SYNTHESIS AND POLYMERIZATION OF NEW PHOSPHONATED MONOMERS FOR DENTAL APPLICATIONS

by

Bahar Yeniad

B.S., Chemistry, Boğaziçi University, 2006

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Chemistry
Boğaziçi University

2008

SYNTHESIS AND POLYMERIZATION OF NEW PHOSPHONATED MONOMERS FOR DENTAL APPLICATIONS

APPROVED BY:

Prof. Duygu Avcı (Thesis Supervisor)	.....
Prof. Viktorya Aviyente	.....
Prof. Gürkan Hızal	.....

DATE OF APPROVAL:

To my family..

ACKNOWLEDGEMENTS

First and foremost, I would like to deeply thank my supervisor Prof. Dr. Duygu Avcı Semiz for her invaluable guidance as well as her encouragement made it possible to complete this study. Without her care, this thesis would not likely have matured.

I would like to thank my commitee members Viktorya Aviyente and Gürkan Hızal for generously giving their valuable time for reviewing the final manuscript and for their constructive comments and suggestions.

I especially thank my labmates, Görkem Şahin, Seda Edizer and Özlem Karahan for making the lab an enjoyable place to work in. Especially, I need to express my deep appreciation to Aylin Ziylan Albayrak for her essential contribution to my knowledge and for her friendship.

I am grateful to Ayla Türkekul and Burcu Selen Çağlayan for their cooperation in never-ending NMR analysis and Nihan Çelebi for dipole moment calculations. I would like to extend my thanks to all members of the Chemistry Department and to our lovely secretary, Hülya Metiner for their kind help whenever i need and for the fun during delicous dishes served after the famous bell.

I want to acknowledge my lovely friends and colleagues, especially Ayşegül Dağlı and Esra Altuntaş, for always offering their kind help and support.

Special thanks go to Asım Can Kolay for his understanding throughout my study and for his love which makes life easier.

Last and surely not least, I thank all my family for giving me the opportunity to be here and for their everlasting support during my studies.

This work was supported by grants from TUBITAK [106S178] and Boğaziçi University Research Fund (07HB504).

ABSTRACT

SYNTHESIS AND POLYMERIZATION OF NEW PHOSPHONATED MONOMERS FOR DENTAL APPLICATIONS

Three novel phosphonated monomethacrylate monomers have been synthesized and studied for their potential use as monofunctional reactive diluents in dental materials. The monomers are based on glycidyl methacrylate (GMA) and are synthesized (i) via reaction of GMA and (diethoxy-phosphoryl)-acetic acid (monomer 1) (ii) via reaction of GMA and (2-hydroxy-ethyl)-phosphonic acid dimethyl ester (monomer 2) (iii) via reaction of monomer 2 and diethylchlorophosphate (monomer 3).

In addition a novel phosphonated dimethacrylate monomer (monomer 4) has been synthesized for the potential use in dental composites. It was prepared by the reaction of Bisphenol A diglycidylether (DER) with (diethoxy-phosphoryl)-acetic acid and subsequent conversion of the resulting diol to the dimethacrylate with methacryloyl chloride. Hydrolysis of this monomer with trimethylsilyl bromide (TMSBr) gave a new phosphonic acid-containing monomer (monomer 5) which can be used in dental adhesive formulations.

The homopolymerization and copolymerization behaviors of the synthesized monomers with glycerol dimethacrylate (GDMA), triethylene glycol dimethacrylate (TEGDMA) and 2,2-bis[4-(2-hydroxy-3-methacryloyloxy propyloxy) phenyl] propane (Bis-GMA) were investigated using photodifferential scanning calorimetry at 40 $^{\circ}$C using 2,2'-dimethoxy-2-phenyl acetophenone (DMPA) as photoinitiator. It was found that monomer 1 and 2 homo- and copolymerize rapidly giving approximately more than 90 per cent conversion within 60 s of UV exposure. In addition to fast rate and high conversion, crosslinked polymers were obtained. These monomers also showed high crosslinking tendencies during thermal bulk and solution polymerizations. Therefore these monomers will show the advantageous properties of crosslinked systems such as great hardness and good resistance to organic solvents, chemicals and UV radiation. Monomer 3 also showed very similar reactivity to monomer 2 in homopolymerization resulting 90 per cent

conversion. As a result these novel mono-functional (meth)acrylates can be used as reactive diluents to improve the cure efficiency, material properties and binding ability of dental composites. The polymerization reactivity of monomer 4 was found to be comparable to commercial dental monomers such as Bis-GMA, TEGDMA and GDMA with higher conversion (more than 70 per cent) than both Bis-GMA and GDMA although it has very rigid and bulky structure, which is very desirable for dental composites.

ÖZET

DİŞÇİLİK UYGULAMALARI İÇİN FOSFOR İÇEREN YENİ MONOMERLERİN SENTEZİ VE POLİMERİZASYONU

Fosfonat grubu içeren üç yeni monometakrilat monomeri sentezlendi ve dişçilik malzemelerinde mono-fonksiyonel reaktif seyreltici olarak kullanılma potansiyelleri incelendi. Monomerler glisidil metakrilata dayanmakta olup (i) glisidil metakrilatın (dietoksi-fosforil)-asetik asit ile reaksiyonundan (monomer 1) (ii) glisidil metakrilatın (2-hidroksi-etil)-fosfonik asit dimetil ester ile reaksiyonundan (monomer 2) (iii) monomer 2'nin dietilklorofosfat ile reaksiyonundan (monomer 3) sentezlenmişlerdir.

Ek olarak diş kompositlerinde kullanılma potansiyeli olabilecek fosfonat içeren yeni bir dimetakrilat monomeri (monomer 4) sentezlendi. Bu monomer Bisfenol A diglicidileterin (DER) (dietoksi-fosforil)-asetik asit ile reaksiyonu ve oluşan diolun metilakriloil klorür ile metakrilata dönüşümünden sentezlendi. Bu monomerin trimetilsilil bromür (TMSBr) ile hidrolizi fosfonik asit içeren ve diş yapıştırıcı formulasyonlarında kullanılabilecek yeni bir monomer (monomer 5) verdi.

Sentezlenen monomerlerin homo- ve gliserol dimetakrilat (GDMA), trietilen glikol dimetakrilat (TEGDMA) ve 2-bis[4-(2-hidroksi-3-metakriloiloksi propiloksi fenil] propan (BisGMA) ile kopolimerizasyonları 2,2'-dimetoksi-2-fenil asetofenon (DMPA) katalizörlüğünde 40 ºC de Foto Diferansiyel Taramalı Kalorimetre (Photo-DSC) ile incelendi. Monomer 1 ve 2'nin çok hızlı homo- ve kopolimerleşerek UV ışığında 60 saniyede yaklaşık yüzde 90'dan fazla polimere dönüştükleri bulunmuştur. Yüksek hız ve dönüşüme ek olarak, çapraz bağlı polimerler elde edilmiştir. Monomerler ısı ile çözücülü ve çözücüsüz polimerleştirildiklerinde de çapraz bağlanma eğilimi göstermişlerdir. Bu nedenle bu monomerler polimerleştiklerinde çapraz bağlı sistemlerin sahip olduğu yüksek sertlik, organik çözücü, kimyasal ve UV radyasyonuna karşı direnç gibi avantajlara sahiptirler. Monomer 3 homopolimerizasyonda monomer 2 ye çok benzer bir reaktiflik göstererek yüzde 90 dönüşüm vermiştir. Sonuç olarak bu yeni mono-fonksiyonel

metakrilatlar, diş kompositlerinin polimerleşme verimini, malzeme özelliklerini ve dişe bağlanma yeteneklerini arttırmak amacıyla reaktif seyrelticiler olarak kullanılabilirler. Monomer 4'un polimerizasyon reaktifliğinin Bis-GMA, TEGDMA ve GDMA gibi ticari dişçilik monomerlerinin reaktifliğine yakın olduğu, esnek olmayan ve hacimli yapısına rağmen diş kompozitlerinde çok istenilen özelliklerden Bis-GMA ve GDMA'dan yüzde 70 daha fazla yüksek dönüşüme gittiği bulunmuştur.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

k_p	Propagation rate constant
R_p	Rate of polymerization
T_g	Glass transition temperature
CI	Co-initiator
CQ	Camphorquinone
DSC	Differential Scanning Calorimetry
NMR	Nuclear Magnetic Resonance Spectroscopy
PI	Photoinitiator
FTIR	Fourier Transform Infra Red Spectroscopy
TEA	Triethyl amine
UV	Ultra Violet Spectroscopy
TGA	Thermal Gravimetric Analysis
AIBN	Azobisisobutyronitrile
V-50	2,2'-azo-bis(2-amidinopropane)dihydrochloride
Irgacure 651	2,2-dimethoxy-2-phenylacetophenone
Bis-GMA	Bisphenol A glycolate dimethacrylate
TEGDMA	Triethyleneglycol dimethacrylate
GDMA	Glycidyl dimethacrylate
HEMA	Hydroxyethyl methacrylate
TMSBr	Trimethylsilyl bromide

1. INTRODUCTION

1.1. Dental Material

1.1.1. Anatomy of Tooth

Teeth are hard, bone-like structures in the upper and lower jaws in mouth.

A human tooth consists of three main parts [1]:

1. Crown; the visible part of the tooth above the gum (gingiva)

2. Neck; the region between crown and root at the gum line

3. Root; the region below the gum and inside the alveolar bone, which keeps the tooth in place (Figure 1.1) [2].

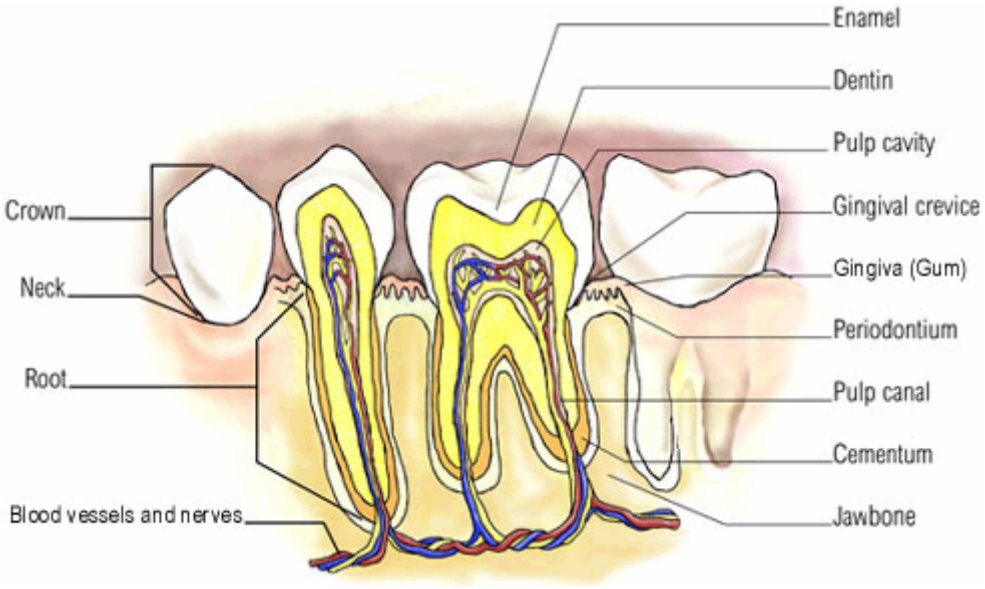


Figure 1.1. The anatomy of tooth

The outermost, white and shiny layer of the crown is called *enamel*. It contains tightly packed rows of calcium and phosphorus crystals with in a protein matrix, which makes the enamel the hardest tissue in the human body, even harder than bone. It protects

the underlying dentin. Once the enamel has been formed, there is a little turnover of its minerals during life. Mature dentin is not considered to be a living tissue [1,3,4,5].

Dentin is the major component of the inside of the tooth and it surrounds the pulp from crown to root under the enamel. It has a bone-like structure comprised of a succession of tiny dentinal tubulus imbedded in a dense homogeneous matrix of collagenous proteins and reaching from the pulp to the dentin-enamel junction. The tubular structure of dentin makes it porous with the tubules serving as the portal through which stimuli enter the pulp. Therefore, it is thought to be a 'live' tissue. Dentin is slightly softer than enamel as well as elastic and compressible in contrast to the brittle structure of enamel [1,3,4,5].

The dentin in the root of the tooth is covered with a layer called *cementum*. Cementum is a hard bone- like substance onto which the periodontal membrane attaches and mainly consists of mineral salts and water. The periodontal membrane contains elastic fibres to allow some movement of the tooth within its bony socket and bonds the root of the tooth to the bone of the jaw [1,3,4,5].

Dentin and enamel are mainly composed of two different materials: hydroxyapatite and collagen in combination with water at different ratioes (Table 1.1).

Hydroxyapatite refers to the group of calcium phosphates. The name apatite has been given to group of materials that are described by the general chemical formula:

$M_{10}(XO_4)_6Z_2$ with $M^{+2} = Ca^{+2}$ or Ba^{+2}; X= P, V, Cr, Mn; $Z^- = F$, OH

Hydroxyapatite [$Ca_{10}(PO_4)_6OH_2$] is the inorganic part of the natural bone and teeth and it is formed in solution in the presence of salvia and other complex physiological fluids.

Collagen is the family name of macromolecular proteins which contain a huge amount of glycine, proline and hydroxyproline providing hydroxyl, carboxyl and amino groups which can be utilized in bonding to this structure [6, 7].

Table 1.1. Composition of Hard Tissues by percentage of volume and weight

	Bone(%)	Dentin(%)	Enamel(%)
Mineral	41	48	92
	(64)	(69)	(97)
Organic	48	29	2
	(31)	(20)	(1)
Water	11	23	6
	(5)	(11)	(2)

Note: % of weight shown in parantheses.

The *pulp* has the central chamber of the tooth. The pulp is made of soft tissue and contains blood vessels to supply nutrients to the tooth, and nerves to enable the tooth to transmit sensations to the brain like heat, cold and pain. It also contains small lymph vessels which carry white blood cells to the tooth to help fight bacteria [1,3,4,5].

The extension of the pulp within the root of the tooth is called the *root canal.* The root canal connects with the surrounding tissue via the opening at the tip of the root. This is an opening in the cementum through which the tooth's nerve supply and blood supply enter the pulp from the surrounding tissue [1,3,4,5].

The *smear layer* has been described as a combination of organic and inorganic microcrystalline debris of cementum and dentin which forms in response to instrumentation such as scaling and root planing, or can occur by burnishing the tooth with a toothbrush, toothpick or other device [8].

1.1.2. Dental Restorative Materials

The main concern of the dentistry is the repair and the treatment of the teeth to give the proper function and esthetics. The main treatment is the repair of tooth damaged by

caries. Although dental caries is apreventable, they have been very widespread and possibly the most common disease of the civilised world.

Dental carries occur as a result of metabolic activity by the bacteria of plaque, leading to the formation of acids, i.e lactic acid from sugar in the diet, and involves a localised attack on the enamel and dentin of the tooth. Carries begin on the surface of the tooth and goes into the bulk, slowly through the enamel and very rapidly through the dentin. Although dental caries are not immediately life threatening, they can lead to serious conditions and even can be fatal. Therefore dental repair is very important and developing the ideal restorative material has been the goal of the many research [6].

Although there has not been introduced any material that meet all of the requirements, there are some features that can be listed for an ideal dental restorative [9].

- Biocompatible (nontoxic, noniritating, nonallergic)
- Mechanically and dimensionally stable and durable
- Resistant to corrosion or chemicals
- Minimally conductive both thermally and electrically
- Esthetic (tooth-colored)
- Easy to handle
- Adherent to tissues
- Tasteless and odorless
- Cost effective

There are two main classes of dental restorations: *Direct* restorations done by inserting filling material directly into the tooth and *indirect* restorations fabricated outside of the mouth (Table 1.2) [10,11].

Table 1.2. Dental restorative materials

Direct Restorative	**Indirect Restorative**
Amalgams	Porcelain (ceramic)
Composite resins	Porcelain fused to metal
Glass ionomer cements	Gold alloys
Hybrid materials	Base metal alloys

Recently esthetic materials made of ceramic and plastic have been taken the attention because they mimic the the appereance of the natural tooth and are more esthetically pleasing where they are visible. However the conventional restoratives such as amalgams, gold and base metal alloys are commonly used due to their strength and durability [9].

1.1.2.1. Amalgams

Amalgams have been used widely for over a centruy in the dentistry for the restoration of teeth. Dental amalgams made of liquid mercury and powdered alloy with the composition of 65-70 wt per cent Ag, 25-27 wt per cent Sn, 0-6 wt per cent Cu and 0-2 wt per cent Zn.

In order to prepare the alloy of dental amalgam, the components are melted together under inert atmosphere and then homogenized at 400 °C for 6-24 hours. The powder is prepared via sawing and the powder is heated at 60-100 °C for few hours. After the amalgam alloy and the mercury freshly mixed, the cavity in tooth is filled with the paste-like material and the amalgamation occurs in mouth via the reaction given below [12].

$$Ag_3Sn + Hg \longrightarrow Ag_2Hg_3 + Sn_{7\text{-}8}Hg$$

Dental amalgam fillings are widely used beacuse they are very strong and durable, they last longer than most other types of fillings (up to 10-20 years), and they are relatively inexpensive [13].

Amalgam is not very technique sensitive and tends to be *self sealing* which is unique to amalgam restorations. Self sealing means that a small amount of corrosion takes place underneath the filling and this corrosion is water resistant and fills microscopic voids between the tooth and the filling preventing further corrosion and the entry of fluids containing sugar and bacteria which are the agents that cause decay [14].

Although amalgam fillings are well tolerated by patients with only rare occurrences of allergic response and no current scientific evidence is available to prove a serious health risk in humans, there is a concern about a possible toxicity due to possible absorption of vapor emitted from amalgam by the patient through inhalation, ingestion or by other means. Because of the concern about its toxicity, the application of amalgam is forbidden since 1997 in Sweden [15]. Amalgams show a short-term sensitivity to hot and cold temperatures The silver-colored filling is not as esthetically pleasing as one that is tooth-colored, especially when the restored tooth is near the front of the mouth (Figure 1.2) [16]. And lastly, beacuse there is no adhesion between amalgam and the tooth, the cavity must be prepared to retain amalgam by making the bottom of the cavity slightly larger than the top, which requires the removal of more tooth structure compared to other types of direct fillings [16,17,18].

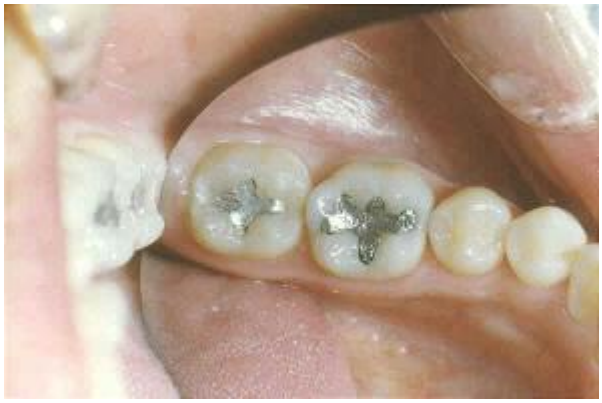


Figure 1.2 General appearance of amalgams

1.1.2.2. Glass Ionomer Cements (GICs)

Glass ionomer cements consist of a water soluble polymeric acid and an ion leachable basic glass, typically a calcium fluoro-alumina silicate. They are basically acid-

base cements and set via neutralization of the acid groups on the polymer by the powdered, solid base. The aim was to produce a cement that have characteristics of both the silicate cement (translucency and fluoride release) with those of the polycarboxylate cement (ability to chemically bound to tooth structure and kindness to the pulp).

Modern cement powders (by weight) are composed of silicon dioxide (41.9 %), aluminum oxide (28.6 %) and calcium fluoride (15.7 %). They may also contain aluminum phosphate (12 %), aluminum fluoride (8 %), and sodium fluoride (9 %).

The liquid is an aqueous solution of polymers and copolymers of acrylic acid, itanoic acid, maleic acid or tartaric acid.

The setting reaction involves three phases. First, when the powder and polymeric acid solution are mixed, hydrogen ions released from polyacrylic acid in water attack the peripheries of the glass particles leading to the release of calcium, aluminum and fluoride ions, and the formation of a silica-based hydrogel around the involved glass particles (Figure 1.3) [19]. Then the polyanion chains chealate with the Ca^{+2} and Al^{+3} ions migrate from the silica hydrogel into the aqueous cement phase along with F^{-} ions and form inter and intramolecular salt bridges resulting in a hard, ionically crosslinked structure (Figure 1.4) [20]. The calcium polycarboxylates form over the first 5 minutes while the stronger and more stable aluminum polycarboxylates form over 24 hours resulting in physical properties improve gradually. Lastly a slow hydration of both the silica-based hydrogel and the polycarboxylates occurs resulting in a further improvement in the cement's physical properties.

Fluoride release which acts as a good antibacterial and protects against the decalcification of the surrounding tooth structure, reduces microleakage and occurence of secondary carries that is greatest immediately after placement and diminishes over time.

GICs are moderately hard, brittle materials, with a relatively high compressive strength, but lower fracture toughness, flexure strength and wear resistance compared to amalgams and composites. They set via an acid/base reaction that is fully capable of

occurring in the dark and exhibit little to no exothermic reaction. They have inherent adhesion to tooth structure and there is no free monomer left in the set matrix.

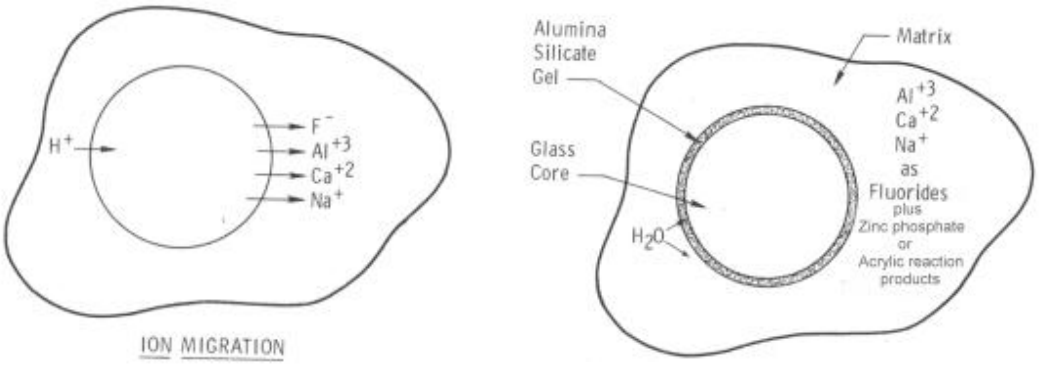


Figure 1.3. A schemetic presentation for ion exchange and formation of silica-based hydrogel

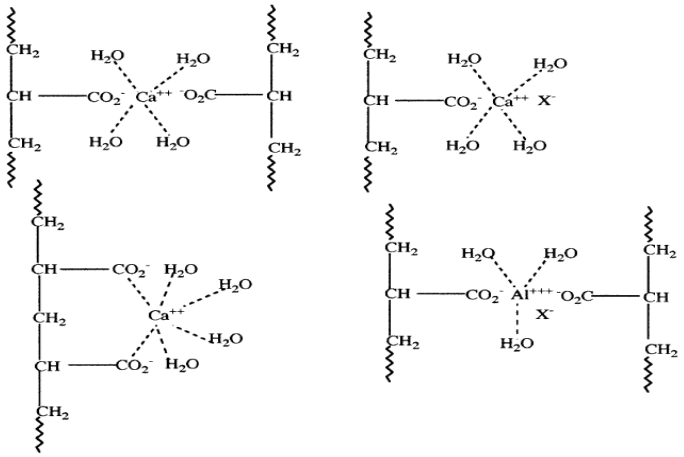


Figure 1.4. Possible intra and intermolecular Ca^{+2} and Al^{+3} carboxylates (salt bridges or molecular structures) in cured GIC, where X represents OH^- or F^-

However, GICs show an early moisture sensitivity which requires protection immediately after placement and they are vulnerable to dessication. They also have low resistance to acids which may lead to disruption of ionic cross-links [20,21].

1.1.2.3. Composites

There has been an increasing demand for the esthetic appealing tooth-colored restorations of the anterior lesions and the defects in the posterior region in the dentistry and hence direct composite fillers which give good clinical results have been taking great attention.

Composite is a mixture of an organic matrix and inorganic fillers (Table 1.3) [22].

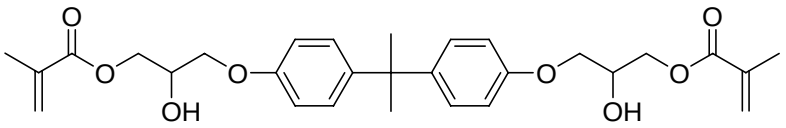
Table 1.3. Typical composition of dental composites

Dental composites		
Inorganic filler	75-85 wt %	Barium alumino silica glass Quartz etc..
Organic filler	15-25 wt %	Polymerizable monomers Initiator system Stabilizar, pigments

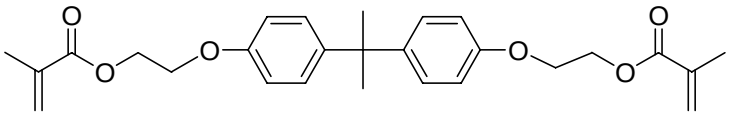
The organic matrix mainly contains methacrylic monomers. The basic physical and chemical requirements are listed below.

- High rate of photopolymerization and crosslinking properties
- Low volume shrinkage
- Optimal mechanical properties and wear resistance
- T_g above 60 °C and low water uptake of the cured resin
- Excellent resistance to oral conditions
- High light and coloration stability of the formed polymer
- Storage stability in the presence of dental fillers and additives
- Low oral toxicity, no mutagenic or cancerogenic effect

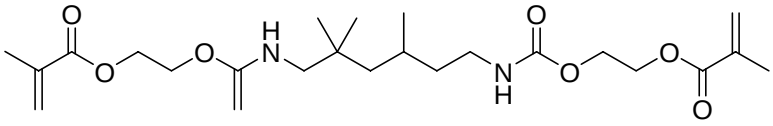
The figure 1.5 shows commonly used commercial methacrylate based monomers in dental composite filling materials.



