties than of HEMA grafted polyurethanes. Preliminary in vitro studies provided interesting results. More elaborate studies on this material as well as newly synthesized material consisting of two or more grafted species will also be attempted with a view to create better biomaterial.

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APPENDIX-B

ABBREVIATIONS

ACD	Acid citrate dextrose solution
BA	n-Butyl acrylate
CCl_4	Carbontetrachloride
'D'	Diffusion coefficient
DSC	Differential Scanning Calorimetry
DMAC	Dimethyl acetamide
GPC	Gel permeation chromatography
HEMA	2-hydroxy ethyl methacrylate
HPLC	High performance liquid chromatography
$H_{12}MDI$	Methylene bis (p-cyclo hexyl di isocyanate)
HS	Hard segment
IR	Infra red
MAA	Methyl methacrylate
MA	Methyl acrylate
M_t	Mass uptake at time 't'
M_∞	Mass uptake at ∞ time
NVP	N-Vinyl pyrrolidone
PEG	Polyethylene glycol
PPG	Polypropylene glycol
PTMG	Polytetramethylene glycol
PBA	Poly butyl acrlyate
PMMA	Poly methyl methacrylate
PMA	Polymethyl acrylate
PHEMA	Poly(2-hydroxy ethyl methacrylate)
PVP	Poly(N-Vinyl pyrrolidone)
PU	Polyurethane

SS	Soft segment
SEM	Scanning electron microscopy
TGA	Thermo gravimetric analysis
THF	Tetra hydro furan
WAXD	Wide angle X-ray diffraction