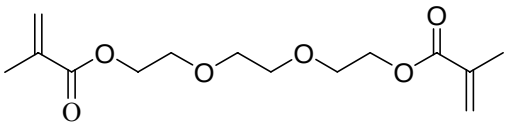
Bisphenol A glycolate dimethacrylate (Bis-GMA)



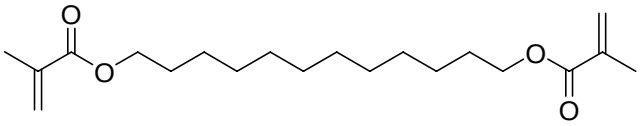
Bisphenol A ethoxylated dimethacrylate (EBPDMA)



Urethane dimethacrylate (UDMA)



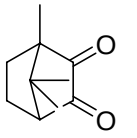
Triethyleneglycol dimethacrylate (TEGDMA)



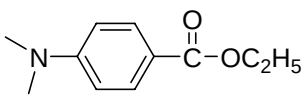
Dodecanediol dimethacrylate (D_3MA)

Figure 1.5. Structure of dimethacrylates frequently used in dental composite filling material

Composite materials are cured by irradiation with visible light in the wavelength range 400-500 nm. Camphorquinone (CQ) which has an absorption maximum at 468 nm is commonly used as the photoinitiator along with an amine accelarator such as ethyl p-dimethylaminobenzoate (DMAB) as a co-initiator (CI) in dental composites [23,24].



Camphorquinone (CQ)



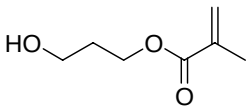
Ethyl-p-dimethylaminobenzoate (DMAB)

Figure 1.6. Structures of CQ and DMAB

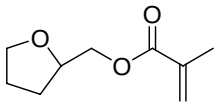
Bis-GMA is widely used in most of the commercial visible light curing restorative materials because its bulky and rigid core provides good mechanical properties and a relatively less polymerization shrinkage (~6 per cent) [25]. Reduced toxicity due to its lower volatility and diffusion to tissues are other advantages. Bis-GMA also contains hydroxyl groups which enhance the adhesion of the material to tooth but these groups are also responsible for high viscosity (1.0-1.2 kPa.s at 23 °C) and sorption of water. Due to high viscosity it does not permit the use of high amount of filler which will improve mechanical properties and reduce shrinkage as well as the thermal expansion coefficient. Therefore a less viscous monomer as diluent monomer, generally TEGDMA is added to Bis-GMA in a ratio of 30-50 wt per cent to achieve easier handling, higher filler loading and greater extent of polymerization. The conversion of Bis-GMA/TEGDMA system has been increased to 60-75 per cent compared with 40-50 per cent conversion of BisGMA. However the incorporation of TEGDMA increases volume shrinkage which damages the composite/tooth bonding and initiates bacterial leakage and limits the lifetime of dental composites [15, 26].

Increased double bond conversion, decreased volume shrinkage and fast rate of polymerization are important factors to improve performance of dental composites. Monofunctional monomers as reactive as multifunctional acrylates and methacrylates that allow almost 100 per cent conversion are highly desirable for dental applications. Therefore research has been carried out to find i) alternative reactive diluent monomers that can replace TEGDMA and overcome the aforementioned problems or ii) new methacrylates with low viscosity to eliminate diluent monomers.

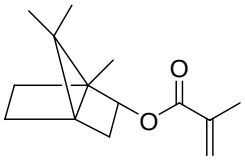
There is a variety of alternative monomers which have been synthesized to replace TEGDMA. Monomethacrylates such as tetrahydrofurfuryl methacrylate (THFMA), hydroxypropyl methacrylate (HPMA) and isobornyl methacrylate (IsoBMA) were copolymerized with Bis-GMA. Although copolymerization of Bis-GMA with these mono methacrylates exhibited lower shrinkage than Bis-GMA/TEGDMA, decreased double bond conversions were obtained (Figure 1.7) [27].



Hydroxypropyl methacrylate (HPMA)



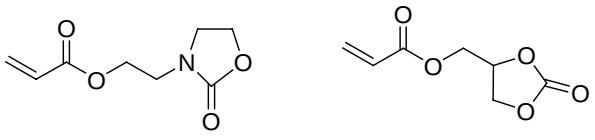
Tetrahydrofurfuryl methacrylate (THFMA)



Isobornyl methacrylate (IsoBMA)

Figure 1.7. Chemical structures of HPMA, THFMA and IsoBMA

Decker et al. were found that acrylic monomers containing a second non-vinyl functionality such as oxetane, dioxolane, oxazolidone or carbonate group copolymerize rapidly to about 90 per cent conversion within 0.02 seconds of UV exposure. Also some of these monomers gave crosslinked polymers with great hardness, high flexibility and good resistance to solvents (Figure 1.8) [28].



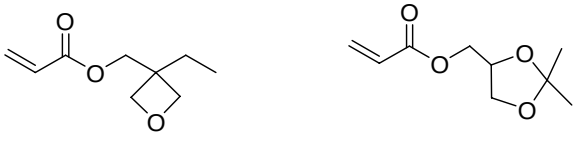


Figure 1.8. Acrylic monomers containing an oxetane, dioxolane, oxalidone or carbonate group in their structural units

Lu et al synthesized a series of ultra-high- reactive mono-(meth)acrylates that contain secondary or even tertiary functionalities, such as cyclic acetal, carbamate, carbonate and morpholine as reactive diluents (Figure 1.9). The polymerization shrinkage was significantly reduced (almost 30 per cent less than that of Bis-GMA/TEGDMA in case of Bis-GMA/ morpholine carbamate methacrylate) and final double bond conversion increased when these mono (meth)acrylates were substituted for TEGDMA [29].

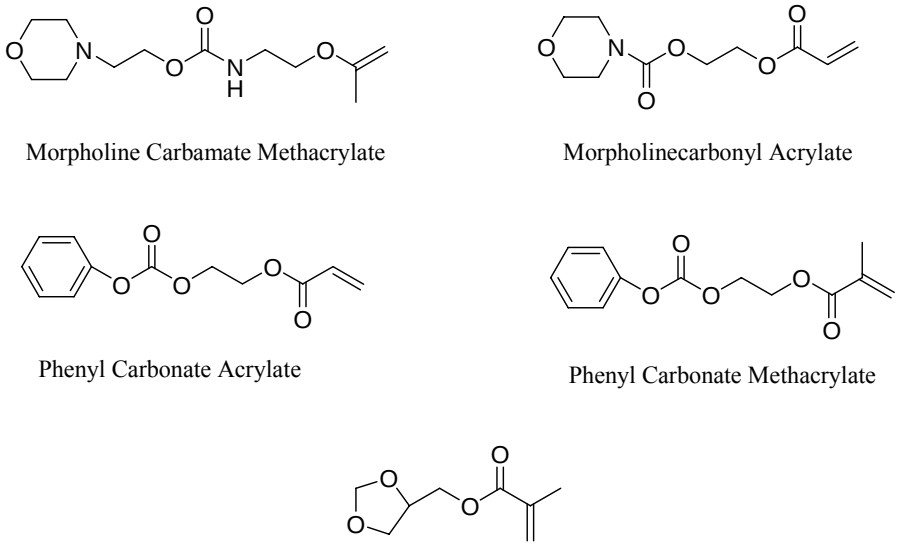
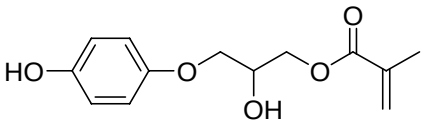


Figure 1.9. Chemical structures of the monomers investigated by Lu et al.

Another reactive diluent which was employed in dental composite to reduce polymerization shrinkage by Kim et al (Figure 1.10) [30].



Tris-[4-(2'-hydroxy-3'-methacryloyloxypropoxy)phenyl]methane

(TTEMA)

Figure 1.10. Structure of TTEMA

In addition a novel monofunctional Bis-GMA analog was also introduced by Rueggeberg et al to have improved monomer conversion while keeping the desirable Bisphenol A rigid structure in the monomer (Figure 1.11) [31].

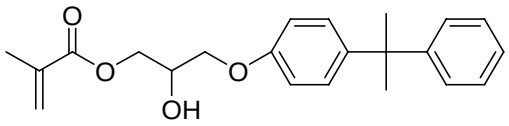


Figure 1.11. Monofunctional Bis-GMA analog

Unfavourable properties of Bis-GMA also have led to development of highly hydrophobic fluorinated Bis-GMA (Figure 1.12) [32] analogous and modified Bis-GMA monomers (Figure 1.13) [33] as alternative to Bis-GMA, which are aimed to reduce polymerization shrinkage and release of fluoride to prevent secondary caries as well as to improve mechanical properties and biocompatibility by reducing the elution of components [7,25].

Another route to obtain a good composite material is to eliminate diluent monomers as well as Bis-GMA and its derivatives and to find new methacrylates with low viscosity. Urethane dimethacrylates are found to have lower viscosity even if they have molecular weights nearly equivalent to Bis-GMA. Therefore urethane dimethacrylates are promosing alternatives to Bis-GMA/TEGDMA systems with improved hydrolytic stability, greater flexibilty and improved toughness. Figure 1.14 shows some urethane dimethacrylates proposed in literature [34,35].

Apart from the aforementioned monomers, some other monomers have been introduced focusing on ring-opening monomers with the potential of low shrinkage [36-43], cross-linking monomers with a new architecture (mesogenic units, hyperbranched structures) [44-46] or solgel polycondensates [47,48].

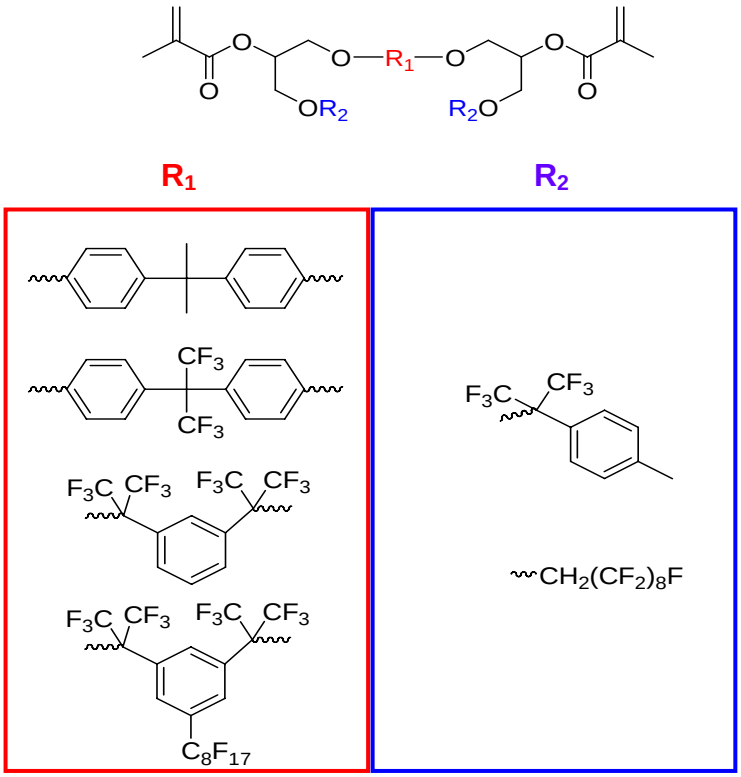


Figure 1.12. Fluorinated Bis-GMA analogs

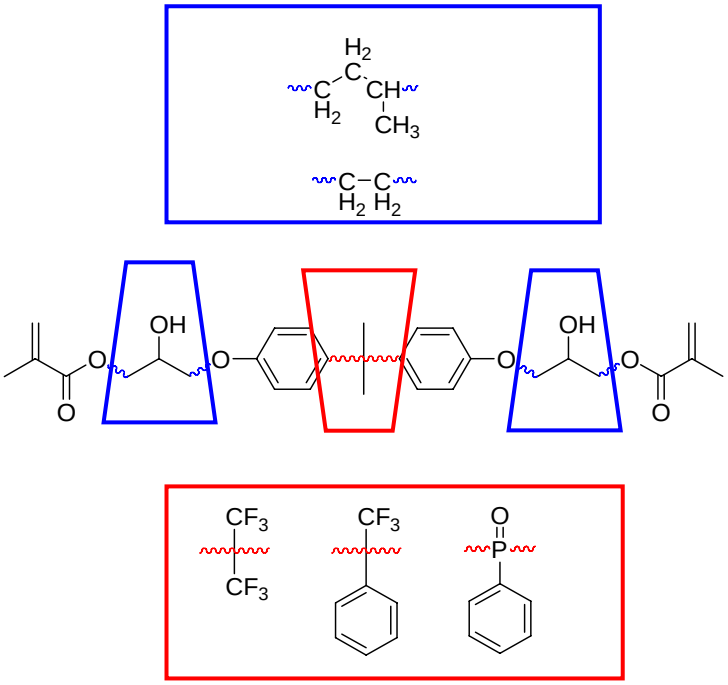


Figure 1.13. Modified Bis-GMA structures

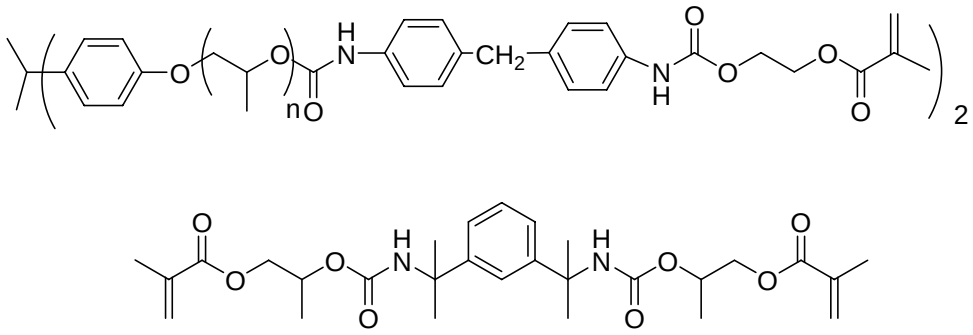


Figure 1.14. Examples of urethane dimethacrylates

It is showned that the polymerization shrinkage can be reduced by ring-opening polymerization of cyclic monomers whereas these monomers are less reactive than methacrylate based monomers. The effect of liquid- crystalline or hyperbranched monomers to the polymerization shrinkage is found to be more limited. Therefore the combination of these monomers with ring-opening groups seems to be promising [7].

Monomers with phosphonate function have been proposed to increase the biocompatibility and the binding of the resin to tooth structure, which are also very desirable for a dental material (Figure 1.15) [49].

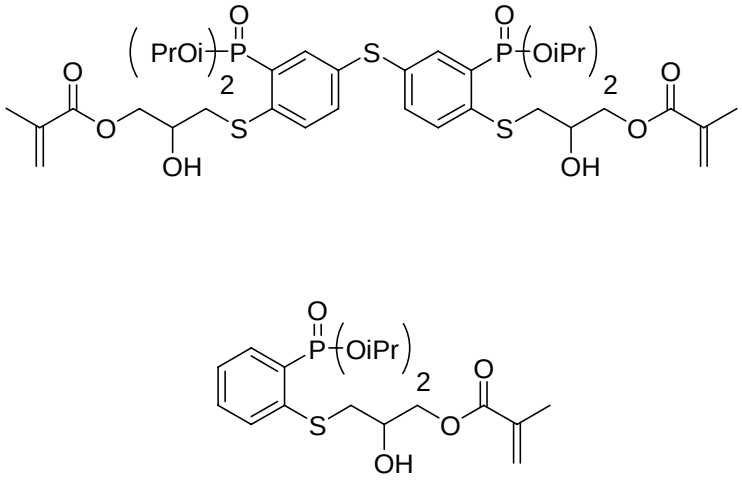


Figure 1.15. Phosphonated analogues of Bis-GMA

The properties of composite restorative materials, such as polymerization shrinkage, radiopacity, mechanical toughness, viscosity, appearence, etc. are remarkably influenced by the fillers that are used along with.

Conventional fillers based on grinded barium, strontium silicate or fluorosilicate glasses with a particle size of about 1-2 μm are used in combination with highly dispersed SiO_2 or Si based mixed oxides with a particle size of 10-500 nm. However these nanoparticles are often agglomerated.

Another attempt to reduce polymerization shrinkage of composites is to admix high density polyethylene spheres to a composite. The addition of 20 wt per cent resulted in about 30 per cent stress reduction compared to conventional composites.

A more promising way to reduce polymerization shrinkage was to add fillers which expand during polymerization such as ammonia-modified montmorillonite. The addition of 4 to 5 per cent ammonia modified montmorillonite resulted in zero polymerization shrinkage.

In addition to avoid possible bacterial colonization adjacent to the filling composite, antimicrobial or antibacterial agents such as fluoroaluminosilicate, chlorohexedine or silver nanoparticles have been added to composite filling materials [48].

Current composite materials provide good esthetics and mechanical properties (Figure 1.16). They are also prefered for the avoidance of mercury pollution of the enviroment. However the lifetime for anterior polymeric restorative materials is about 8 years and is not longer than 2-4 years for posterior materials which seems to be very short compared to conventional dental amalgams. Thereby the investigations towards improving the composite resins are carried on [15].

Figure 1.16. A comparison of the apperance of amalgam and composite resins

1.1.2.4. Hybrid Materials

Hybrid materials are resin modified glass-ionomer cements which involves both photo-chemical process (from organic phase) and neutralization reaction (from glass ionomer phase) (Figure 1.17).

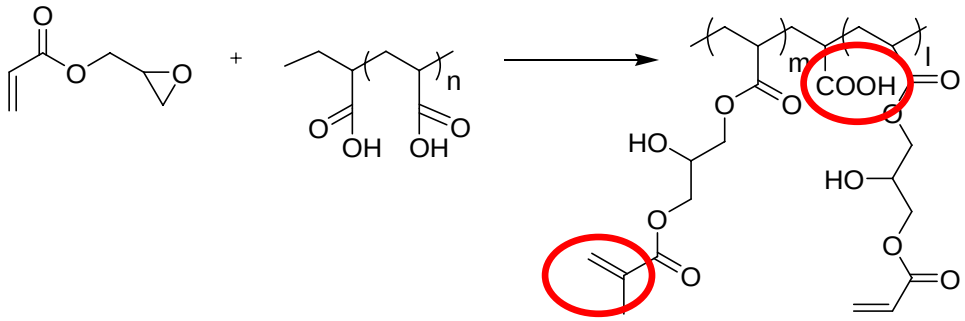


Figure 1.17. Synthesis of a hybrid material

Another type of hybrid material known as compomers is also introduced. The name ‘compomer’ is a combination of *compo*site and glass iono*mer* and refers to a water-free, single component, light cured composites consisting of acid modified dimethacrylate combined with silanized calcium-, strontium- or barium-aluminum-fluorosilicate glass particles [50].

Figure 1.18 shows an example of an aliphatic COOH-containing dimethacrylate for compomers [47].

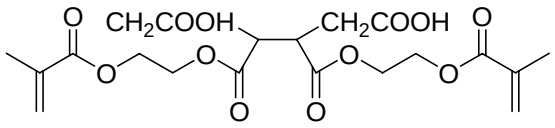


Figure 1.18. Aliphatic COOH-containing dimethacrylate for compomers

The compomer monomers react simultaneously with methacrylate groups by free radical polymerization and by acid-base neutralization reaction, with the cations released from the glass particles by the action of water. This new type of hybrid materials is introduced to combine the advantages of composite resins (good mechanical properties and good clinical handling) and glass ionomer cements (no polymerization shrinkage, inherent adhesion to the tooth structure and fluoride release) but it has been showned that they behave more similar to composites than to GICs (Table 1.4) [7, 51].

Table 1.4. Properties of composites, compomers and GICs.

	Composite	**Compomer**	**GIC**
Flexural strength (MPa)	100-145	90-125	30-60
Compressive strength (Mpa)	280-480	200-260	100-200
Modulus of elasticity (GPa)	10-25	5-8	5-20
Release of fluoride ions ($\mu g/cm^2$)	0-10	30-60	50-600

A comparison of aferomentioned restorative materials is showned in table 1.5.

Table 1.5. Comparison of dental restoratives

	Amalgams	Composite resins	GICs	Hybrid materials
Leakage	Moderate	Low	Low	Low
Clinical considerations	tolerant to moisture during placement	very little tolerant to moisture during placement	very little tolerant to moisture during placement	very little tolerant to moisture during placement
Resistance to wear	High	Moderate(low than amalgam)	High	High
Biocoompatibility	well tolerated	well tolerated	well tolerated	well tolerated
Post sensitivity	early sensitivity to hot and cold	dependence on ability to adequately bond	Low	dependence on ability to adequately bond
Esthetics	Silver or gray color	Mimics natural tooth color	Mimics natural tooth color	Mimics natural tooth color
Cost to patient	Generally lower depending on size	Moderate depending on size and technique	Moderate depending on size and technique	Moderate depending on size and technique

1.1.3. Adhesion to tooth structure

As described in the earlier chapter, various kinds of restoration materials have been used such as metals, organic polymers and ceramics. The vital problem is to securely bond these filling materials to teeth (enamel and dentin) and particularly obtain a strong adhesion in a wet condition [52].

Adhesion to tooth can be obtained by different mechanism: micromechanical retention, chemical bonding (covalent bonding, ionic interactions, complex interactions) and physical forces (van der Waals interaction, dipol-dipol interactions and hydrogen bonds).

Acid etching of enamel causes decalcification and solution processes on the hydroxyapatite crystals, which leaves a porous and rough surface. These microporosities enlarge the surface area of enamel and get wet by capillary attraction with the use of fluid resin. After the curing of the resin, adhesion occurs due to a strong micromechanical interlocking with the enamel [53,54].

It is much more difficult to achieve a good bond to dentin which has a wet and hydrophilic surface. The hybrid layer which is an interdiffusion zone created by the hydrophilic components of the adhesive systems is the most important mechanism for adhesion on the polar dentin [55]. The chemical adhesion is generated by the suitable adhesive groups with dental hard tissue such as ionic bonds formed between the acidic groups of the monomers in the adhesive resin and hydroxyapatite, coordinative linkages between the chelating groups and the calcium ions of tooth, covalent bonds between the collagen fibers in dentin and the adhesives by amino or hydroxyl groups and secondary valence forces (hydrogen bridges, Van der Waals forces or induced dipoles) [56].

1.1.4. Dental Adhesives

Current dental adhesives may be divided into two major categories based on the number of clinical steps: total-etch (etch& rinse) and self-etch adhesives.

Pretreatment of the dentin and enamel surface before the application of the adhesives is neccessary because of the formation of smear layer which is deposited on the dentin as a result of cavity preparation and consists of dentin particles, collagen fibers, residues from the odonto-blasts and bacteria. The smear layer may prevent the intimate contact between the adhesives and the tooth structures [7].

To remove smear layer and achieve a strong bond between a dental filling material and the tooth, there are two major techniques currently used based on the number of clinical steps: total-etch (etch& rinse) and self-etch adhesives [57].

1.1.4.1. Etch and Rinse Adhesives

Etch and rinse adhesives have been introduced to the market in the early 1990's and require three steps employing an acidic conditioner, primer and bonding resin.

In the first step, a 35 to 40 per cent phosphoric acid is applied for 15-20 seconds to remove smear layer, demineralize the dentin and open dentinal tubules to depts of 0.5 to 7.5 μm. This step increases the permeability of the dentin for the next steps [7, 58].

Before the application of the second step, the acid must be rinsed off and the surface of the tooth must be dried [9, 59]. Drying process plays a crucial role in determining the quality of the bond because the dentin surface needs to be moist enough to prevent collagen collapse but the 'moist dentin' is not easily defined clinically.

In the second step, a primer which contains hydrophilic monomers is applied to promote adhesion to dentin. Finally the adhesive resin is applied.

Etch and rinse adhesives provides a good enamel etch and long-term clinical studies whereas they are very sensitive to the level of dentin wetness after rinsing off the acidic conditioner and it is possible to have less than ideal bonds if the dentin is excessively wet or dried [58, 60].

1.1.4.2. Self-Etching Adhesives

Self-etch adhesives combine the acidic conditioner with the primer in the initial step so that they simultaneously condition and prime the tooth and then a bonding resin is applied in the second step.

The combination of etching and priming steps reduces the working time and offers a simpler clinical application by eliminating the technique–sensitive rinsing step used in the total-etch systems [7, 60].

Figure 1.19 shows the clinical follow of a replacement of an amalgam restoration by an adhesively placed composite filling (A). For this purpose, the surface of the cavity is etched and primed with using a modern self-etching enamel dentin adhesive resulting in a porous and rough surface (B). After filling the cavity with composite and curing a high esthetic tooth colored restoration is obtained (C).

Recently, one component self-etching adhesives are introduced to the marked [56]. However currently available self-etching adhesives contains methacrylates based monomers with a pH value in the range of 1.5-2.5 which is a very strong acidic medium and may lead to hydrolytic degradation of esters such as HEMA and TEGDMA. In

addition, one component self-etching adhesives have a relatively high water uptake which may cause the formation of water trees at the interface [61].

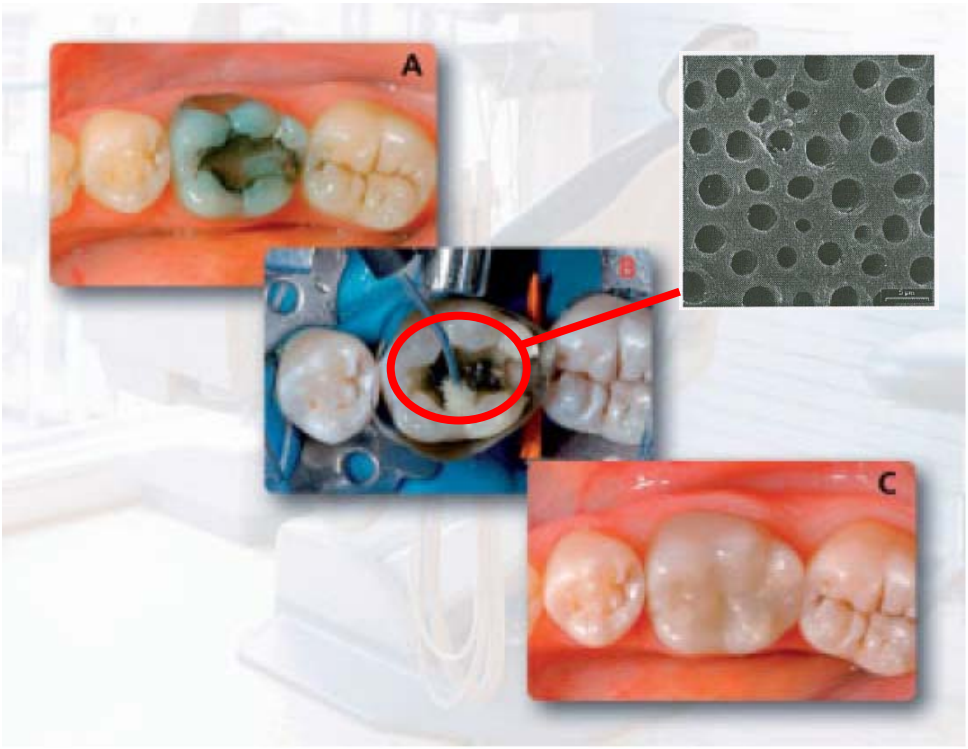


Figure 1.19. The clinical follow of a replacement of an amalgam restoration by an adhesively placed composite filling

Commercial Self-etching adhesives consists of three main groups:

- Self-etching adhesive monomers
- Cross-linking monomers
- Monofunctional co-monomers

All of these monomers have to fulfill the following requirements:

- High rate of free-radical homopolymerization or copolymerization with the other monomers in the adhesive set.

- Optimal miscibility with the aqueous solutions of acetone and ethanol, which are mainly used solvents in commercial self-etching adhesives.
- Sufficient stability both the monomer and the polymer not only against premature polymerization but also against degradation by oxygen, light, heat and water during storage.
- Minimal water uptake and low swelling degree of the formed polymer.
- Low polymerization shrinkage of the monomers.
- Low oral toxicity and cytotoxicity of the monomers.

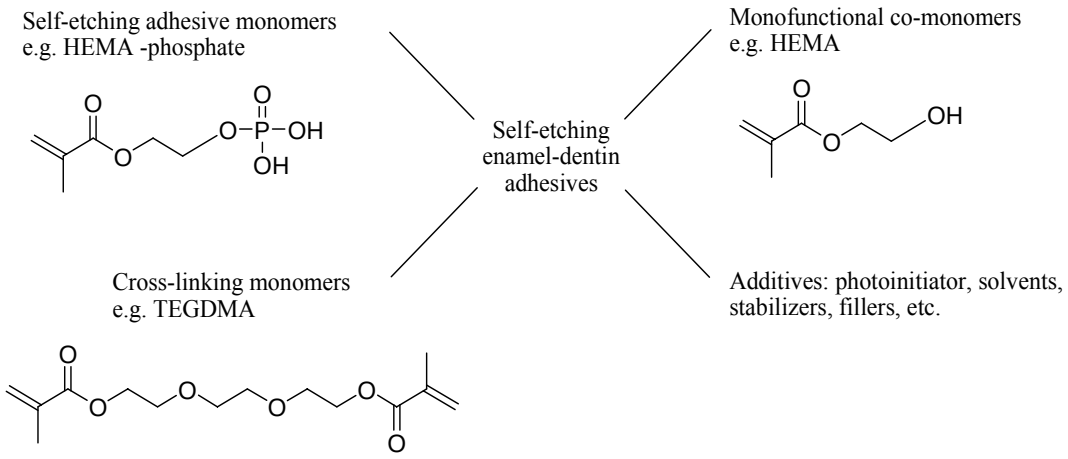


Figure 1.20. Components of currently available self-etching enamel-dentin primers/adhesives

It is possible to fulfill these requirements with special structure-designed monomers.

Self-etching Adhesive Monomers in Commercial Adhesives:

General structure of an adhesive monomer is given in figure 1.21 [62].

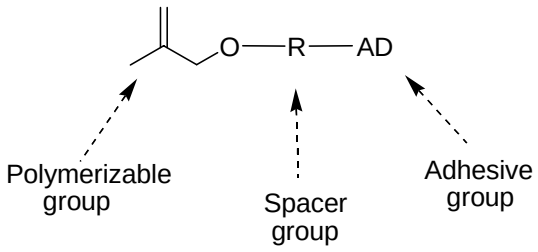


Figure 1.21. General structure of a self etching adhesive monomer

Polymerizable group reacts both with the other monomers of the adhesive and the restorative material by copolymerization. There is a variety of free-radically polymerizable groups (Figure 1.22).

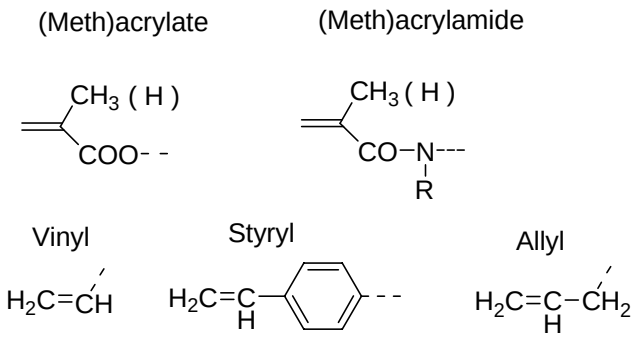


Figure 1.22. Example of polymerizable groups.

Among these groups, methacrylates are found to show sufficient reactivity. Although acrylates are more reactive, they have a potential of toxicity. Vinyl and styryl monomers are less reactive. Allyl monomers show a low tendency towards homopolymerization and a degradative chain transfer is possible in case of mixing with other monomers. (Meth)acrylamides show an enhanced hydrolytic stability under acidic conditions [56].

The spacer group has a crucial effect both on the monomer (volatility, solubility, viscosity, wetting or penetration) and the resulting polymer (hydrophilicity, swelling properties, flexibility or stiffness) (Figure 1.23).

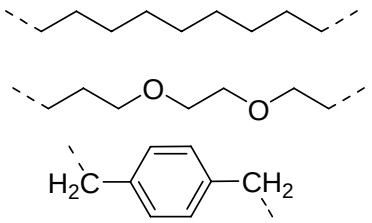


Figure 1.23. Examples of spacer groups R in adhesive monomers.

The adhesive group (AD) is capable of both etching the dental hard tissues and interacting with the tooth substance (Figure 1.24).

The general potential of acidic monomers to etch largely depends on the acidity of the monomers that increases in the following order:

Carboxylic acids < phosphonic acids < acid phosphates < sulfonic acids

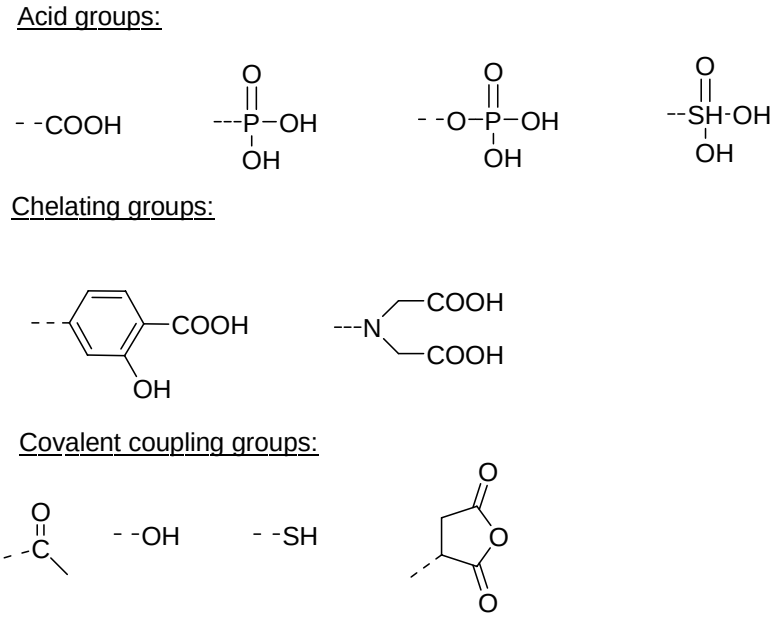


Figure 1.24. Adhesive groups AD enable chemical adhesion to enamel or dentin.

Various phosphoric acid, phosphonic acid and phosphinic ester derivatives have been synthesized and used in dentin adhesives [48, 62-66].

Among these monomers glycerol dimethacrylate ester of phosphoric acid (GDMA) was one of the first compound proposed by Buonocore et. al to improve bonding with human dentin [67]. Further examples of acidic methacrylate phosphonates have been synthesized to improve bonding on dentin such as, methacryloyloxyethyl phenyl hydrogen phosphate (MEP-P), 10-methacryloyloxy methacrylate (MDP) and methacryloyloxyethyl dihydrogen phosphate (MEP, HEMA-phosphate) based on the the reaction of phosphorus oxychloride ($POCl_3$) with the corresponding OH-group containing methacrylate (Figure 1.25) [52,68].

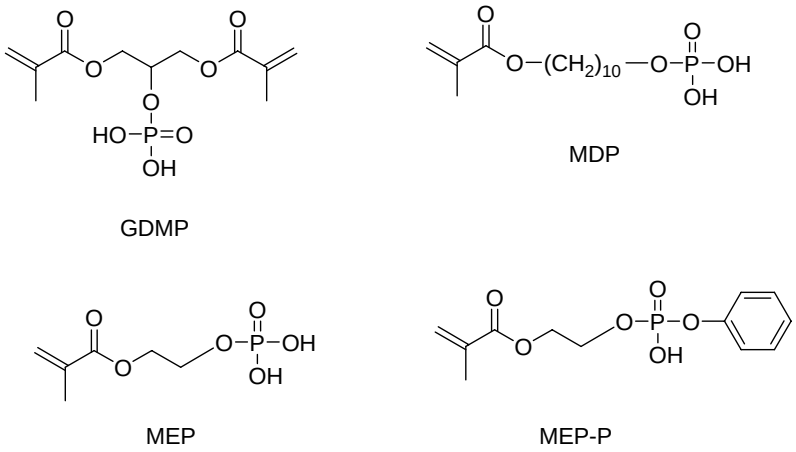


Figure 1.25. Examples of polymerizable acidic phosphates used in dentin adhesives.

In the case of acidic methacrylate phosphates, an additional hydrolytic instability results from the hydrolysis of the methacrylate ester bond [67]. The problem with the hydrolytic instability of the methacrylate phosphates can be solved with the insertion of more hydrolytically stable bonds such as ether or amide linkages between the polymerizable groups and the strongly acidic phosphorous groups of the monomers.

It is possible to convert methacrylated phosphonates to the corresponding phosphonic acids by using bromotrimethylsilane followed by the hydrolysis of the silylated intermediate by an excess of methyl alcohol (Figure 1.26) [69].

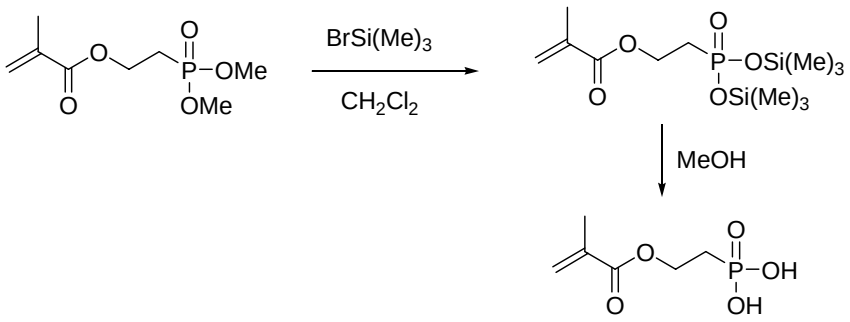


Figure 1.26 Hydrolysis of dimethyl(2-methacryloyloxyethyl)phosphonate

To summarize, the phosphorous containing monomers are capable of etching enamel and dentin so they can be used as self-etching primers. The invention of more hydrolytically stable acrylic phosponic acids have improved the self-etching adhesive systems remarkably.

Monofunctional co-monomers in commercial adhesives:

Monofunctional co-monomers are of key importance in influencing the properties of the adhesive material such as viscosity, wetting, monomer penetration or polymerization reactivity.

Among various monofunctional co-monomers, HEMA is the most widely used monomer because it is a low viscous, water soluble monomer that enhances the miscibility and solubility of the polar and non-polar adhesive components and the wetting behaviour of the adhesive on the dental hard tissue. Furthermore, HEMA is tought to stabilize the collagen fibril network and so improve the dentinal permeability and monomer diffussion.

Cross-linking Monomers in Commercial Adhesives:

Cross-linking dimethacrylates used in enamel dentin adhesives play an improtant role in determining the polymerization rate of the system and mechanical properties of the cured dental material. They increase the polymerization rate of the adhesive due to the gel effect and form a three-dimensional (3D) network which improves the mechanical properties and decreases the the degree of swelling of the material.

Bis-GMA, UDMA, TEGDMA and GDMA are not only the most widely used dimethacrylates in composite resins but also in commercial self-etching adhesives.

1.2. Photopolymerization

Light induced polymerization, also called UV curing, is used in dental curing which needs to be a fast process at room temperature.

Dental polymerizable systems are usually made of three main components [70]:

i. A photoinitiator that effectively absorbs the incident light and generates radicals or ions,

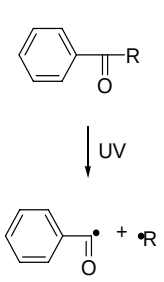
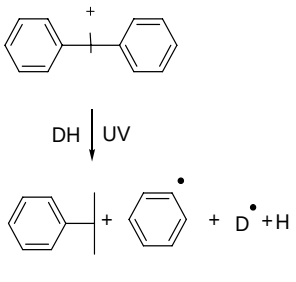
ii. Functionalized monomer or oligomer that will polymerize,

iii. A reactive diluent to adjust viscosity.

Photopolymerization is divided into two groups, depending on whether the reaction proceeds by cationic type or radical type mechanism (Table 1.6). In photoinduced radical polymerization, aromatic ketones are used as initiators to generate free radical and initiate the polymerization of vinyl monomers by a step growth addition mechanism. On the other hand, in photoinduced cationic polymerization, a protonic acid is generated by photolysis of triarylsulfonium (TAS) or diaryliodonium salts to initiate the polymerization of epoxides or vinyl ethers [70].

Radical type system is mostly prefered in photo-induced curing applications [71].

Table 1.6 Different types of photopolymerization

Mechanism	RADICAL	CATIONIC
Photoinitiator	Aromatic ketone 	Aryliodonium salt 

1.2.1. Photoinitiators

Photoinitiators are crucial in UV-curable systems due to their significant role in determining the rate of initiation and the depth of the cure. The selection of an appropriate initiator which has the highest initiation efficiency and undergoes a fast photobleaching upon UV exposure is required to achieve a deep-through cure [70].

Classification of photoinitiators is based on the type of polymerization system they initiate, i.e. free radical or cationic. There are also a few cases of initiators (e.g. iodonium and sulphonium salts, arene complexes), which are able to initiate polymerizations via both cationic and radical processes.

Radical photoinitiating systems are commonly classified according to the nature of the mechanism that produces the free-radical intermediates upon irradiation of the initiators [72]. Photofragmentation that generates radical pairs through a highly efficient L-cleavage process (type-I) and the H abstraction process from donor molecules (type-II) are two main mechanisms that clasify the radical photoinitiating systems.

Type-I class includes aromatic carbonyl compounds that are known to undergo a homolytic C-C bond scission upon UV exposure (Figure 1.27). The benzoyl radical is the major initiating species, while the other fragment may, in some cases, also contribute to the

initiation. The most efficient photointiators include benzoin ether derivatives, benzyl, ketals, hydroxyalkylpheneones, L-aminoketones and acylphosphine oxides.

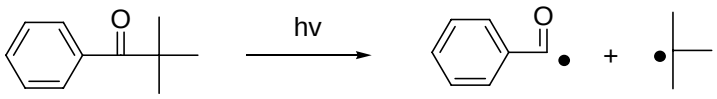


Figure 1.27. Example to type-I initiator

Type-II systems usually consist of two components: An aromatic ketone with a H donor molecule. Aromatic ketones, when promoted to their excited states by irradiation, do not undergo a fragmentation but rather abstract a H atom from a H-donor molecule to generate a ketyl radical and a donor radical. The donor radical initiates polymerization (Figure 1.28).

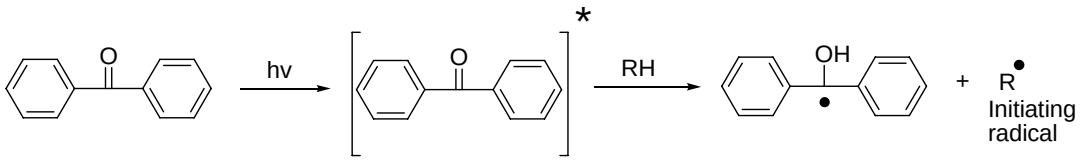
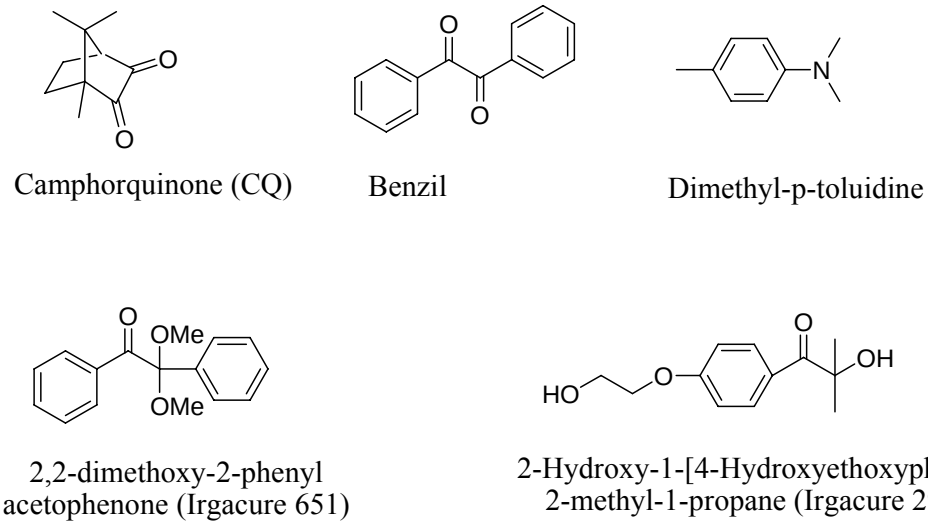


Figure 1.28. Example to type-II photoinitiator.

Other examples are xanhones, thioxanthones, aromatic diketones, phenyl glyoxalates, 3-ketocoumarins, camporquinone, etc.

Figure 1.29 shows the structures of some photoinitiators which are commonly used in both dentistry and other applications [70].



Camphorquinone (CQ) Benzil Dimethyl-p-toluidine

2,2-dimethoxy-2-phenyl acetophenone (Irgacure 651)

2-Hydroxy-1-[4-Hydroxyethoxyphenyl]-2-methyl-1-propane (Irgacure 2959)

Figure 1.29. Commonly used initiators

Among these initiators, Camhorquinone is widely used in visible light curing dental materials. Camhorquinone is used with an amine accelator such as ethyl p-dimethylaminobenzoate. In this case initiating radicals are formed via proton and electron transfer (Figure 1.30).

The inherent problem of this photoinitiator in case of self-etching enamel dentin adhesives is the acid-base reaction of the acidic monomers with amine accelarator used in the initiator system. Therefore, amine concentration should be exactly adjusted to the concentration of acid in self-etching systems [56].

In this respect, Acylphosphine oxides which absorb light in the wavelength of 400-500 nm and do not require amine accelarator have been introduced on the market. However these new type of initiators are prone to solvolytic cleavage of carbon-phosphorous bond in the presence of nucleophilic compounds such as water or alcohols.

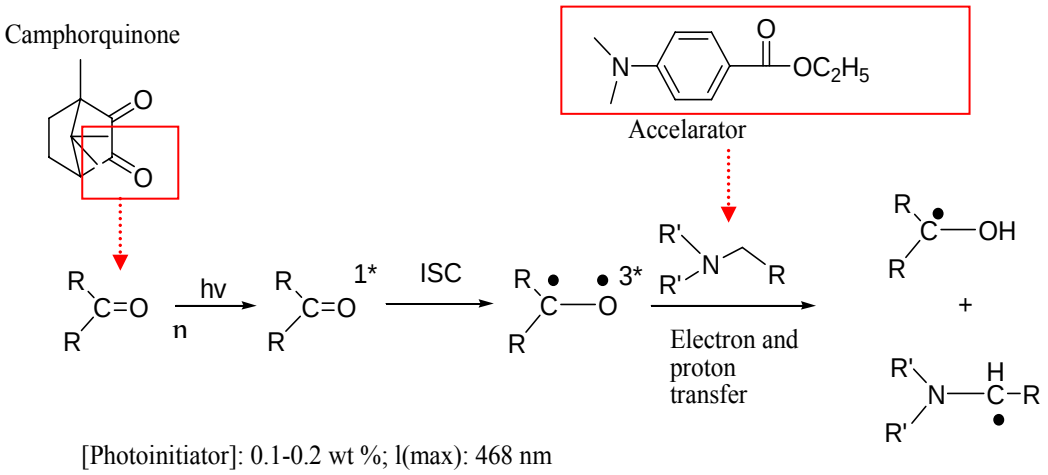
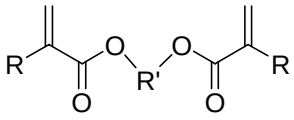


Figure1.30. Initiator system for camphorquinone type initiators.

1.2.2. Monomers

Because of the importance of speed in photocuring, the dental restorative materials are based on various (meth)acrylate monomers and oligomers due to their high reactivity [73].

Figure 1.31 shows the general structure of the commonly used acrylate/methacrylate based resin systems [71].



R= H, CH_3
R' = polyether, polyester, polymethane

Figure 1.31. Commonly used (meth)acrylate monomers for light curable systems.

The polymerization of dimethacrylate monomer, initiated by UV- generated benzoyl radicals, is assumed to develop according to following scheme (Figure 1.32).

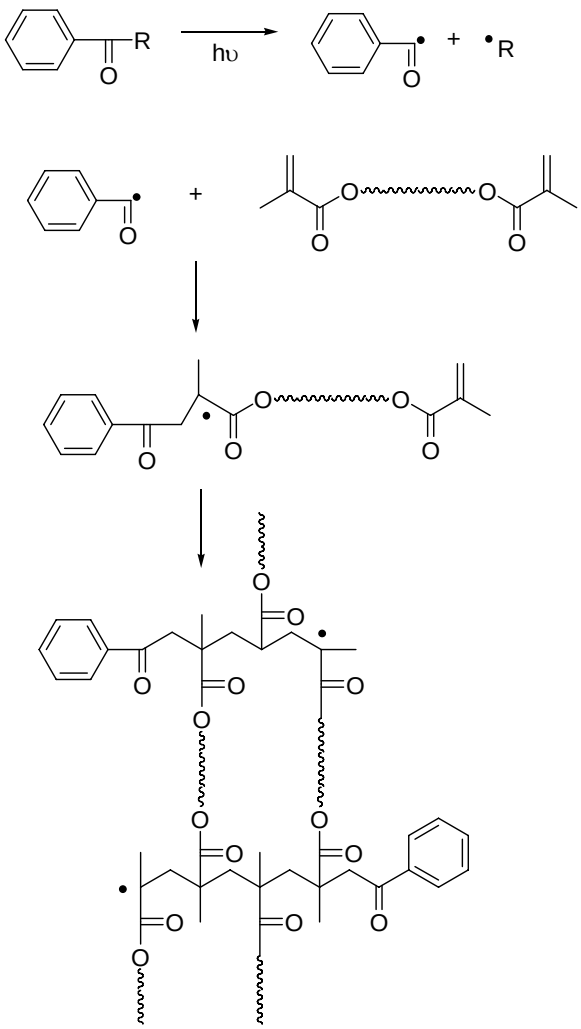


Figure 1.32. Mechanism of the photopolymerization of a dimethacrylate monomer

The rate of mono or multi-functional (meth)acrylate polymerizations depends on many factors such as reactivity of the functional groups, its concentration, viscosity of the resin, distance and flexiblity between the functional groups, etc. These factors determine the final degree of polymerization, as well as the physical and chemical characteristics of the UV-cured polymer. In order to have a comprehensive understanding of how structural characteristics and monomer traits influence polymerization mechanism and network evaluation, various researches have been conducted [75].

For instance, a series of mono-(meth)acrylic monomers containing a second or even tertiary non-vinyl functionalities that enhance polymerization kinetics have been synthesized and investigated. These monomers have an improved capability to overcome

diffusional limitations and achieve increased double bond conversion. The increased polymerization rate is attributed to a highly efficient hydrogen abstraction that involves labile hydrogen from the secondary functional group and highly efficient chain transfer [28, 70, 72, 75-78].

Andrzejewska reported the heteroatom effect including oxygen and sulfur in the side chain which led to higher reactivity [79].

It is stated that hydrogen bonding leads to an enhancement on the maximum rate of the photoinitiated polymerizations [80]. This effect is explained by two scenarios. One is based on the formation of pseudo-multifunctional monomers via strong hydrogen bonds between the molecules whereas the other one based on preorganization of the monomers forcing the double bonds in close approximity to each other [73, 80, 81].

It has been also shown that hydrogen bonding to the carbonyl group could alter the electron density of the acrylate double bond, thereby enhancing the rate constant for propagation [82].

However, there is a critical distance between double bond and the hydrogen bonding moiety (alkyl bridge length) beyond which there is no effect on Rp in the case of the preorganization theory. This is because conformational mobility of the skeletal bonds between the hydrogen-bonding moiety, the double bond will reach a level whereby the double bond can be regarded as isolated from the hydrogen bonding moiety [80, 83].

Dimethacrylate polymerizations are known to exhibit diffusion controlled kinetics [84,85] and have the kinetic constants that follow Arrhenius-type behaviour [84, 86]. Therefore increasing the cure temperature dramatically improves the mobility of the reaction media, thus leading to increase the reaction rate [87].

However the rate of monomers capable of hydrogen bonding was shown to decrease with increasing temperature, unlike conventional acrylates due to the distruption of hydrogen bonding [88].

Jansen et al. reported that when the dipole moment (μ_{calc}) is above a threshold value (~ 3.5), the polymerization rate of some novel monoacrylates increases linearly with dipole moment (electronic effect) [78, 80].

In summary, the development of monomers that exhibit high reactivity, good mechanical properties and enhanced aging characteristics has been the ultimate goal and three primary factors are stated as important to the advantageous polymerization characteristics: hydrogen bonding, hydrogen abstraction and electronic effects [75].

1.2.3. Light sources

Another important factor in the photo-curing process is the light source because the initiation rate strongly depends on the light intensity.

There are two types of lights mainly used:
i. Arc light
ii. Laser light

An arc lamp produces light by an electric arc (or voltaic arc). The lamp consists of two electrodes typically made of tungsten which are seperated by a gas. When a direct current applied through the electrodes to generate an arc, the gas is discharged and light is emitted. The output of the lamp depends on the pressure and the type of the gas. The type of lamp is often named by the gas contained in the bulb; including neon, argon, xenon, sodium, metal halide, and mercury.

The gas pressure can be low (10-3 torr), medium (1-2 atm), or high (> 2 atm). The medium-pressure mercury lamp is the most important light source used in the photo- or UV-curing industry [89].

The word 'LASER' stands for 'Light Amplification by Stimulated Emission of Radiation'. Lasers offer the prospect of an excitation source of exceedingly high intensity compared to classical light sources. The output of a laser is available in both UV and

visible wavelengths. Some lasers offer fixed wavelength, whereas some others offer tunable wavelengths [89].

In dentistry, 420-500 nm light in visible region is used [90].

1.2.4. Photopolymerization kinetics

It is possible to study photopolymerization with various methods such as differential scanning calorimetry, dilatometry, fluorescence spectroscopy and RT-FTIR spectroscopy. By these techniques, heat evolved, volume shrinkage, increase in viscosity or disappearance of the reactive groups can be monitored.

By using differential scanning calorimetry technique, the rate of polymerization, propagation, and termination rate constants can be calculated from heat flow during polymerization according to the equations in Figure 1.33.

At the very beginning of the irradiation autoacceleration occurs because of the rapid increase in viscosity until the reaction reaches its maximum rate value. It is followed by a period where the polymerization develops (0.3 s), the time after which autodeceleration starts taking place when propagation becomes diffusion controlled. Ultimately, vitrification leads to a complete stop of the curing process through the end of the polymerization. A certain amount of unreacted acrylic double bonds remains in the crosslinked polymer, which may ultimately affect the long term properties of the UV-cured material (Figure 1.34) [89].

$$R_p = \frac{(Q/s)\ M}{n\ \Delta H_p\ m} \qquad \frac{k_p}{k_t^{1/2}} = \frac{R_p}{[M]\ (\Theta I_0 \varepsilon [A])^{1/2}}$$

Q/s) : heat flow per second during reaction
M : molar mass of the monomer
n : number of double bonds per monomer molecule
ΔHp : heat released per mol of double bonds reacted
m : the mass of the monomer in the sample
Θ : the initiator efficiency
[M] : molar concentration of the double bonds
I_0: incident light intensity
ε : extinction coefficient of the initiator
[A] : initiator concentration

Figure 1.33. Equation of the rate of polymerization

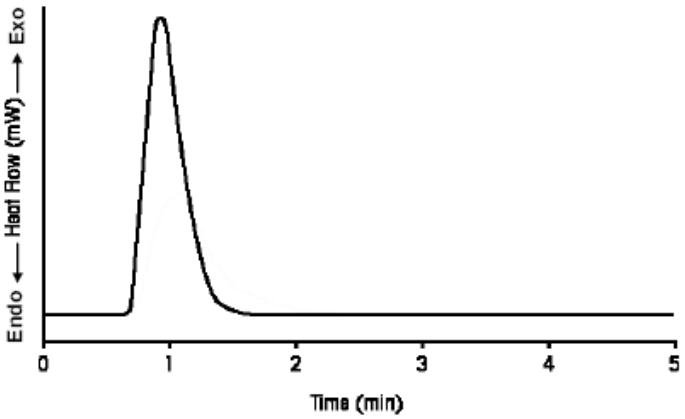


Figure 1.34. Representative heat flow versus time plot obtained from differential scanning calorimetry technique

1.2.5. Other Applications of Photopolymerizing Systems

Photocuring technology has found a variety of industrial applications due to the unique properties, such as high speed, solvent-free formulations, low energy consumption, ambient temperature operations, and tailor-made properties of the photocured polymers.

Besides its wide use in dental restorative filling systems, photopolymerization has also found applications in coating industry, for instance fast-drying varnishes, paints or printing inks, quick-setting adhesives, sealants; and also information storage systems, aspherical lenses for CD applications, microcircuits, and contact lenses are some of the other areas which photocuring technology is used [70, 80, 91].

2. OBJECTIVES

The aim of this project was to synthesize and investigate the polymerization behavior of novel dental monomers to improve current dental composites by two different approach: (i) to synthesize phosphonated ultra reactive diluent mono methacrylates with improved adhesion (by hydrogen bonding ability) and biocompatibility (by phosphonate functionality) to replace TEGDMA in conventional dental composites in order to eliminate or minimize the problems caused by the reactive diluents. (ii) to synthesize an alternative Bis-GMA analog with reduced viscosity, enabling easy handling of the material as well as providing improved thermal stability and biocompatibility. The monofunctional monomers were synthesized from one pot reaction of Glycidyl methacrylate (GMA) whereas difunctional Bis-GMA analogs were synthesized based on Bisphenol A diglycidylether (DER). As an extension of the work, the synthesis of an adhesive monomer was also studied.

3. EXPERIMENTAL

3.1. Materials and Apparatus

3.1.1. Materials

Glycidyl methacrylate (GMA), (diethoxy-phosphoryl)-acetic acid, Bisphenol A diglycidylether (DER), Diethylchlorophosphate (DECP), 2,6-di-tert-butyl-4-methylphenol (BHT), triethyl amine (TEA), pyridine (pyr), 2-hydroxyethyl methacrylate (HEMA), glycerol dimethacrylate (GDMA), triethylene glycol dimethacrylate (TEGDMA), 2,2-bis[4-(2-hydroxy-3-methacryloyloxy propyloxy) phenyl] propane (Bis-GMA), $NaHCO_3$ and Na_2SO_4 were purchased from Aldrich and used as received. Methacryloyl chloride was obtained from Fluka and distilled before use. (2-hydroxy-ethyl)-phosphonic acid dimethyl ester was a gift from Ivoclar Vivadent.

Dichloromethane used in the reactions was dried. The solvents used for column chromatography were obtained from Akkimya and distilled before use.

The thermal initiators azobisisobutyronitrile (AIBN) and 2,2'-azo-bis(2-amidinopropane)dihydrochloride (V-50) as well as photoinitiator 2,2-dimethoxy-2-phenylacetophenone (DMPA) were used as recieved.

3.1.2. Apparatus

^{1}H, ^{13}C and ^{31}P NMR spectroscopy was taken with Varian Gemini 200 MHz instrument. Fourier transform infrared (FTIR) spectroscopy on thin films on NaCl plates (Mattson 5000) was performed on a Perkin Emler 1600 FT-IR spectrometer. High performance liquid chromatography was done on a Shimadzu LC 20A. Photopolymerizations were carried out on a TA Instruments Q100 differential

photocalorimeter (DPC). Thermogravimetric analysis was done with a TA Instruments (Q50).

3.2. Synthesis of Phosphonated Novel Monomers

3.2.1. Synthesis of Monomer 1

GMA (0.50 g, 3.5 mmol), (diethoxy-phosphoryl)-acetic acid (0.72 g, 3.7 mmol), TEA (47.0 mg, 0.47 mmol) and 2,6-di-tert-butyl-4-methylphenol (BHT) (1.28 mg, 0.0058 mmol) were added to a round bottom flask with a water condenser and nitrogen inlet. The mixture was stirred at 60 °C for 18 h. The purification of the crude product by column chromatography (using CH_2Cl_2 initially and gradually changing to 3 per cent methanol in CH_2Cl_2 as eluent) resulted in a very light yellow oil (52 per cent yield).

^{1}H NMR ($CDCl_3$): δ= 1.3 (t, 3H, C*H*$_3$-CH_2), 1.9 (s, 3H, CH_3-C), 3.0 (d, 2H, CH_2-P), 4.1-4.4 (m, 9H, CH_2-O and CH-O), 5.3, 5.6 (s, 2H, CH_2=C)

^{13}C NMR ($CDCl_3$): δ= 15.9 (*C*H_3-CH_2), 17.9 (*C*H_3-C), 33.4, 34.7 (CH_2-P), 62.7 (CH_2-O), 64.4 (CH_2-O), 66.1 (CH-O), 66.9 (CH_2-O), 125.8 (*C*H_2=C), 135.4 (*C*=CH_2), 165.2 (C=O), 166.7 ppm (C=O).

^{31}P NMR ($CDCl_3$): δ=21.6, 21.9 ppm

FTIR (NaCl): 3383 (O-H), 2984 (C-H), 1739 (C=O), 1720 (C=O), 1636 (C=C), 1272 (P=O), 1024 cm^{-1} (P-O-Et).

Figure 3.1. NMR and FT-IR data of monomer 1

3.2.2. Synthesis of Monomer 2

GMA (1.02 g, 7.2 mmol), (2-hydroxy-ethyl)-phosphonic acid diethyl ester (2.17 g, 14.1 mmol), N,N-dimethylbenzyl amine (51.2 mg, 0.42 mmol) and 2,6-di-tert-butyl-4-methyl-phenol (BHT) (7.8 mg, 0.045 mmol) were added to a round bottom flask with a water condenser and nitrogen inlet and stirred at 130 ºC for 5 h, 85 °C for 18 h and 130 ºC for 5 h. The crude product was purified by column chromatography (using CH_2Cl_2 initially and gradually changing to 4 per cent methanol in CH_2Cl_2 as eluent) to give a colorless viscous oil (32 per cent yield).

^{1}H NMR ($CDCl_3$): δ= 1.9 (s, 3H, CH_3-C), 2.0 (m, 2H, CH_2-P), 3.5-3.9 (m, 11H, CH_2-O, CH-OH, CH_3-O), 4.2 (d, 2H, CH_2-O), 5.6, 6.1 (s, 2H, *C*H_2=C) ppm.

^{13}C NMR ($CDCl_3$): δ=18.1 (*C*H_3-C),27.4, 28.8 (CH_2-P), 52.3 (CH_3-O), 56.3 (CH_2-O), 63.5 (CH_2-O), 65.4 (CH_2-O), 70.1 (CH-O), 125.9 (*C*H_2=C), 135.9 (*C*=CH_2), 167.5 (C=O) ppm.

^{31}P NMR ($CDCl_3$): δ= 34.2 ppm

FTIR (NaCl): 3372 (O-H), 2951 (C-H), 1713 (C=O), 1634 (C=C), 1213 (P=O), 1020 cm^{-1} (P-O-Me).

Figure 3.2. NMR and FT-IR data of monomer 2

3.2.3. Synthesis of Monomer 3

Monomer **2** (0.53 g, 1.79 mmol), pyridine (0.707 g, 8.93 mmol) and 10 ml dry CH_2Cl_2 were added to a round bottom flask with a nitrogen inlet and placed in an ice bath. Then diethylchlorophosphate (0.926 g, 5.36 mmol) was added dropwise and the mixture

was stirred at 0 °C for 1 hour and at room temperature for 5 hours. CH_2Cl_2 was removed under reduced pressure. Residual liquid was washed with hexane three times successively and once overnight to get rid of excess diethylchlorophosphate. Then hexane was removed under reduced pressure and THF was added which resulted in precipitation of salts. The salts were filtered off and then THF part was extracted with brine four times. The mixture was concentrated under reduced pressure and a yellow non-volatile liquid was left (36.6 per cent yield).

^{1}H NMR ($CDCl_3$): δ= 1.3 (s, 3H, C*H*$_3$-CH_2), 1.9 (s, 3H, CH_3-C), 2.2 (m, 2H, CH_2-P), 3.7 (d, 6H, CH_3-O), 4.0-4.4 (m, 11H, CH_2-O, CH-O), 5.6 and 6.1 (s, 2H, *C*H_2=C) ppm.

FTIR (NaCl): 2985 (C-H), 1718 (C=O), 1632 (C=C), 1267 (P=O), 1015 cm^{-1} (P-O-Et, P-O-Me).

Figure 3.3. NMR and FT-IR data of monomer 3

3.2.4. Synthesis of Monomer 4

DER (4.09 g, 12.0 mmol), (diethoxy-phosphoryl)-acetic acid (5.82 g, 29.7 mmol), TEA (98.0 mg, 0.97 mmol) and BHT (9.2 mg, 0.04 mmol) were added to a round bottom flask with a water condenser and nitrogen inlet. The mixture was stirred at 60 °C for 18 h and a viscous colorless diol intermediate was obtained. The diol was purified by column chromatography using CH_2Cl_2 initially and gradually changing to 4 per cent methanol in CH_2Cl_2 as eluent to give a colorless viscous oil. To this intermediate (2.63 g, 3.6 mmol) dissolved in dry CH_2Cl_2 (25 ml), TEA (0.73 g, 7.2 mmol) and DMAP (10.7 mg, 0.088 mmol) were added. The reaction mixture was cooled to 0 °C in an ice bath and methacryloyl chloride (0.94 g, 9.0 mmol) in CH_2Cl_2 (15ml) was added dropwise. The mixture was stirred at room temperature overnight and then extracted with 3×20ml $NaHCO_3$ (5 per cent), 3×20ml HCl (1 per cent) and 3×20ml water. After drying of the CH_2Cl_2 phase with anhydrous Na_2SO_4 and the evaporation of the solvent, the crude product

(89 per cent yield) was purified by column chromatography (using CH_2Cl_2:hexane (50:50) initially and then CH_2Cl_2 and changing to 1 per cent methanol in CH_2Cl_2 as eluent) to give a viscous yellow oil (56 per cent yield).

^{1}H NMR ($CDCl_3$): δ= 1.3 (t, 12H, C*H*$_3$-CH_2), 1.6 (s, 6H, (*C*H_3)$_2$-C), 1.9 (s, 6H, *C*H_3-C), 2.9 (d, 4H, CH_2-P), 4.1-4.2 (m, 12H, CH_2-O), 4.5 (m**,** 4H, CH_2-O), 5.4 (m, 2H, CH-O), 5.6, 6.1, (s, 4H, *C*H_2=C), 6.8, 7.1 (d, 8H, CH-Ar) ppm.

^{13}C NMR ($CDCl_3$): δ= 16.2 (*C*H_3-CH_2), 18.1(*C*H_3-C), 30.9 (*C*H_3-C), 33.5, 34.8 (CH_2-P), 41.7 [*C*-(CH_3)$_2$], 62.7 (CH_2-O), 63.3 (CH_2-O), 65.8 (CH_2-O), 69.9 (CH-O), 113.9 (Ar-CH), 126.4 (*C*H_2=C), 127.9 (Ar-CH), 135.7(Ar-C), 143.4 (C=CH_2), 156.1 (C(Ar)- O), 165.4 (C=O), 166.6 (C=O) ppm .

FTIR (NaCl): 2970 (C-H), 1739 and 1719 (C=O), 1634 (C=C), 1245 (P=O), 1018 cm^{-1} (P-O-Et).

Figure 3.4. NMR and FT-IR data of monomer 4

3.2.5. Synthesis of Monomer 5

TMSBr (0.26 g, 1.71 mmol) was added dropwise to a solution of monomer 4 (0.25 g, 0.28 mmol) in 1 ml CH_2Cl_2 in an ice bath under N_2. The mixture was stirred at 40 °C for 160 min. After evaporation of CH_2Cl_2 under reduced pressure, 2 ml of MeOH was added and the mixture was stirred overnight at room temperature. Then MeOH was evaporated and a very viscous orange-yellow liquid was obtained. 0.4 ml distilled water was added to the crude product, which caused the color change from orange to white. Then 0.02 g $NaHCO_3$ was added slowly in ice bath while stirring throughly. The water phase was extracted with CH_2Cl_2 three times. After discarding organic part, concentrated HCl was added dropwise to the water phase in an ice bath till the pH of the solution was 1. Then the aqueous part was extracted with CH_2Cl_2 three times. After the organic part was dried with

sodium sulfate, the salts were filtered off and CH_2Cl_2 was removed under reduced pressure leaving a light yellow liquid (15 per cent yield).

^{1}H NMR ($CDCl_3$): δ= 1.2 (t, 12H, C*H*$_3$-CH_2), 1.6 (s, 6H, (*C*H$_3$)$_2$-C), 1.9 (s, 6H, *C*H$_3$-C), 2.9 (d, 4H, CH_2-P), 3.9-4.2 (m, 12H, CH_2-O), 5.6, 6.1 (s, 4H, *C*H$_2$=C), 6.8, 7.1 (d, 8H, CH-Ar) ppm.

FTIR (NaCl): 3325 (O-H), 2962 (C-H), 1723 and 1713 (C=O), 1634 (C=C), 1239 (P=O).

Figure 3.5. NMR and FT-IR data of monomer 5

3.3. Photopolymerizations

3.3.1. Polymerization Procedure

Photopolymerizations were carried out on a TA Instruments Q 100 Photo-DSC employing a mercury arc lamp as the light source and 2,2-dimethoxy-2-phenyl acetophenone (Irgacure 651) as the photoinitiator (Figure 3.6).

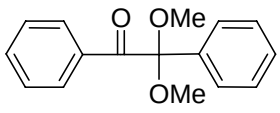


Figure 3.6. 2,2-dimethoxy-2-phenylacetophenone (Irgacure 651)

Approximately 3.0 mg of sample was placed in an aluminium DSC pan. A CH_2Cl_2 solution of the photoinitiator was added with a microsyringe to give a final concentration in the monomer of 2.0 mol per cent after evaporation of the solvent. The sample and the reference pans were placed in the DSC chamber, the system was purged with nitrogen flow to remove air and CH_2Cl_2 for 10 min before polymerization and purging was continued

during polymerization. Heats of photoreactions were measured using a DPC equipped with a mercury arc lamp. The samples were irradiated for 10 min at 40 °C with an incident light density of 20 mW/cm^2. The heat flux as a function of reaction time was monitored using DSC under isothermal conditions and both the rate of polymerization (Rp) and conversion were calculated as a function of time. The theoretical values used for the heats of reaction (ΔH_p) were 13.1 kcal/mol for methacrylate double bonds [85,92]. Rates of polymerization were calculated according to the following formula:

$$\text{Rate} = \frac{(Q/s)\, M}{n\, \Delta H_p\, m} \qquad (3.1)$$

where Q /s is heat flow per second, M the molar mass of the monomer, n the number of double bonds per monomer molecule, ΔH_p is the heat released perm ole of double bonds reacted and m the mass of monomer in the sample.

3.4. Free radical polymerizations in Bulk and Solution

3.4.1. Polymerization Procedure

All polymerizations (bulk or solution) were carried out in an oil bath at 60 ºC with AIBN or V-50 in septum-sealed glass tubes using standard freeze-evacuate-thaw procedures. For the polymerizations in solution, the tube was charged with the monomer, solvent and the initiator while no solvent was used for the polymerizations in bulk. The viscous polymer solutions were dissolved in methanol and precipitated into ether, filtered and dried under reduced pressure.

3.5. Calculation of dipole moments

Spartan ‘04 program is used to calculate the Boltzmann-averaged dipole moments of the given monomers [93]. A set of starting geometries were generated using three fold rotation between two sp^3 hybridized atoms and two fold rotation between two sp^2 hybridized atoms. This resulted in a total of 2209 conformations for monomer 1 and 1225

conformations for monomer 2. All these conformations were minimized at the PM3 level of theory. The convergence criterion for the maximum gradient was 0.0001 a.u. and the maximum number of geometry optimization cycles was taken to be 20 + the number of independent geometrical parameters for geometry optimization. The unique structures were sorted in the order of increasing energy. The dipole moments of the first 100 conformers are Boltzmann averaged at 298.15 K according to the following formula:

$$\left\langle \mu_{calc} \right\rangle = \sum D_j \frac{e^{\Delta H_j / RT}}{\sum_i e^{\Delta H_i / RT}} = \sum_j D_j p_j \qquad (3.2)$$

where D_j is the dipole moment of the conformation j, ΔH_j is the difference between the heat of formation of conformation j and the heat of formation of the global minimum conformation, T is the absolute temperature, R is the Boltzmann constant and p_j is the probability of finding the monomer in conformation j at the temperature T [80].

4. RESULTS and DISCUSSION

4.1. Synthesis of Novel Phosphonated Monomers

4.1.1. Synthesis of Monomer 1

The synthesis of monomer 1 was carried out in a one step ring opening reaction of glycidyl methacrylate (GMA) with (diethoxy-phosphoryl)-acetic acid in the presence of a base catalyst (Figure 4.1).

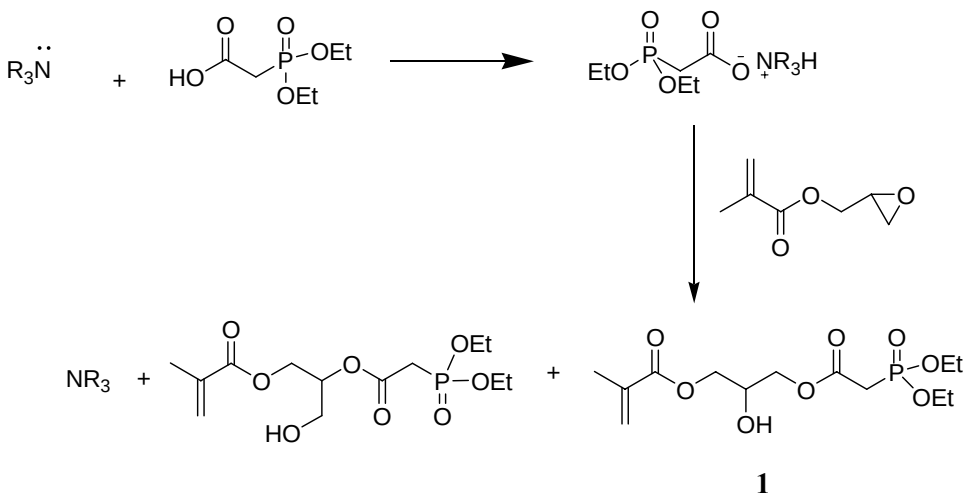


Figure 4.1. General mechanism for the synthesis of monomer 1

BHT was added in order to prevent homopolymerization of GMA during reactions. For the synthesis of monomer 1, TEA was used and reaction proceeded at 60 ºC for 18 h. The reactions were monitored by ^{13}C NMR spectrum and HPLC. The disappearance of the characteristic epoxy peaks at 44.3 and 49.8 ppm in the ^{13}C NMR spectra were used to follow product formation.

The ring opening reaction of the epoxides is not regiospecific. There are two possible site for attack of alcohols, acids and anhydrides [83,94]. If the attack occurs from the less hindered side linear isomer is obtained otherwise branched isomer or both are products.

The reaction conditions and catalyst are important factors to determine this ratio [95]. Monomer 1 went to almost complete conversion. The yield of our reactions after column chromatography was 52 per cent for monomer 1 containing mostly linear isomer with a very small amount of branched isomer. Monomer 1 was soluble almost in all organic solvents such as ether, acetone, dichloromethane, THF and methanol except hexane and it was also soluble in water which is of key importance for dental materials (Table 4.3).

The ^{1}H NMR spectra of monomer 1 showed characteristic peaks for methyl protons at 1.3 ppm (triplet) and 1.9 ppm (singlet), methylene protons attached to phosphorus at 3 ppm (doublet), methylene protons next to oxygen atoms at 4.1-4.4 ppm (multiplet), olefenic protons at 5.3 and 5.6 ppm (singlet) (Figure 4.2).

The ^{13}C NMR spectra of monomer 1 showed characteristic peaks for methyl carbons at 15.9 and 17.9 ppm, a tertiary carbon at 66.1 ppm, methylene carbon attached to phosphorus at 33.4 and 34.7 ppm (doublet), other methylene carbons at 62.7, 64.4 and 66.9 ppm, double bond carbons at 125.8 and 135.4 ppm and carbonyl carbons at 165.2 and 166.7 ppm (Figure 4.3). The small peaks at 60.6 (CH_2), 62.1 (CH_2) and 73.8 (CH) ppm were due to the branched isomer. The ratio of tertiary carbon (66.1 ppm) for linear isomer to that of branched isomer (73.8 ppm) indicates relative ratios of the isomers which is 5:1.

The ^{31}P NMR spectra showed two peaks at 21.6 and 21.9 ppm with the ratio of their areas of about 4.2:1 (Figure 4.4).

The FTIR spectrum showed the presence of alcoholic OH bond at 3383 cm^{-1}, the characteristic ester C=O at 1739 and 1720 cm^{-1}, the double bond at 1636 cm^{-1} and the peaks due to phosphonate group at 1272 and 1024 cm^{-1} (Figure 4.5).

Hydrolysis of the phosphonate esters of this monomer with TMSBr at different conditions was unsuccessful.

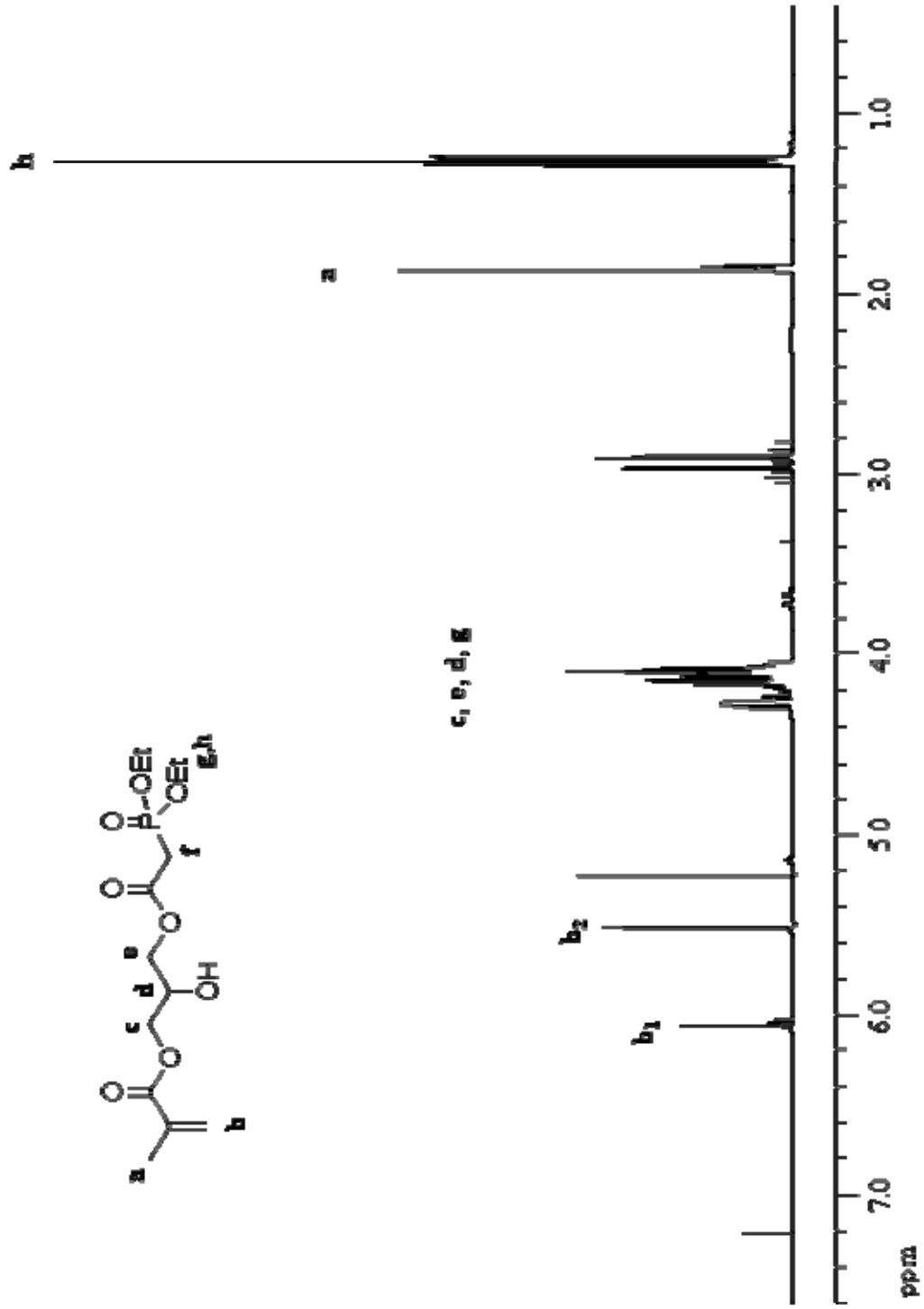


Figure 4.2. ^{1}H NMR spectra of monomer 1

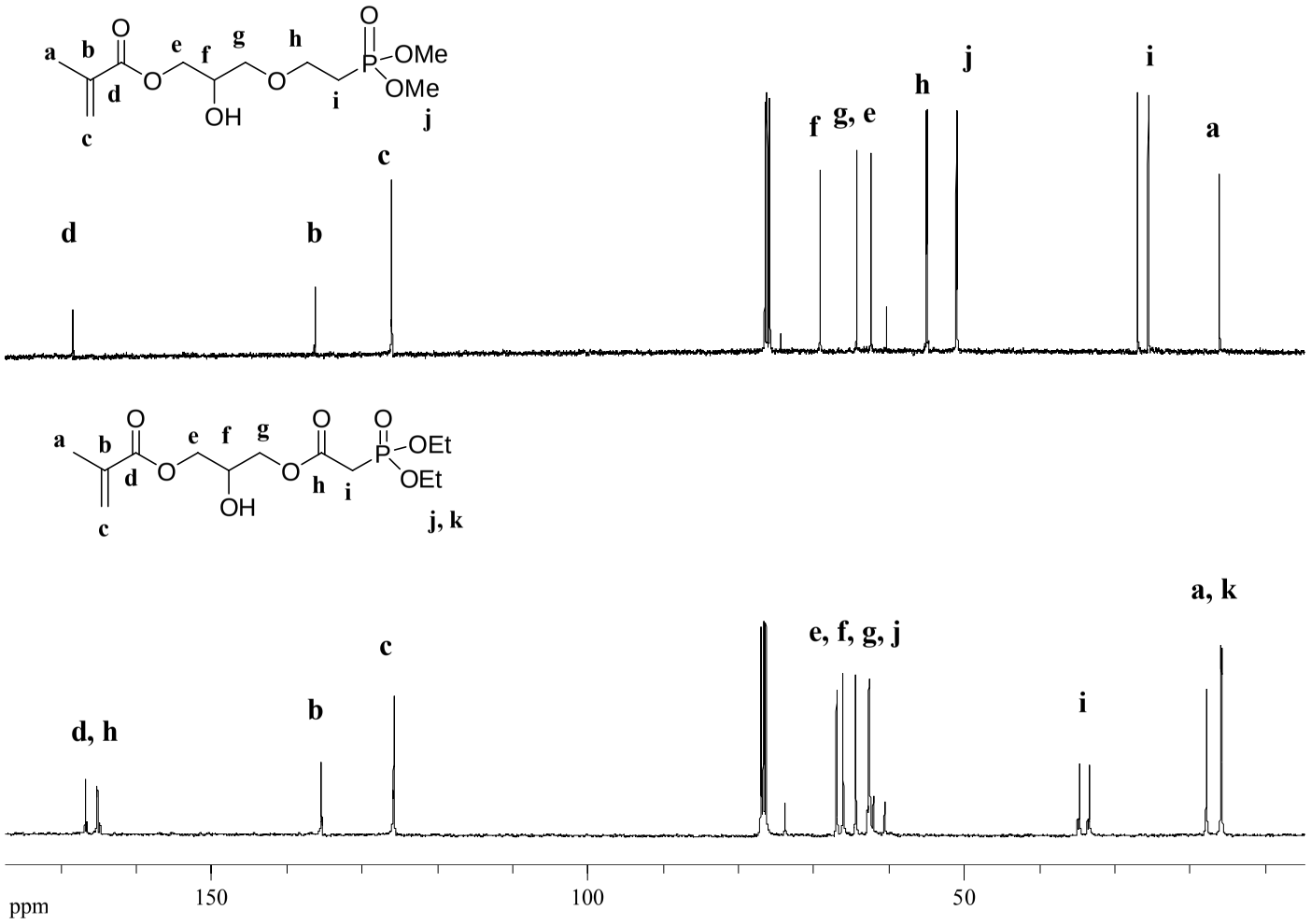


Figure 4.3. ^{13}C NMR spectra of monomer 1 and 2

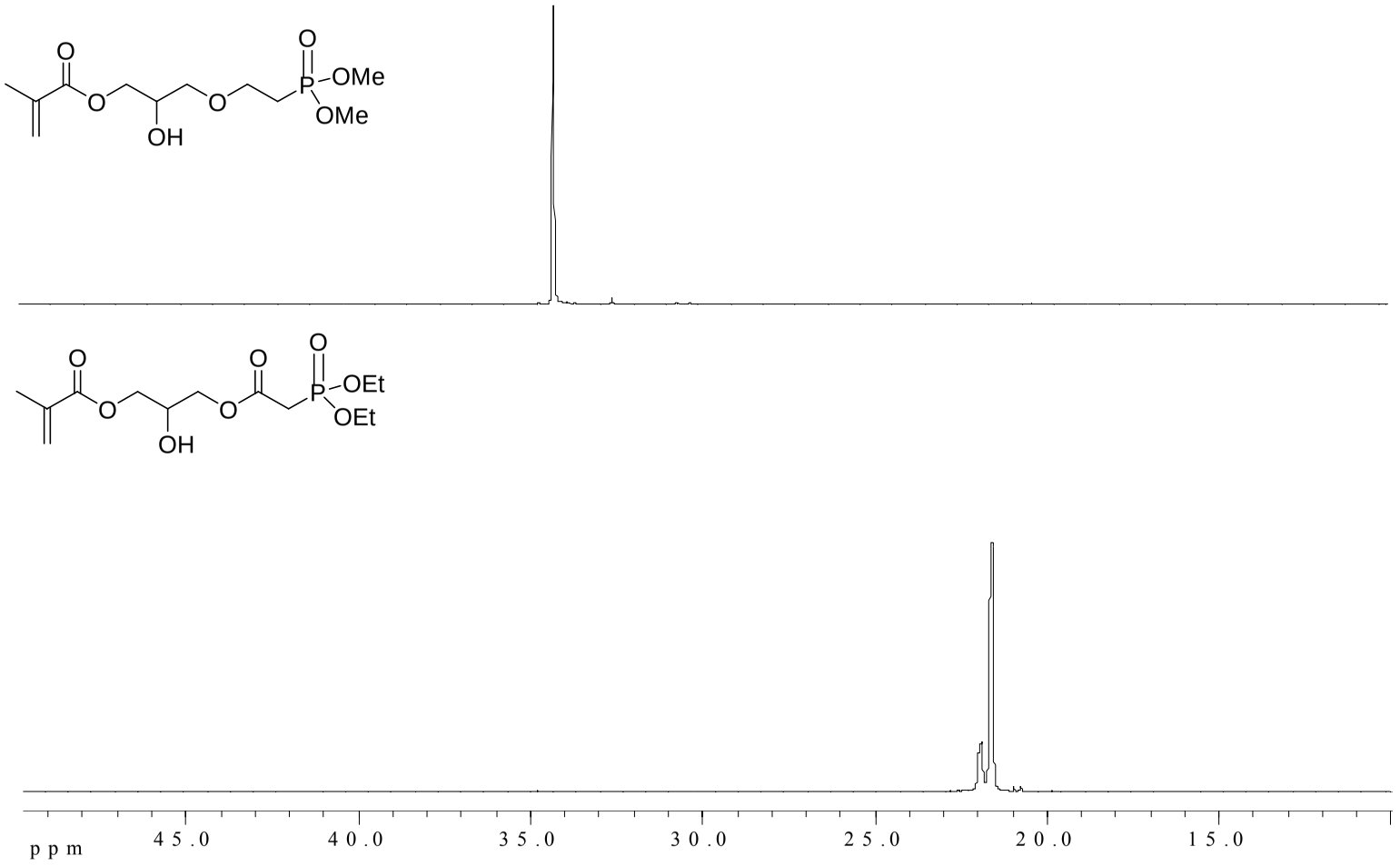


Figure 4.4. ^{31}P NMR spectra of monomer 1 and 2

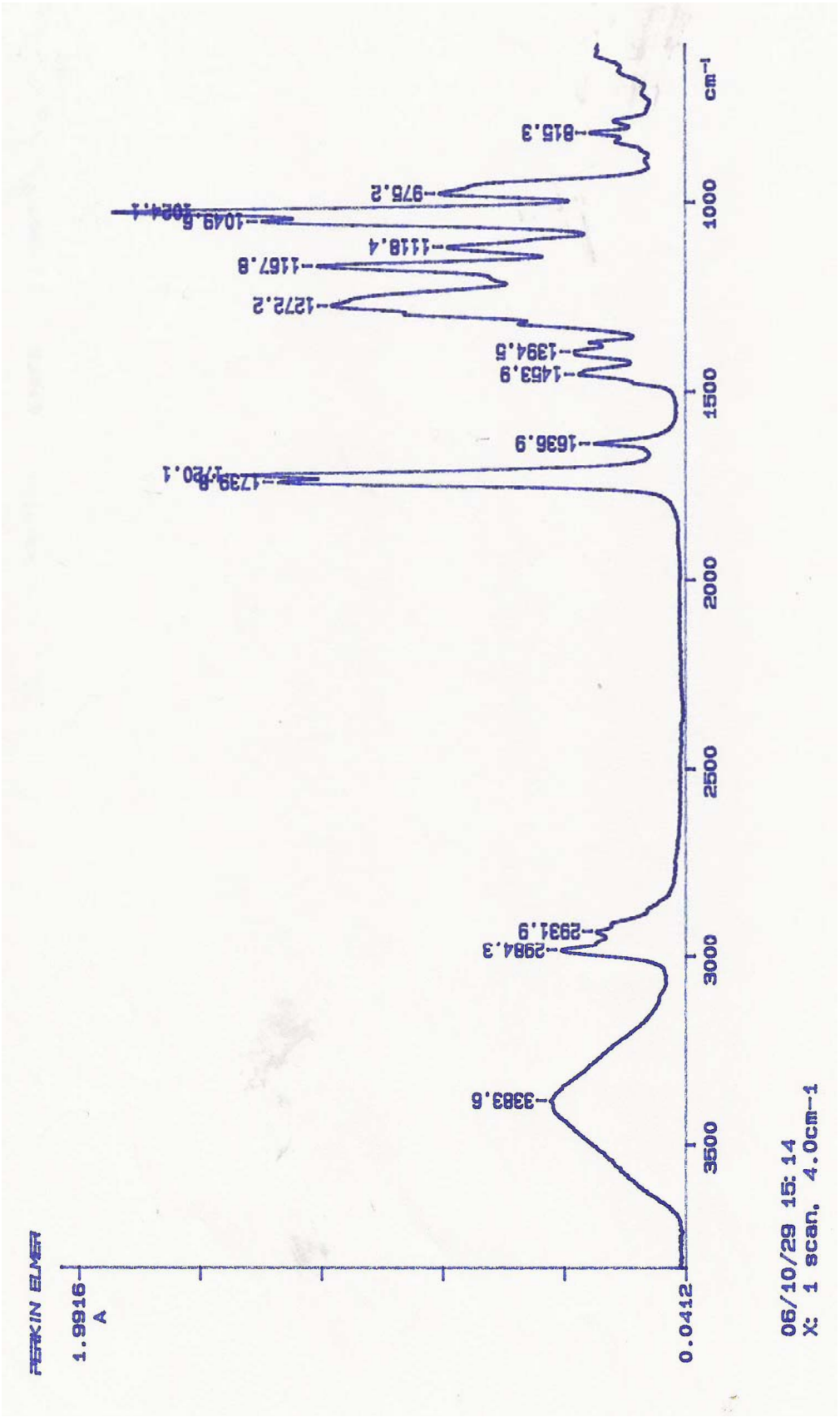
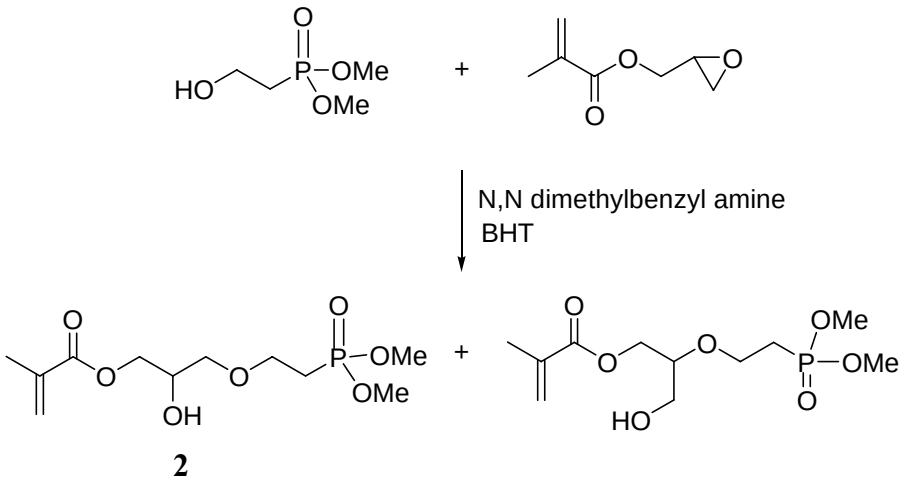


Figure 4.5. FT-IR spectrum of monomer 1

4.1.2. Synthesis of Monomer 2

The synthesis of monomer 2 was carried out in a one step ring opening reaction of glycidyl methacrylate (GMA) with (2-hydroxy-ethyl)-phosphonic acid dimethyl ester in the presence of a base catalyst (Figure 4.6).



2

Figure 4.6. Synthesis of monomer 2

BHT was added in order to prevent homopolymerization of GMA during reactions that employ high temperatures. Synthesis of monomer 2 was tried in the presence of N,N-dimethylbenzyl amine under nitrogen at 85 ºC for 19 h or at 130 ºC for 5h. The reactions were monitored by ^{13}C NMR spectrum and HPLC. The disappearance of the characteristic epoxy peaks at 44.3 and 49.8 ppm in the ^{13}C NMR spectra were used to follow product formation. Monomer 2 conversions were around 25-30 per cent. Use of different accelarators such as triphenylphosphine, triethylamine or N,N dimethyl p-toluidine did not result in any change or improvements in the conversion of monomer 2. In order to increase yield of 2 the reaction was carried out in a cycle of 5 h at 130 ºC followed by 18 h at 85 ºC and followed again by 5 h at 130 ºC. This way almost no residual GMA was observed at ^{13}C NMR. Although the ring opening reaction of the epoxides is not regiospecific and leads to the formation of both linear and branch isomers, linear isomer was the major product. The yield of monomer 2 after column chromatography was 32 per cent.

Monomer 2 was soluble in almost all organic solvents such as ether, acetone, dichloromethane, THF and methanol except hexane and it was also soluble in water (Table 4.3).

The ^{1}H NMR spectra of monomer 2 showed characteristic peaks for methyl protons at 1.9 ppm (singlet), methylene protons attached to phosphorus at 2.0 ppm (multiplet), methylene protons next to oxygen atoms at 3.5-3.9 ppm (multiplet) and 4.2 ppm (doublet), olefenic protons at 5.6 and 6.1 ppm (singlet) (Figure 4.7).

The ^{13}C NMR spectra of monomer 2 also confirmed product formation (Figure 4.3). The small peaks at 63.8 (CH_2) and 77.0, (CH) ppm are due to the branched isomer. The ratio of tertiary carbons (65.4 ppm for linear isomer and 77.0 ppm for branched isomer) indicates relative ratios of the isomers which is approximately 12:1.

The ^{31}P NMR spectra showed only one peak at 34.2 ppm (Figure 4.4).

The FT-IR spectrum showed the presence of alcoholic OH bond at 3372 cm^{-1}, the characteristic ester C=O at 1713 cm^{-1}, the double bond at 1634 cm^{-1} and the peaks due to phosphonate group at 1213 and 1020 cm^{-1} (Figure 4.8).

Hydrolysis of the phosphonate esters of this monomer with TMSBr at different conditions was unsuccessful.

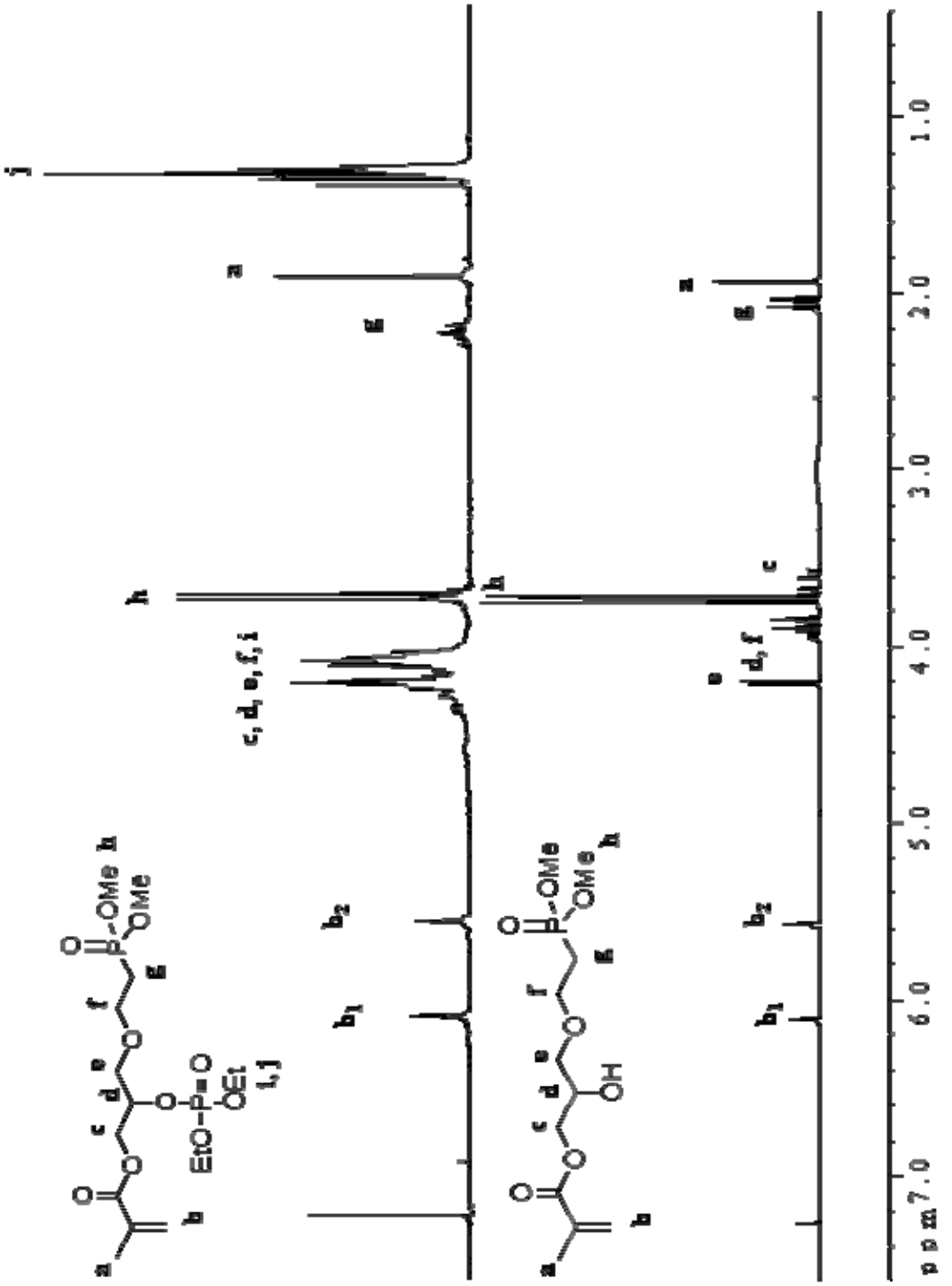


Figure 4.7. ^{1}H NMR spectra of monomer 2 and 3

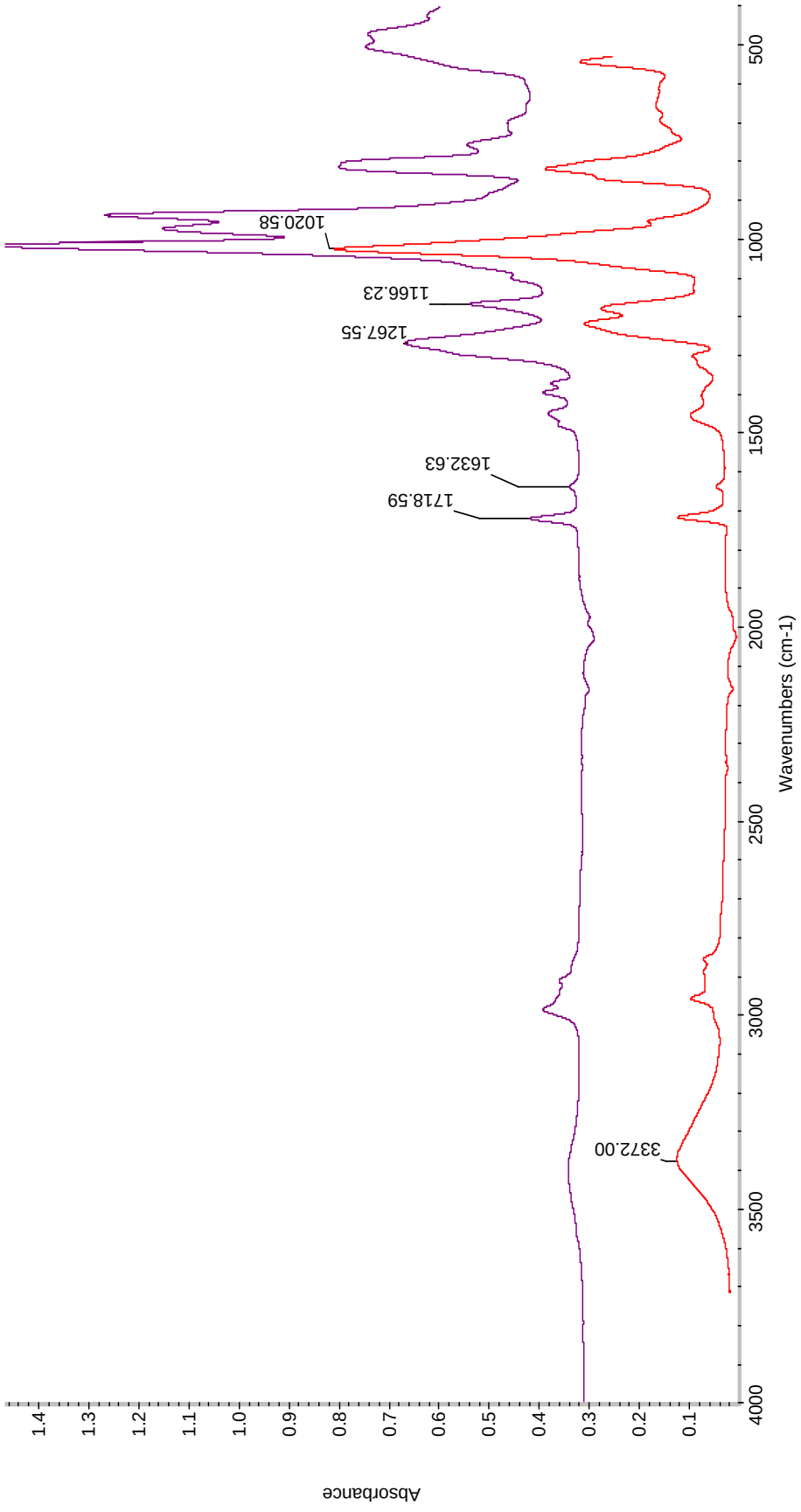


Figure 4.8. FT-IR spectrum of monomer 2 (red) and 3 (blue)

4.1.3.Synthesis of Monomer 3

It is possible to functionalize monomer 2 through the pendant hydroxyl group. The diethylphosphate derivative was synthesized by the reaction of monomer 2 with diethylchlorophosphate in the presence of a catalyst (Figure 4.9).

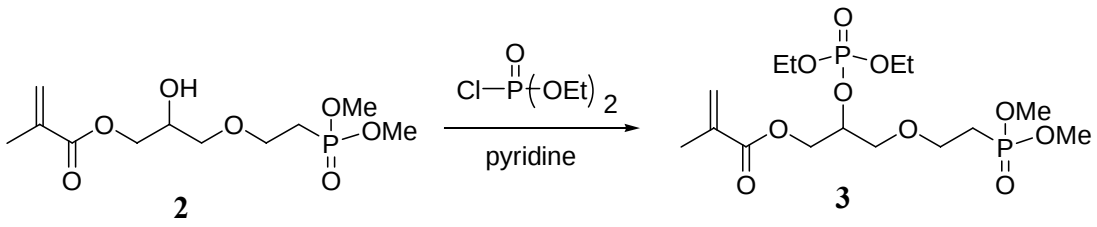


Figure 4.9. Synthesis of monomer 3

For the synthesis of monomer 3, pyridine was used as catalyst beacuse TEA was unsuccessful. The reaction proceeded at 0 ºC for 1h and at room temperature for 5h and monitored by ^{1}H NMR. The reaction went to complete conversion and monomer 3 was obtained in 36.6 per cent yield after purification. In the ^{1}H NMR spectra the peaks due to methylene protons next to oxygen atoms in monomer 2 shifted from 3.5-3.9 (multiplet) to 4.0-4.4 (multiplet) ppm and from 4.2 (doublet) to 3.7 (doublet) ppm in monomer 3. The disapperance of OH band of monomer 2 in the FT-IR spectrum also proved the complete conversion of monomer 2 to monomer 3. Monomer 3 was soluble in almost all organic solvents such as acetone, dichloromethane, THF and methanol except ether and hexane, and it was also soluble in water.

The ^{1}H NMR spectrum of monomer 3 showed characteristic peaks for methyl protons at 1.3 ppm (triplet) and 1.9 ppm (singlet), methylene protons attached to phosphorus at 2.2 ppm (doublet), methylene protons next to oxygen atoms at 4.0-4.4 ppm (multiplet) and at 3.7 ppm (doublet), olefenic protons at 6.1 and 5.6 ppm (singlet) (Figure 4.7).

The FTIR spectrum showed the presence of the characteristic ester C=O at 1718, the double bond at 1632 cm^{-1} and the peaks due to phosphonate group at 1267 and 1015 cm^{-1} (Figure 4.8).

4.1.4. Synthesis of Monomer 4

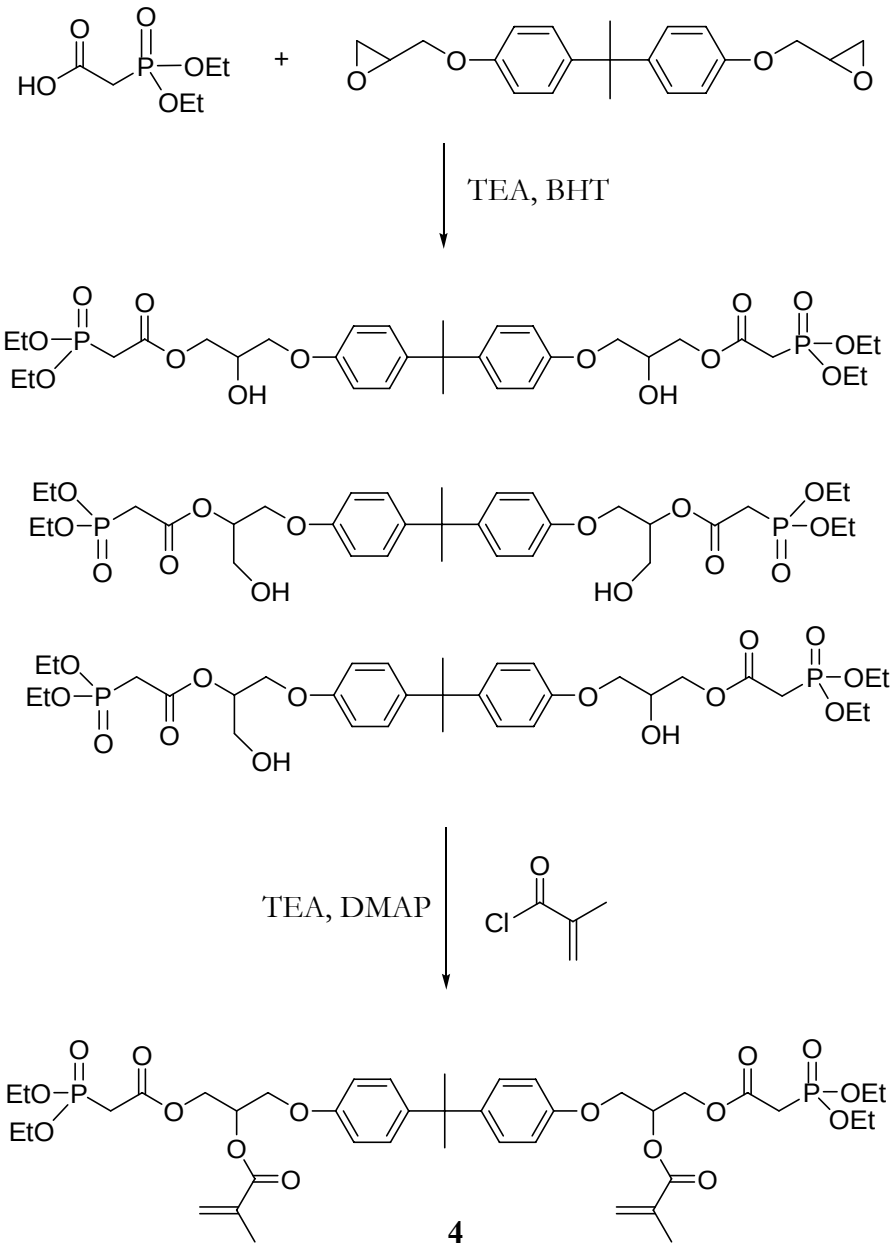
The ring opening reaction of an aromatic diepoxide (DER) with (diethoxy-phosphoryl)-acetic acid was used to prepare a diol intermediate which was then converted to a dimethacrylate using methacryloylchloride (Figure 4.10). Because we used a difunctional reagent there is a possibility of formation of three isomers during the reaction.

The pure product which was a mixture of the isomers was obtained as a viscous yellow oil after chromatography in 56 per cent yield.

The ^{1}H NMR spectra confirmed the structure of monomer 4 (Figure 4.11).

The ^{13}C NMR spectrum of one of the fractions showed characteristic peaks for methyl carbons at 16.2, 18.1 and 30.9 ppm, a t-butyl carbon at 41.7 ppm, methylene carbons at 62.7, 63.3 and 65.8 ppm, aromatic carbons at 113.9, 127.9, 135.7 and 156.1 ppm, double bond carbons at 126.4 and 143.4 ppm and two carbonyl carbons at 165.4 and 166.6 ppm (Figure 4.12). The small peak at 70.8 ppm is due to one of the branched isomers.

The FTIR spectrum of this fraction showed the presence of the characteristic ester C=O at 1739 and 1719 cm^{-1} and the peaks due to phosphonate group at 1245 and 1028 cm^{-1}. The disapperance of OH band of diol at 3367 cm^{-1} and existence of double bond peaks at 1634 cm^{-1} prove the product formation (Figure 4.13).



4

Figure 4.10. Synthesis of monomer 4

This monomer was soluble in ether, acetone, dichloromethane, THF and methanol but insoluble in water and hexane.

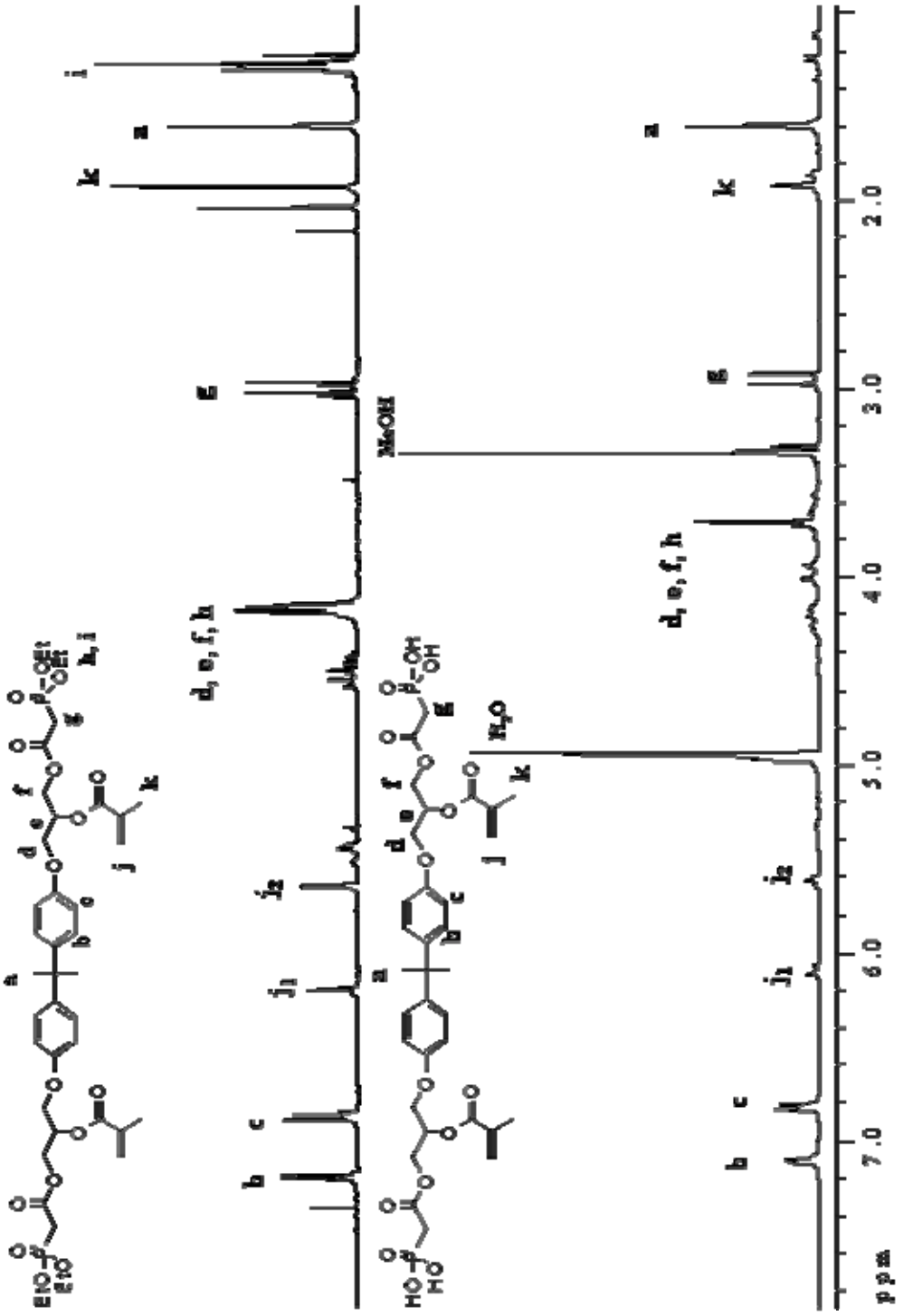


Figure 4.11. ^{1}H NMR spectra of monomer 4 and 5

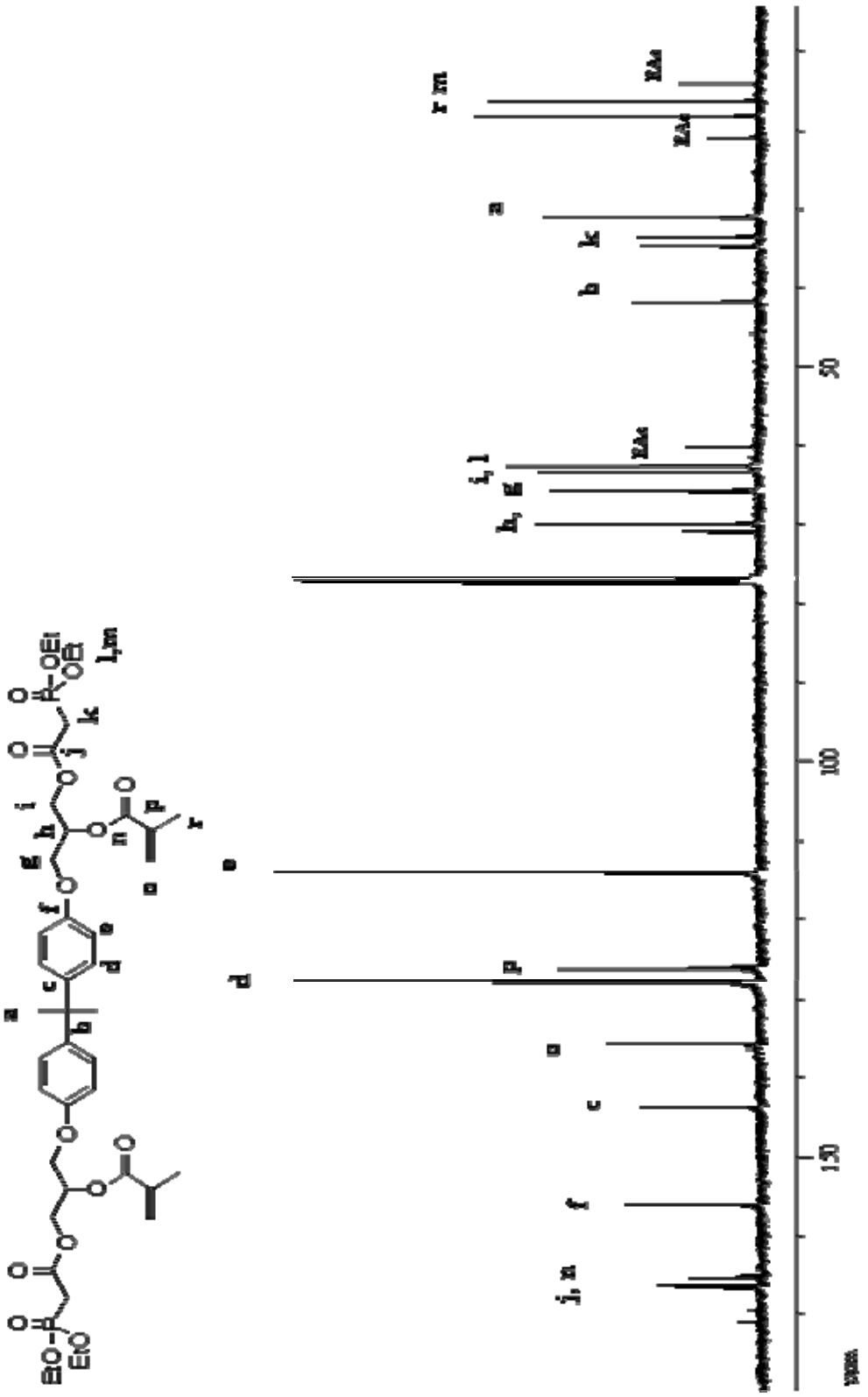


Figure 4.12. ^{13}C NMR spectra of monomer 4

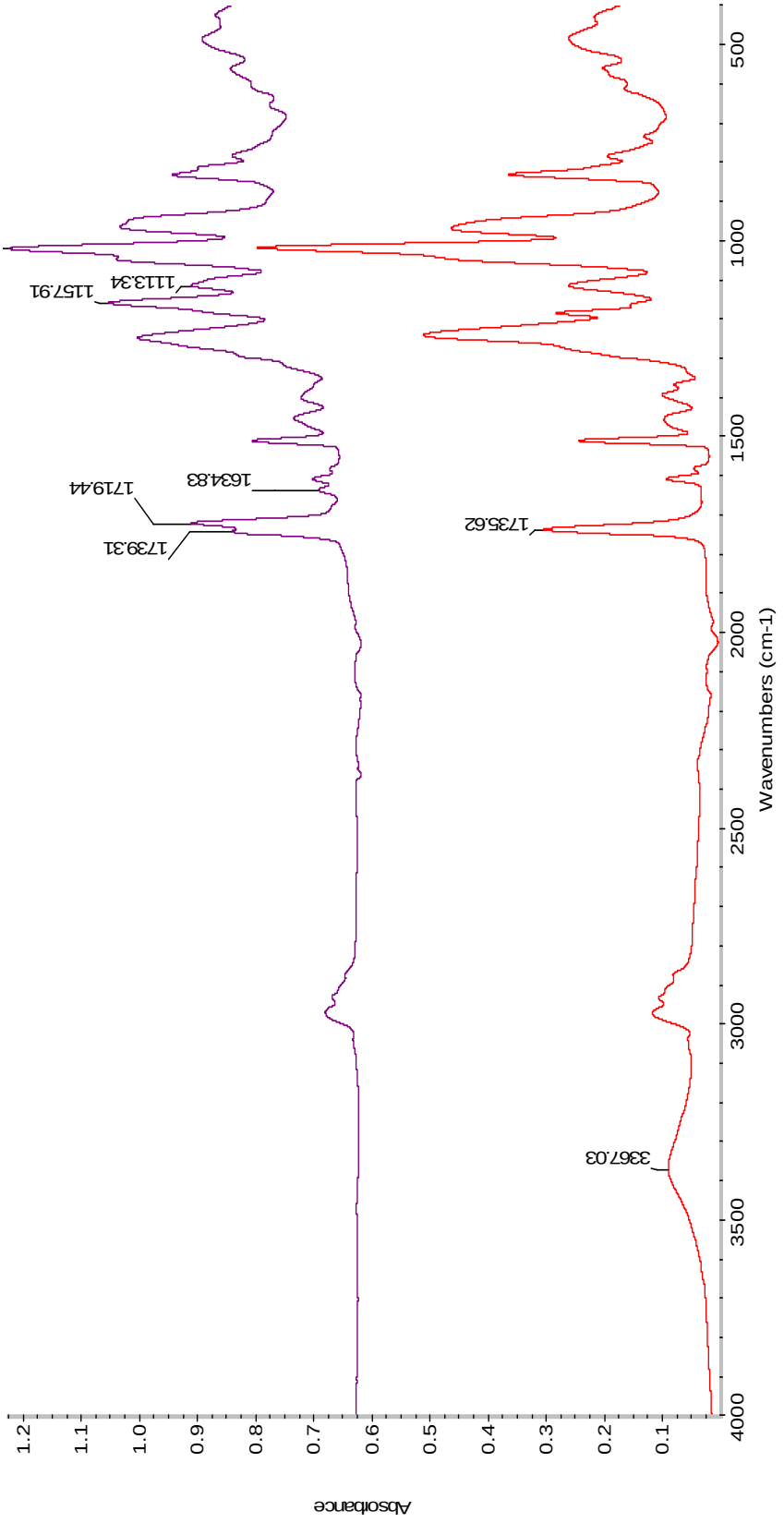


Figure 4.13. FT-IR spectrum of diol intermediate (red) and monomer 4 (blue)

4.1.5.Synthesis of Monomer 5

Monomer 5 was obtained by the hydrolysis of phosphonate esters of monomer 4 with TMSBr (Figure 4.14).

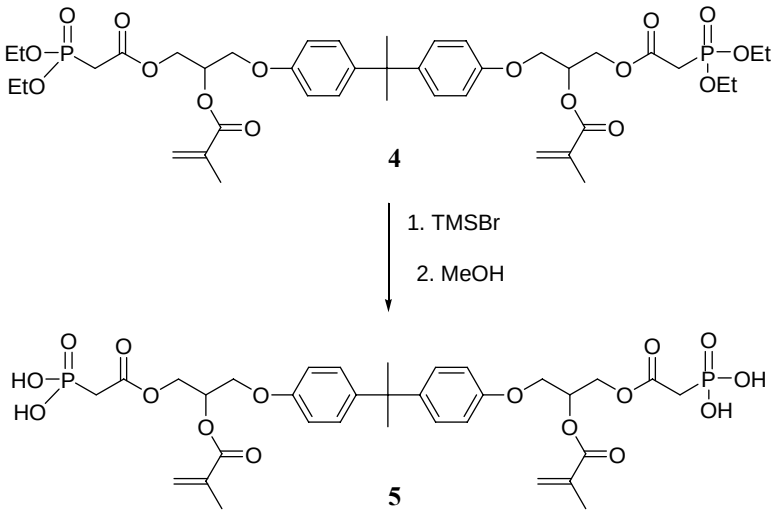


Figure 4.14. Hydrolysis of monomer 4 with TMSBr

The reaction was monitored with ^{1}H NMR. The disapperance of ethyl peaks at 1.2 ppm proved the hydrolysis of the phosphonate esters. However hydrolysis did not went to completion and 10 per cent of the phosphonate esters remained unhydrolyzed . In addition, a 30 per cent loss of double bonds was observed in ^{1}H NMR. The crude product was washed as described in the experimental part to eliminate the unhydrolysed monomer 4 and other impurities. However washing didn't not change the purity dramatically.

The ^{1}H NMR spectrum of 5 showed characteristic peaks for methyl protons at 1.6 ppm (singlet) and 1.9 ppm (singlet), methylene protons attached to phosphorus at 2.9 ppm (doublet), protons attached to carbons next to oxygen atoms at 3.9-4.2 ppm (multiplet), olefenic protons at 5.6 and 6.1 ppm (singlet) and aromatic protons at 6.8 and 7.0 ppm (doublet) (Figure 4.11).

4.2. Photopolymerizations

The photopolymerization behavior of the synthesized monomers was investigated using photodifferential scanning calorimeter (Photo-DSC). All the polymerizations were performed under identical conditions of initiator concentration (2.0 mol per cent) and UV light intensity (15 mW/cm^2) and temperature (40 ^oC).

First the homopolymerization behavior of the synthesized monomers was investigated and compared with those of the commercial monomers used in dentistry such as (2-hydroxyethyl methacrylate) HEMA, triethyleneglycol dimethacrylate (TEGDMA), 2,2-bis[4-(2- hydroxy-3-methacryloxyprop-1-oxy)phenyl]propane (BisGMA) and glycerol dimethacrylate (GDMA). BisGMA is very rigid and H-bonding monomer while TEGDMA is flexible and non H-bonding. The rate versus time and conversion versus time curves were showned in figures 4.15-4.16.

It is known that as the monomer functionality increases, the rate of polymerization increases while the conversion decreases. Thus, dimethacrylates (Bis-GMA, TEGDMA and GDMA) would be expected to have higher rates of polymerization than monomers 1 and 2. However, monomer 1 showed the higher maximum rate of polymerization (0.064 s^{-1}) and conversion (94.2 per cent) than Bis-GMA and GDMA and comparable to TEGDMA (Figures 4.14 and 4.15, Table 4.1). This monomer with one vinyl group reacts very rapidly and still forms a crosslinked network during polymerization with very low residual unsaturation. The crosslinking will lead to increased modulus and hardness of the polymer. This monomer was found to be faster than a hydrogen bonding monomethacrylate monomer, HEMA with a maximum rate of polymerization and conversion of 0.027 s^{-1} and 90.6 per cent.

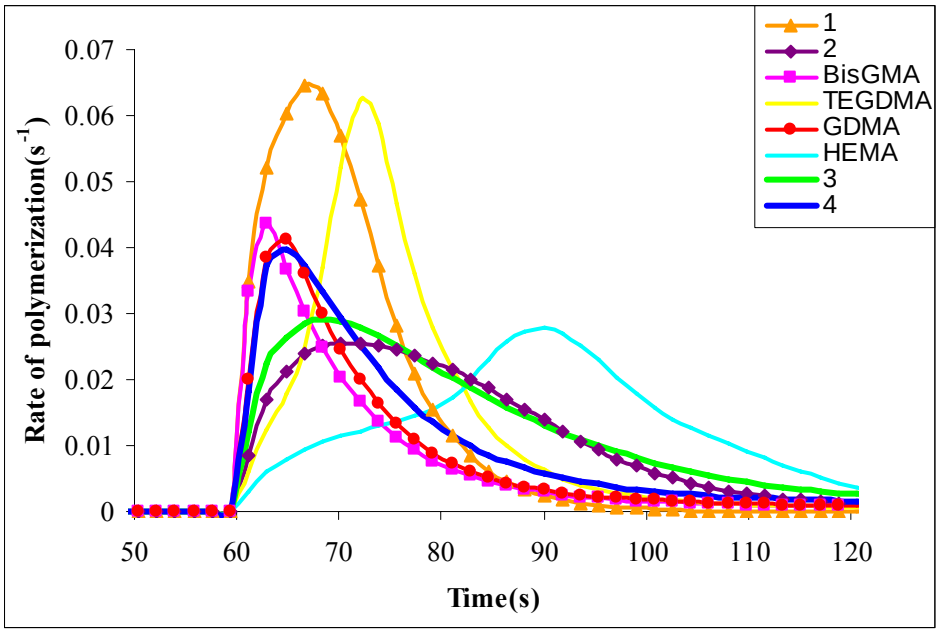


Figure 4.15. Rate of polymerization of monomers 1, 2, 3, 4, HEMA, TEGDMA, GDMA and Bis-GMA.

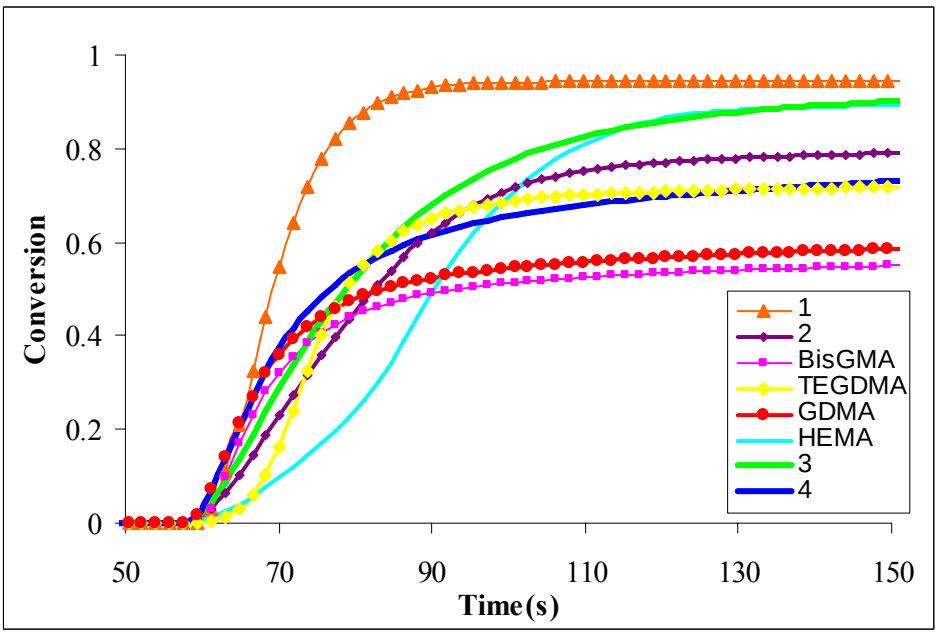


Figure 4.16. Conversions of monomers 1, 2, 3, 4, HEMA, TEGDMA, GDMA and Bis-GMA.

Although monomers 1 and 2 have similar chemical structures (both H-bonding, flexible, etc) monomer 2 has much lower rate of polymerization than 1, comparable to that of HEMA. The only difference between monomers is the electronic effect due to ester (in monomer 1) versus ether linkages (in monomer 2).

Monomer 1 is a hydrogen bonding and flexible monomer with an ester linkage which causes an electronic effect. Jansen et al. found a direct correlation between rate of polymerization and the calculated Boltzmann-averaged dipole moment. According to them the polymerization rate increases linearly with dipole moment if the dipole moment is greater than 3.5. In order to observe the polarity effect the Boltzmann-averaged dipole moments of monomers 1 and 2 were calculated from 100 minimum energy conformers: μ_{calc}= 4.28 for monomer 1 and μ_{calc}= 2.93. These values seemed to hold the correclation suggested by Jansen, monomer 1 with higher dipole moment was found to be more reactive.

Bowman et al. synthesized monomers with the following structure where R_2 is alkyl or phenyl group and R_3 is the secondary functionality. They investigated the effect of the monomers' secondary functionality and indicated the following trend in the reactivity: β-keto ester>> ester> ether where R_p (β-keto ester)= 3.3 R_p (ester)= 3.5 R_p (ether).

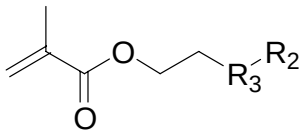


Figure 4.17. The structure of the monomers synthesized by Bowman et al.

Similarly monomer 1 with a secondary functionality similar to β-keto ester was found to be 2.6 times more reactive than monomer 2 with ether functionality.

The reactivity of monomer 3 was slightly higher than monomer 2 and less than monomer 1, very comparable to HEMA. It also had a higher monomer conversion than monomer 2. This may result from a change in electronic effect due to the insertion of a phosphate function.

The reactivity of monomer 4 was found to be between those of monomer 1 and monomer 2 and comparable to the commercial dental dimethacrylates studied here. The maximum rates of polymerization for GDMA, TEGDMA, Bis-GMA and 4 were 0.041, 0.062, 0.043 and 0.039 s^{-1}, respectively. The conversion for monomer 4 were lower than TEGDMA but much higher than Bis-GMA.

Copolymerization behavior of the synthesized monomers with base monomers (bis-GMA, TEGDMA and GDMA) were also investigated (Figure 4.18-4.23). 50 mol per cent of the synthesized monomers was added to these monomers and clear solutions were obtained.

It was observed that the maximum rate of polymerizations of the mixtures (except TEGDMA: 4) was higher than those of both components (Figures 4.18, 4.20 and 4.22, Table 4.1). For example, maximum rate of polymerization of TEGDMA and 1 were 0.062 and 0.064 s^{-1}, whereas the mixtures of TEGDMA with monomer 1 gave maximum rate of polymerizations of 0.092 s^{-1}.

Addition of monomer 1 and 2 to the rigid, very viscous, H-bonding bis-GMA monomer improved both the rate and conversion of this monomer. The higher rate of copolymerizations and conversions of the mixtures may be attributed to the hydrogen bonding capability and flexibility of the synthesized monomer.

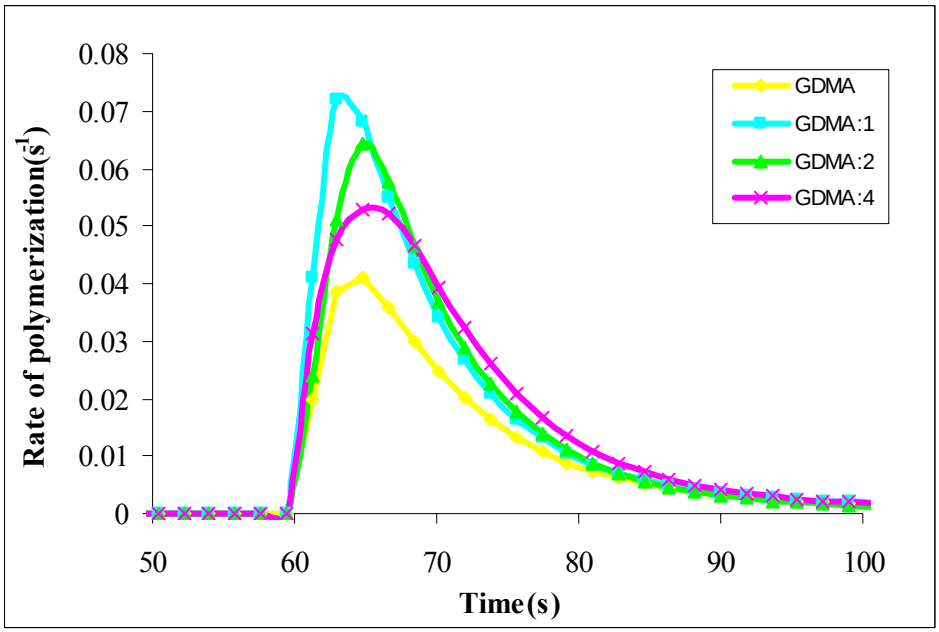


Figure 4.18. Rate of polymerization of GDMA, GDMA:1 (50:50 mol %), GDMA:2 (50:50 mol %) and GDMA:4 (50:50 mol %).

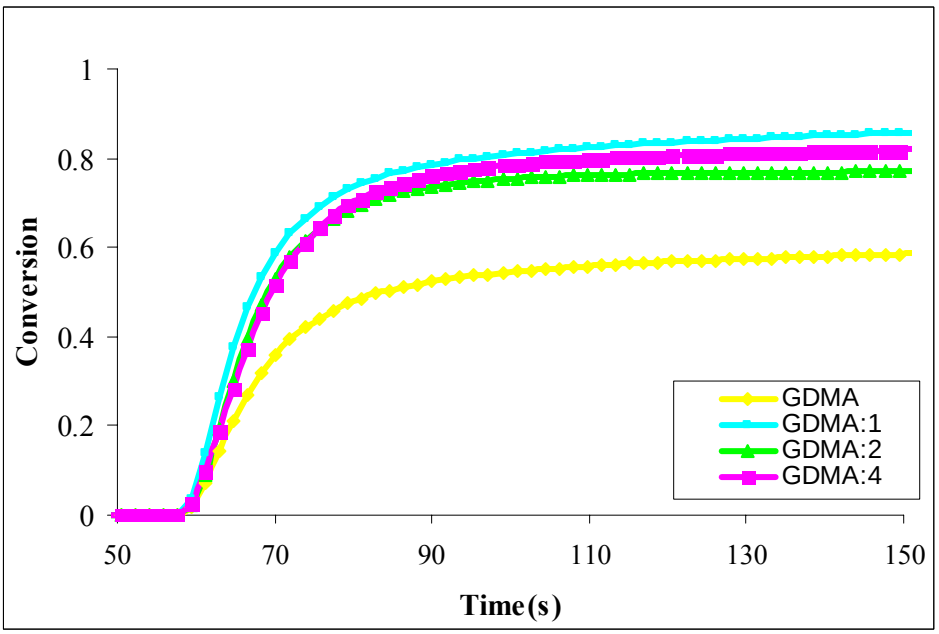


Figure 4.19. Conversions of GDMA, GDMA:1 (50:50 mol %), GDMA:2 (50:50 mol %) and GDMA:4 (50:50 mol %).

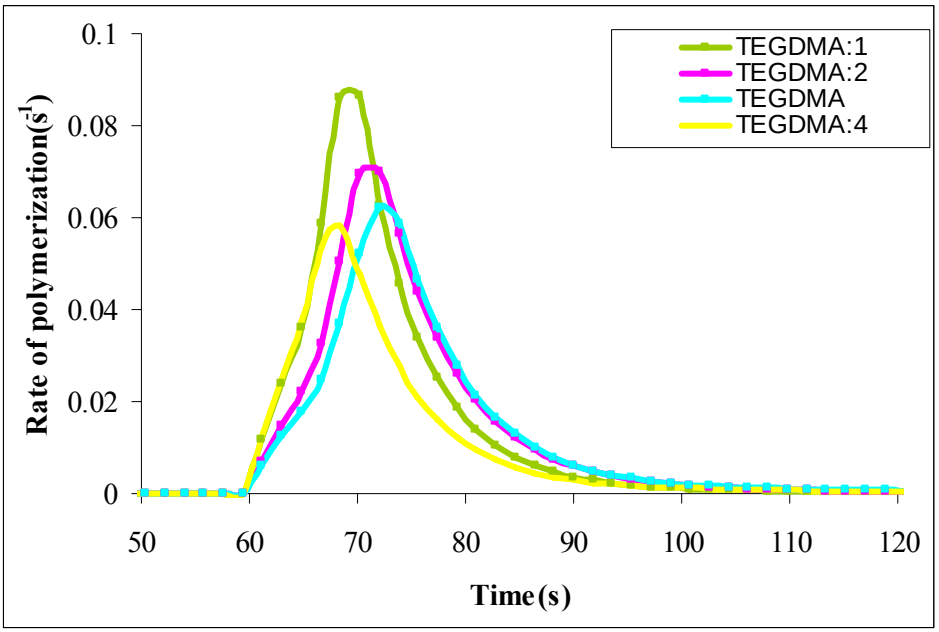


Figure 4.20. Rate of polymerization of TEGDMA, TEGDMA:1 (50:50 mol %), TEGDMA:2 (50:50 mol %) and TEGDMA:4 (50:50 mol %).

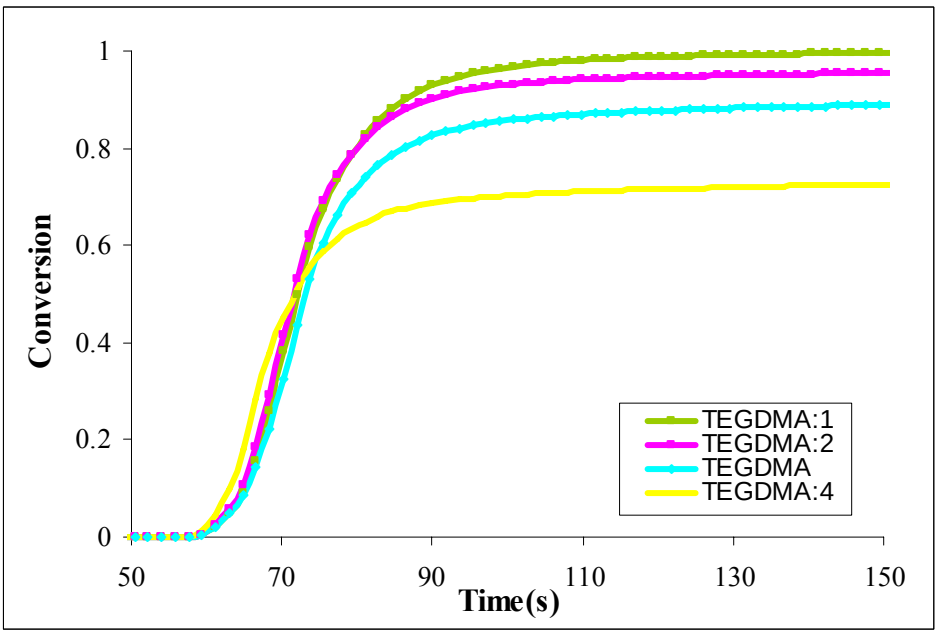


Figure 4.21. Conversions of TEGDMA, TEGDMA:1 (50:50 mol %), TEGDMA:2 (50:50 mol %) and TEGDMA:4 (50:50 mol %).

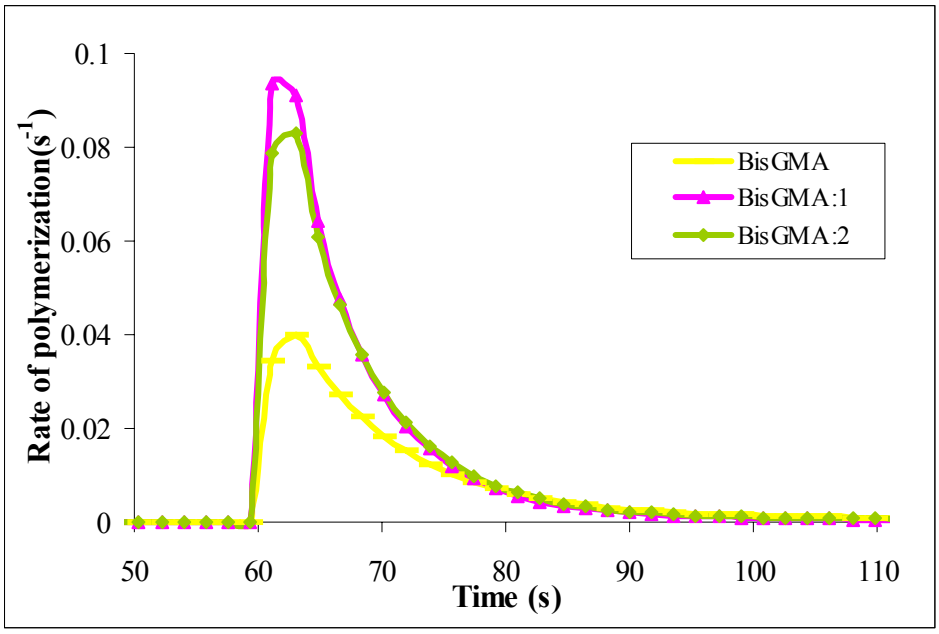


Figure 4.22. Rate of polymerization of Bis-GMA, Bis-GMA:1 (50:50 mol %) and Bis-GMA:2 (50:50 mol %).

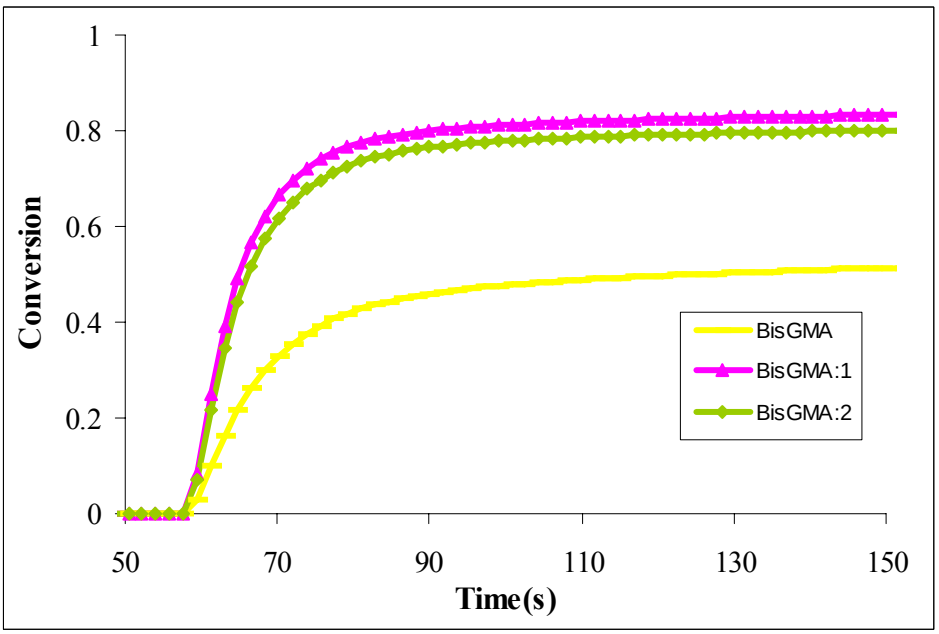


Figure 4.23. Conversions of Bis-GMA, Bis-GMA:1 (50:50 mol %) and Bis-GMA:2 (50:50 mol %).

Table 4.1 Photopolymerization Results

Monomer	**R_p (s^{-1})**	**Conversion (%)**
1	0.064	94.2
2	0.025	83.9
3	0.029	95.6
4	0.039	79.9
HEMA	0.027	90.6
GDMA	0.041	62.9
TEGDMA	0.062	90.4
BisGMA	0.043	58.9
GDMA-**1** (50:50)	0.071	90.3
GDMA-**2** (50:50)	0.069	84.7
GDMA-**4** (50:50)	0.052	82.2
TEGDMA-**1** (50:50)	0.092	97.8
TEGDMA-**2** (50:50)	0.070	95.7
TEGDMA-**4** (50:50)	0.058	72.4
BisGMA-**1** (50:50)	0.093	85.2
BisGMA-**2** (50:50)	0.082	81.1

4.3. Free Radical Polymerizations in Bulk and Solution

Free radical polymerization of monomer 1 and 2 in bulk and solution was carried out with AIBN and V-50 at 60 ºC using standard freeze-evacuate-thaw procedures. The polymers were obtained as white solids after reprecipitation into nonsolvents. Table 4.2 shows the conditions used for polymerization and the characteristics of the resulting polymers.

Both of the monomers showed very high polymerization rates and crosslinking tendency. For example, bulk polymerization of both monomers gave crosslinked polymers in less than 15 minutes.

Soluble polymers of monomer 1 and 2 could be obtained only in DMSO at low monomer and initiator concentrations. The high reactivity of the monomers may be due to hydrogen abstraction/chain transfer, hydrogen bonding and electronic and resonance effects. Hydrogen bonding (increasing radical concentration by ordering the double bonds close to each other or by decreasing termination with an increase in viscosity) has probably

an impact on the polymerization rate of this monomer but it does not explain crosslinked polymer formation. Decker and Bowman formulated new monoacrylate monomers with carbonate, cyclic carbonate, carbamate and oxazolidone groups that react extremely rapidly despite one vinyl group and still form crosslinked polymers. They mentioned that crosslinking due to hydrogen abstraction reactions causes an increase in viscosity, earlier gelation and autoacceleration which lead to high rate of polymerization [77,79]. Similarly a hydrogen abstraction mechanism from the labile hydrogens on the carbon attached to phosphorus atom can be proposed to account high reactivity and crosslinked polymer formation in case of monomer 1 and 2.

Table 4.2 Bulk and solution polymerization results of monomers 1 and 2

Monomer	[M]	[I] (10^{-2})	Solvent	t(min)	Yield (%)
1	3.00	0.5 [a]	water	30	Crosslinked
1	3.00	2,50 [a]	water	9	Crosslinked
1	1.00	0,50 [a]	water	21	Crosslinked
1	1.00	2,50 [a]	water	15	Crosslinked
1	3.00	1,00 [b]	DMSO	15	13
1	1.00	0,50 [b]	DMSO	60	74
1	[c]	[d]	-	15<	Crosslinked
2	3.00	0,50 [a]	water	32	Crosslinked
2	3.00	2,50 [a]	water	0	Crosslinked
2	1.00	2,50 [a]	water	33	Crosslinked
2	3.00	1,00 [b]	DMSO	35	Crosslinked
2	1.00	0,50 [b]	DMSO	90	42
2	[c]	[d]	-	12	Crosslinked

a: V-50, b: AIBN, c: bulk polymerization, d: amount of initiator (AIBN) was 0.5 wt per cent of the monomer.

Polymers were insoluble in most of the organic solvents and water and soluble in methanol and DMSO (Table 4.3).

Table 4.3 Solubilities of Monomers 1, 2,3, 4, Poly-1 and Poly-2

Monomer/Polymer	H_2O	Ether	Acetone	CH_2Cl_2	THF	Hexane	Methanol
1	+	+	+	+	+	-	+
2	+	+	+	+	+	-	+
3	+	-	+	+	+	-	+
4	-	+	+	+	+	-	+
Poly-**1**	-	-	-	-	-	-	+
Poly-**2**	-	-	-	-	-	-	+

^{1}H NMR of monomer 1 and its polymer are shown in Figure 4.23. The double bond peaks at 5.3 and 5.6 ppm completely disappeared from the monomer after polymerization. The backbone protons appeared at 1.9 ppm. Figure 4.24 also showed the stereochemistry of the polymer evidenced by the spectral pattern of α-methyl protons. The polymer triad tacticities were mm/mr/rr = 4.7 : 33.8 : 61.5, respectively, similar to metharylates synthesized by the radical polymerization. Because polymer 1 was insoluble in water and THF it was impossible to determine its molecular weight by GPC. The measurement of intrinsic viscosity of polymer 1 in DMSO gave a value of 0.37 dl/g.

The thermal stabilities of the poly-1 and poly-2 (crosslinked) were investigated by thermogravimetric analysis (TGA) and showed weight losses mainly due to ester thermolysis (Figure 4.25). Poly-1 began to decompose around 225°C whereas degradation began at 250°C for poly-2. The higher decomposition temperature of poly-2 is expected due to its crosslinked structure which maintained integrity of the chains. The char residues was 25 and 30 per cent for poly-1 and poly-2, which is comparable with the other phosphorus-containing monomers studied by Avci et al [98].

The DSC analysis of poly-1 showed no T_g between 25 and 150 ºC.

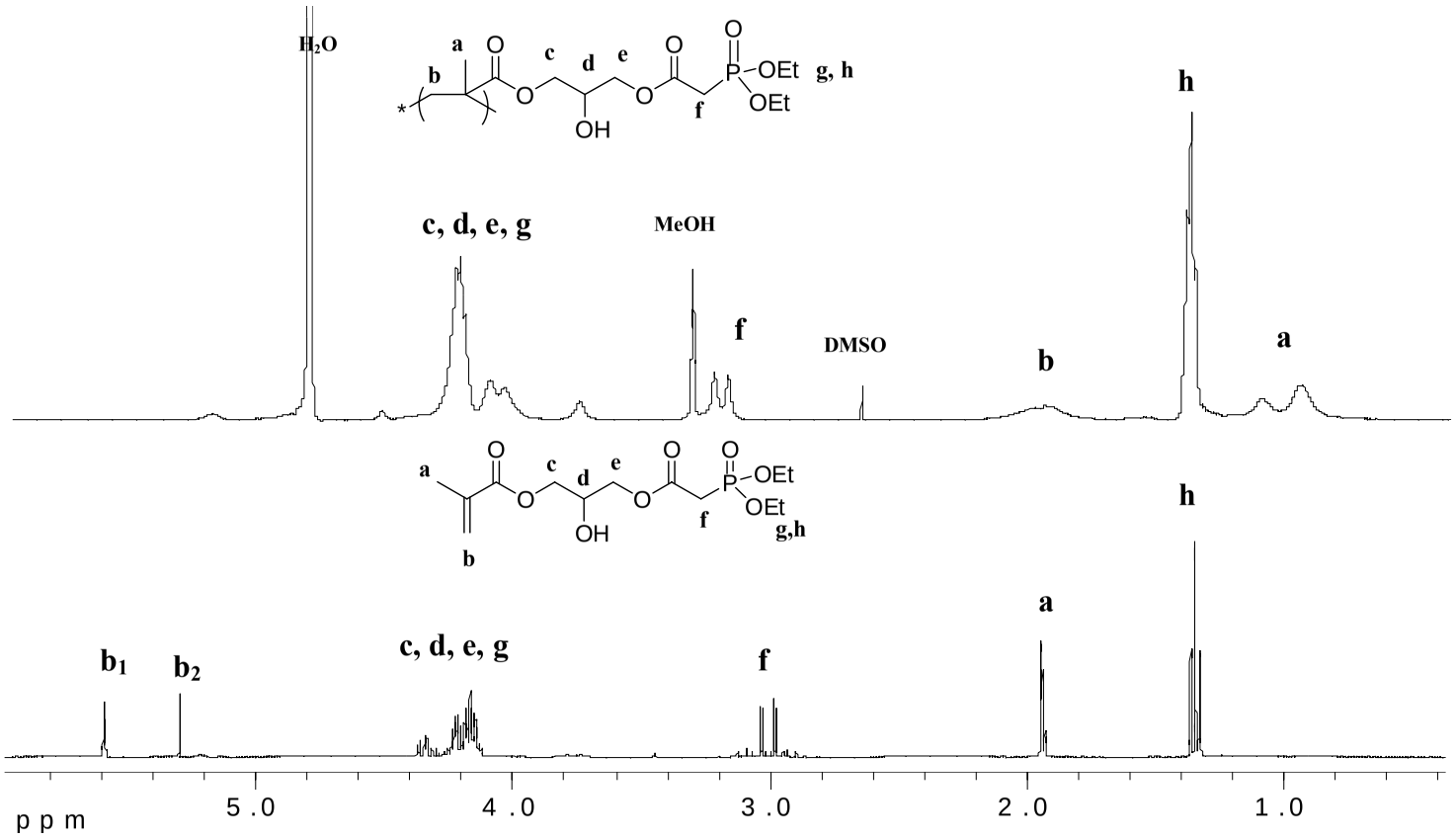


Figure 4.24. ^{1}H NMR spectra of monomer 1 and poly-1

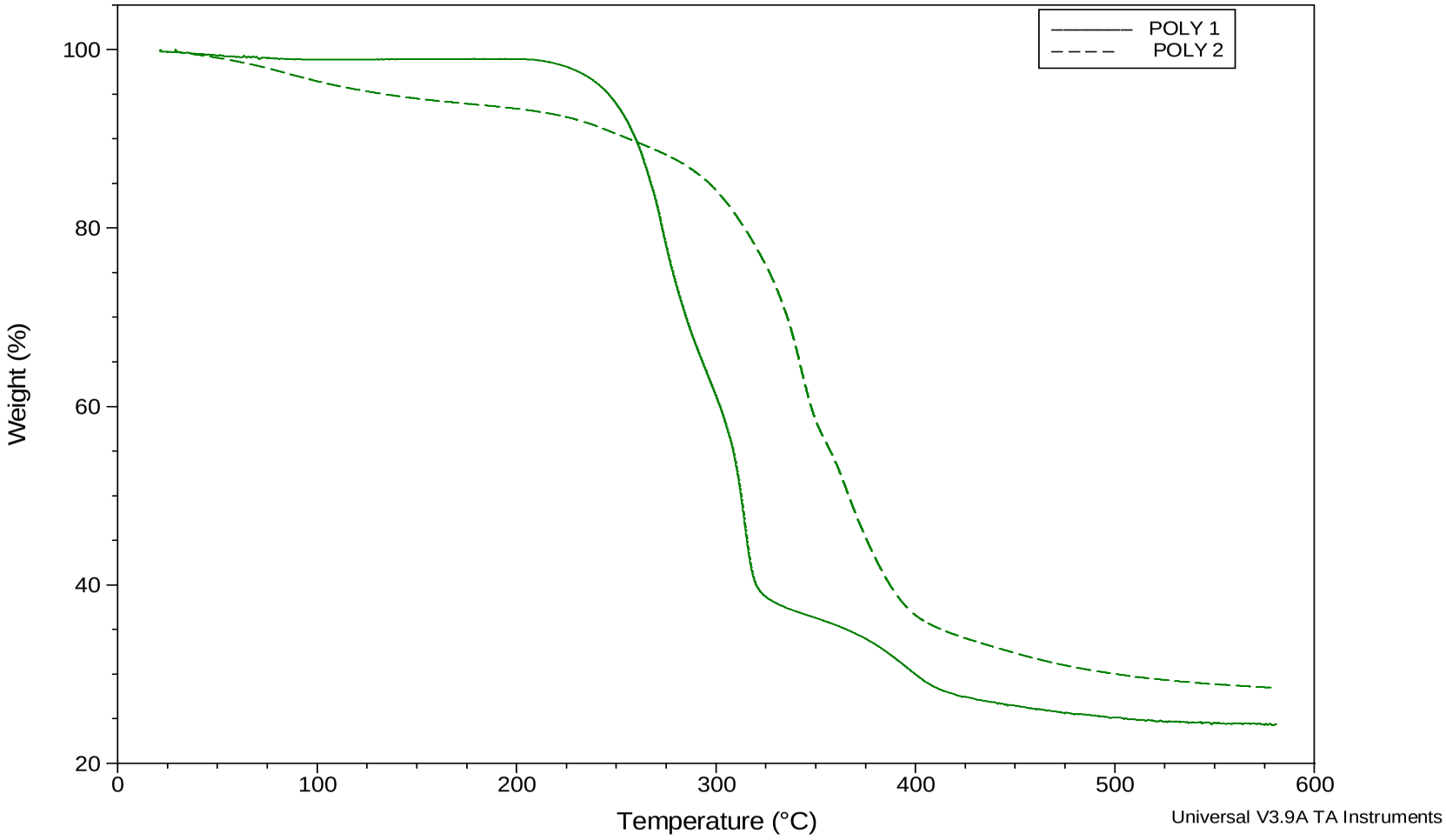


Figure 4.25. TGA of poly-1 and poly-2

5. CONCLUSIONS

Five novel phosphorus-containing mono- and dimethacrylates (monomers 1-5) for use as dental materials were synthesized with commercially available starting materials and their polymerization reactivities were evaluated.

The general procedure which involved ring opening reactions of epoxides with phosphonated acids and alcohols was found to be an easy method to prepare these monomers.

Monomers 1 and 2 polymerized rapidly despite having one double bond and showed tendencies to give crosslinked polymers probably due to a hydrogen abstraction mechanism. The conversions reached were 80-90 per cent in 60 sec. The maximum rate of polymerizations decreased in the following order: 1~TEGDMA>GDMA~Bis-GMA>2. A synergistic effect in the rate of polymerization was observed during copolymerizations of monomers 1 and 2 with Bis-GMA, TEGDMA and GDMA. The reactivity difference between monomers 1 and 2 was explained by the effect of polarity as represented by the calculated dipole moment. Due to their extremely high reactivity, high monomer conversions, crosslinking ability and solubility in solvents used in dental formulations such as water, these monomers can be used as reactive diluents in conventional composite resins to improve the cure efficiency and the properties of the final material. In addition, the presence of hydroxyl and phosphonate groups are expected to improve binding ability of composite resins. On the other hand, hydrolysis of monomers 1 and 2 to new phosphonic acid derivatives was not successful.

Monomer 3 seems to be the first dental monomer which combines both the phosphonate and phosphate functionalities. It photopolymerized rapidly and gave conversions higher than 95 per cent. This reactive monomer also has a potential for use as a reactive diluent in composite resins.

The photopolymerization reactivity of the synthesized dimethacrylate monomer (monomer 4) was comparable to commercial dental monomers such as Bis-GMA, TEGDMA and GDMA. Due to its aromatic structure this monomer is expected to give materials with improved mechanical properties. Furthermore, crosslinked polymer obtained from this monomer will exhibit the advantageous properties of crosslinked polymers. Monomer 5 which is a phosphonic acid derivative of monomer 4 is expected to have adhesion to tooth structure as well as good enamel-dentin etching property. This monomer needs further purification. These monomers can constitute a new set of monomers for potential use in dental adhesives and composites.

REFERENCES

1. *Tooth: Structure of A Normal Tooth*, http://www.mydr.com.au/default.asp, 2003.

2. *Kindandental: Your Tooth*, http://www.kindandental.com/teeth.html.

3. *Tooth Structure*, http://www.doctorndtv.com/teeth/oraldetailtopics.asp?id=2&b, 2001.

4. *Tooth*, http://en.wikipedia.org/wiki/Tooth, 2008.

5. *Web Dental Office: Parts of A Tooth- Tooth Anatomy, Structure and Morphology*, htt p://www.users.forthnet.gr/ath/abyss /dep1142.html, 2007.

6. Nicholson, J. W., "Adhesive Dental Materials-A Review", *International Journal of* Ad*hesion & Adhesives*, Vol. 18, pp. 229-236, 1998.

7. Shalaby, S. and U. Salz, *Polymers for Dental and Orthopedic Applications*, 1st ed., CRC press, Taylor and Francis Group, 2006.

8. Natural Desensitization, http://www.adha.org/CE_courses/course9/naturaldesensiti zation/html, 2003.

9. Ferracane, J. L., *Materials in Dentistry*, 2nd ed., Lippincott Williams & Wilkins, Baltimore, 2001.

10. Barette, S., *How Dental Restorations Compare*, http://www.quackwatch.com/03 Health Promotion/ dentalmaterials.html, 2002.

11. Restorative Dental Materials, http://www.ada.org/prof/resources/topics/materials/ index.asp, 2005.

12. Espevik, S., "Dental Amalgam", *Annual review of Material Science*, Vol. 7, pp. 55-42, 1977.

13. *Questions and Answers on Dental Amalgam*, http://www.fda.gov/cdrh/ consumer/amalgams.html, 2008

14. *Dental Fillers*, http://www.doctorspiller.com/Fillings.html, 2000.

15. Bogdal, D., J. Pielichowski and A. Boron, "Application of Diol Dimethacrylates in Dental Composites and Their Influence on Polymerization Shrinkage", *Journal of Applied Polymer Science, Part A: Polymer Chemistry*, Vol. 66, pp 2333, 1997.

16. Titus, W., *Amalgam vs Composites*, www.williamdtitusdmd.com/1716914.html, 2008.

17. *Dental amalgam Overview*, http://www.qualitydentistry.com/dental/amalgam/ amalgam 4.html, 2004.

18. *Restorating Your Smile: Dental Filling Choices*, http://www.sccds.org/public /Keytooralhealth/oralhealthtopics AZ/D/Dental%20Fillings%20(Amalgam).pdf.

19. *Composites used as Restoratives and Cements*, http://www.doctorspiller.com/dental_ materials.htm#Glass%20Ionomer, 2000.

20. Culbertson, B. M., "Glass Ionomer Dental Restoratives", *Progress in Polymer Science*, Vol. 26, pp. 577-604, 2001.

21. Charlton, D., *Glass-Ionomer Cements*, https://decs.nhgl.med.navy.mil/ DMNOTES/ gic.pdf.

22. Matsuane, K. and S. Akahane, *Dental Adhesive Set*, US patent, 2001; 6 217 644, GC Co (Tokyo).

23. Stansburry, J. W., "Curing Dental Resins and Composites by Photopolymerization", *Journal of Esthetic Dentistry*, Vol. 12, pp. 300-308, 2000.

24. Ullrich, G., D. Herzog, R. Linska, P. Burtscher and N. Moszner, "Photoinitiators with Functional Group VII, Covalently Bonded Camphorquinone-Amines", *Journal of Polymer Science, Part A: Polymer Chemistry*, Vol. 42, pp. 4948-4963, 2004.

25. Moszner, N. and U. Salz, "New Developments of Polmeric Dental Composites", *Progress in Polymer Science*, Vol. 26, pp. 535-576, 2001.

26. Lu, H., J. W. Stansbury, J. Nie, K. A. Berchtold and C. N. Bowman, "Development of Highly Reactive Mono-(meth)acrylates as Reactive Diluents for Dimethacrylate-based Dental Resin Systems", *Biomaterials,* Vol. 26, pp. 1329, 2005.

27. Labella, R., K. W. M. Davy, P. Lambrechts, B. Van Meerbeek and G. Vanherle, "Monomethacrylate Co-monomers for Dental Resins", *European Journal of Oral Science*, Vol. 106, pp. 816-824, 1998.

28. Decker C. and K. Moussa, 'Light-induced Polymerization of New Highly Reactive Acrylic Monomers.', *Journal of Polymer Sciencei Part A: Polymer Chemistry*, Vol. 31, pp. 2197-2203, 1993.

29. Lovell, L. G., J. W. Stansbury, D. C. Syrpes and C. N. Bowman, "Effects of Composition and Reactivity on the Reaction Kinetics of Dimethacrylate/ Dimethacrylate Copolymerizations", *Macromolecules*, Vol. 32, pp. 3913, 1999.

30. Chung, C. M., J. G. Kim, M. S. Kim, K. M. Kim and K. N. Kim, "Developmentof New Photocurable Composite Resin with Reduced Curing Shrinkage", *Dental Materials*, Vol. 18, pp. 174-178, 2002.

31. Tamareselvy, K. and A. Rueggeberg, "Synthesis and Characterization of a Monofunctional Analog to Bis-GMA : A Dental Monomer', *Journal of Applied Polymer Science*, Vol. 57, pp. 705-716, 1995.

32. Stansbury, J. W., and J. M. Antonucci, "Dimethacrylate Monomers with Varied Fluorine Contents and Distributions", *Dental Materials*, Vol. 15, pp. 166-173, 1999.

33. Taylor, D. F., S. Kalachandra, M. Sankarapandian and J. E. McGrath, "Relationship between Filler and Matrix Resin Characteristics and the Properties of Uncured Composite Pastes", *Biomaterials*, Vol. 19, pp. 197-204, 1998.

34. Peutzfeldt, A., "Resin Composites in Dentistry: Monomer Systems", *European Journal of Oral Science*, Vol. 105, pp. 97-117, 1997.

35. Moszner, N., T. Völkel, U. K Fisher, A. Klester and V. Rheinberger, "Synthesis and Polymerization of New Multifunctional Mrethane methacrylates", *Die Angewandte Macromolekulare Chemie*, Vol. 265, pp. 31-35, 1999.

36. Bailey, W. J. and R. L. Sun, "The Polymerization of Spiro Ortho Ester", *Polymer Preprints*, Vol.13, pp. 281-286, 1972.

37. Thompson, V. P., E. F. Williams and W. J. Bailey, "Dental Resins with Reduced Shrinkage During Hardening", *Journal of Dental Research*, Vol.58, pp. 1522-1532, 1979.

38. Stansbury, J. W., "Synthesis and Evaluation of New Oxaspiro Monomers for Double Ring Opening Polymerization", *Journal of Dental Research*, Vol. 71, pp. 1408-1412, 1992.

39. Byerley, T. J., J. D. Eick, G.P. Chen, C. C. Chappelow and F. Millich, "Synthesis and Polymerization of New Expanding Dental Monomers", *Dental Materials*, Vol. 8, pp. 345-350, 1992.

40. Chappelow, C. C., J. D. Eick C.S. and C. S.Pinzino, *Polymeric Compositions and Composites Prepared from Spiro Orthocarbonates and epoxy Monomers*, US patent, 5 808 215, 1998.

41. Reed, B., J. Stansbury and J. Antonucci, "Ring Opening Dental Resins Systems Based on Cyclic Acetals", *Polymer Preprints*, Vol. 33, pp. 520-521,1972.

42. Moszner N., F. Zeuner, T. Völkel and V. Rheinberger, "Synthesis and Polymerization of Vinylcyclopropane", *Macromolecular Chemistry and Physics,* Vol. 200, pp. 2173-2187, 1999.

43. Moszner N., F. Zeuner, T. Völkel and V. Rheinberger, "Radical Ring-opening Monomers for Dental Composites", *Polymer Preprints,* Vol. 38, pp. 86-87, 1997.

44. Rawls, H. R., V. T. Wellinghoff, B. K. Norling, S. H. Leamo, N. F. Swynnerton and S. T. Wellinghoff, "Low Shrinkage Resins from Liquid Crystal Diacrylate Monomers", Polymer Preprints, Vol. 38, pp. 167-168, 1997.

45. Klee, J. E., U. Walz, D. Hötler, H. Frey and R. Mühlhaupt, "Branched macromonomers and their application in dental composites. 3. Monomers for low shrinkage composites", *Angewante Macromolecular Chem*istry, Vol. 269, pp. 71-75, 1998.

46. Wan, Q., S. R. Schricker and B. M. Culbertson, 'Hyperbranched Multi Methacrylates: Their Application in Dental Resin Systems, *Polymer Prepr*ints, Vol. 41, pp. 155-156, 2000.

47. Moszner, N. and U. Salz, "New Developments of Polymeric Dental Composites",*Progress in Polymer Science*, Vol. 26, pp. 535-576, 2001.

48. Moszner, N. and U. Salz, "Recent Developments of New Components for Dental Adhesives and Composites", *Macromolecular Materials and Engineering*, Vol. 292, pp. 245-271, 2007.

49. Pham, T., N. Sibold, P.J. Madec and S. Masson, "Synthesis and Characterization of (co)polymers Containing a Phosphonate Function for Use in Dental Composites", *Polymer*, Vol. 43, pp. 7247-7267, 2002.

50. Ruse, N. D., "What is a compomer?", *Journal of Canadian Dental Association*, Vol. 65, pp. 500-504, 1999.

51. Meyer, J. M., M. A. Cattani-Lorente. and V. Dupuis, "Compomers: Between Glass-Ionomer Cements and Composites", *Biomaterials*, Vol. 19, pp. 529-539, 1998.

52. Omura, I., J. Yamauchi, Y. Nagase and F. Uemura, *Adhesive Composition*, US Patent, 4 650 847,1984.

53. Marshall, G. W., S. J. Marchall, J. H. Kinney and M. Balooch, "Dentin Substrate: Structure and Properties Related to Bonding", *Journal of Dentistry*, Vol. 25, pp. 441-458, 1997.

54. Buonocore, M.G., "A Simple Method of Increasing the Adhesion of Acrylic Filling Materials to Enamel Surfaces", *Journal of Dental Research*, Vol. 34, pp. 849-853, 1995.

55. Nakabayashi, N., K. Kojima and E. Masuhara, "The Promotion of Adhesion by Infiltration of Monomers into Tooth Substrates", *Journal of Biomedical Materials Research*, Vol. 16, pp. 265-273, 1982.

56. Moszner, N., U. Salz and J. Zimmermann, "Chemical Aspects of Self-etching Enamel-Dentin Adhesives: A Systematic Review", *Dental Materials*, Vol. 21, pp. 895-910, 2005.

57. Van Meerbeek B., J. D. Munck, Y. Yoshida, S. Inoue, M. Vargus, P. Vijay, K. Van Landuyt, P. Lamberchts and G. Vanherle, "Adhesion to Enamel and Dentin: Current Status and Future Challenges", *Operative Dentistry*, Vol. 28, pp. 215-235, 2003.

58. Schulze, K. A., Oliviera, S. A., Wilson, R. S., Gansky, S. A., Marshall, G. W.and S. J., Marshall, "Effect of Hydration Variability on Hybrid Layer Properties of a Self-etching Versus Acid-Etching System", *Biomaterials*, Vol. 26, pp. 1011-1018, 2005.

59. Itou, K., Torii, Y., Nishitani, Y., Ishikawa, K., Suzuki, K. and K. Inoue, "Effect of Self-etching Primers Containing N-acryloyl Aspartic Acid on Dentin Adhesion", *Journal of Biomedical Materials Research*, Vol.51, pp. 569-574, 2000.

60. Kugel, G. and M. Ferrari, “The Science of Bonding: From First to Sixth Generation”, *JADA*, Vol. 131, pp.20-25, 2000.

61. Tay, F. R., Pashley, D. H., Suh, B. I., Carvallo R. M. and A. Itthagarun, “Single-step Adhesives are Permeable Membranes”, *Journal of Dentistry*, Vol. 30, pp. 371-382, 2002.

62. Moszner, N., Zeuner, F., Pfeiffer, S., Schurte, S., I. Rheinberger and M. Drache, “Monomers for Adhesive Polymers, 3”, *Macromolecular Materials and Engineering*, Vol. 286, pp. 225-231, 2001

63. Mou, L., Singh, G. and J. W. Nicholson, “Synthesis of a Hydrophilic Phosphonic Acid Monomer for Dental Materials”, *Chemical Communications*, pp.345, 2000.

64. Sibold, N., Madec, P.-J., Masson, S. and T.-N Pham, “Synthesis and Characterization of (Co)polymers Containing a Phosphonate Function for Use in Dental Composites”, Polymer, Vol.43, pp. 7257-7267, 2002.

65. Xu, X., Wang, R., Ling, L. and J. O. Burgess, “Synthesis and Stability Study of Dental Monomers Containing Methacrylamidoethyl Phosphonic Acids”, *Journal of Polymer Science Part A: Polymer Chemistry*, Vol. 45, pp. 99, 2007.

66. Ikemura, K., Tay F., Nishiyama, F. R., Pashley, D. H. and T. Endo, “Design of New Phosphonic Acid Monomers for Dental Adhesives- Synthesis of(Meth)acryloxyalkyl 3-phosphonopropionates and Evaluation of their Adhesion-promoting Functions ”, *Dental Materials Journal*, Vol. 25, pp. 566, 2006.

67. Buonocore, G., Wileman, W. and F. Brudevold, ‘ A Report on Resin Composition Capable of Bonding Human Dentin Surfaces’, *Journal of Dental Research*, Vol. 35, pp. 846-851, 1956.

68. Hino, K., Yamauchi, J. and K. Nishida, *Dental Compositions*, US patent, 1994: 5 321 053, Kuraray Co.

69. N.Moszner, F. Zeuner, U.K. Fischer and V.Rheinberger, "Synthesis and Radical Polymerization of Hydrotically Stable Acrylic Phosphonic Acids", *Macromolecular Chemistry and Physics*, Vol. 200, pp. 1062-1067 ,1999.

70. Decker, C., "Kinetic Study and New Applications of UV Radiation Curing", *Macromolecular Rapid Communication*, Vol. 23, pp. 1067-1093, 2002.

71. Andrajewska, E., "Photopolymerization Kinetics of Multifunctional Monomers", *Progress in Polymer Science*, Vol. 26, pp. 605-665, 2001.

72. Decker, C., "Photoinitiated Crosslinking Polymerization", *Progress in Polymer Science*, Vol. 21, pp. 593-650, 1996.

73. T. Y. Lee, T. M. Roper, E. S. Jönsonn, C. A. Guymon and C. E. Hoyle, "Influence of Hydrogen Bonding on Photopolymerization Rate of Hydroxalkyl Acrylates", *Macromolecules* Vol. 37, pp. 3659, 2004.

74. Lee, I. B., B. H. Cho, H. H. Son and C. M. Um, "A New Method to Measure the Measurement of Polymerization Shrinkage in Dental composites", *Dental Materials*, Vol. 15, pp. 447-449, 1999.

75. Berchtold, K. A., J. Nie, J. W. Stansbury, B. Hacioglu, E. R. Beckel and C. N. Bowman, "Novel Monovinyl Methacrylic Monomers Containing Secondary Functionality for Ultrarapid Polymerization: Steady-State Evaluation", *Macromolecules*, Vol. 37, pp. 3165-3179, 2004.

76. Decker C. and K. Moussa, "A New Class of Highly Reactive Acrylic Monomers. 1. Light-Induced Polymerization", *Macromolekulare Chemie, Rapid Communications*, Vol.11, pp. 159-67, 1990.

77. Decker C. and K. Moussa, "Photopolymerization of Multifunctional Monomers. 4. Acrylates with Carbamate or Oxalidine Structure", *European Polymer Journal*, Vol.27, pp. 403-411, 1991.

78. Jansen J. F. G. A., Dias A., Dorschu M. and B. Coussens, "Effect of Dipole Moment on the Maximum Rate of Photoinitiated Acrylate Polymerization", *Macromolecules*, Vol.35, pp. 7529-7531, 2002.

79. Andrzejewska, E. and M. Andrzejewska, "Polymerization Kinetics of Photocurable Acrylic Resins", *Journal of Polymer Science Part A: Polymer Chemistry*, Vol. 36, pp.665, 1998.

80. Jansen J. F. G. A., Dias A., Dorschu M. and B. Coussens, "Fast Monomers: Factors Affecting the Inherent Reactivity of Acrylate Monomers in Photoinitiated Acrylate Polymerization", *Macromolecules*, Vol.36, pp. 3861-3873, 2003.

81. Jansen J. F. G. A., Dias A., Dorschu M. and B. Coussens, "Effect of Preorganization due to Hydrogen Bonding on the Rate of Photoinitiated Polymerization", *Polymer Preprints*, Vol.42, pp. 435, 2001

82. Beuermann, G. R., "Impact of Hydrogen Bonding on Propagation Kinetics in Butyl Methacrylate Radical Polymerizations", *Macromolecules*, Vol. 37, pp. 1037, 2004

83. Beckel, E. R., J. Nie, J. W. Stansbury and C. N. Bowman, "Effect of Aryl Substituents on the Reactivity of Phenyl Carbamate Acrylate Monomers", *Macromolecules*, Vol. 37, pp. 4062-4069, 2004.

84. Odian, G., Principle of Polymerization, 3rd Ed. New York: John Wiley & Sons, Inc, 1991.

85. Anseth, K. S., Wang, C. M: and C. N. Bowman, "Kinetic Evidence of Reaction Diffusion During the Polymerization of Multi(meth)acrylate Monomers", *Macromolecules*, Vol.27, pp. 650-655, 1994

86. Bowman, C. N. And N. A. Peppas, "Coupling of Kinetics and Volume Relaxation During Polymerizations of Multiacrylates and Multimethacrylates", *Macromolecules*, Vol. 24, pp. 1914-1920, 1991.

87. Lovell, L. G., Lu H., Elliott J. E., Stansbury J. W. and C. N. Bowman, "The Effect of Cure Rate on the Mechanical Properties of Dental Resins", *Dental Materials*, Vol. 17, pp. 504-511, 2001.

88. Lee, T. Y., Roper, T. M., Jönsson, E. S., Guymon C. A. and C. E. Hoyle, "Influence of Hydrogen Bonding on Photopolymerization Rate of Hydroxyalkyl Acrylates", *Macromolecules*, Vol. 37, pp 3659-3665, 2000.

89. Chandra, R. and R. K. Soni, "Recent Developments in Thermally Curable and Photocurable Systems", *Progress in Polymers Science*, Vol. 19, pp. 137-169, 1994.

90. *Dental Composite Depth of cure With Halogen and Blue Led Technology*, http:/www.spectravuitc.com/Downloads/Dental%20composite%20depth-of-cure%20Halogen%20vs%20LED.pdf, 2005.

91. Dietz, J. E. and N. A. Peppas, "Reaction Kinetics and Chemical Changes During Polymerization of Multifunctional (Meth)acrylates for the Production of Highly Crosslinked Polymers Used in Information Storage Systems", *Polymer*, Vol. 15, pp. 3767-3781, 1997.

92. Brandrup, J. and E. H. Immergut, *Polymer Handbook*, Wiley, New York, 1975.

93. SPARTAN Version 4.0, Wavefunction, Inc., 18401 Von Karman Ave., No. 370, Irvine, CA 92715 U.S.A © Wavefunction, Inc.

94. Davy, K. W. M., Kalachandra, S.,M. S. Pandain and M. Braden, "Relationship Between Composite Matrix Molecular Structure and Properties", *Biomaterials*, Vol. 19, pp. 2007-2014, 1998.

95. Beckel, E. R., J. W. Stansbury and C. N. Bowman, "Evaluation of a Potential Ionic Contribution to the Polymerization of Highly Reactive (Meth)acrylate Monomers", *Macromolecules*, Vol. 38, pp. 9474-9481, 2005.