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Review Article: Recycling of Polystyrene

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Recycling of polystyrene can be done by mechanical, chemical, and thermal methods. High impact polystyrene is a promising material for mechanical recycling since its properties are not extremely affected even after multiple processing of upto nine cycles. Production of liquid products and gaseous products are highly dependent on the reaction condition. The catalysts used are highly selective for the production of liquid as well as gaseous products. In this article we have reviewed the various types of methods followed so far for recycling of polystyrene.

Keywords Blends; Chemical recycling; Composites; Mechanical recycling; Polystyrene; Thermal recycling

1. INTRODUCTION

Polystyrene is a versatile polymer, which has been used for many purposes such as packaging, consumer goods, etc., but the disposal of these products creates environmental pollution because of their nondegradable nature. Therefore, increased attention is devoted to the recycling, reuse, and making them biodegradable by various means. The present review article is aimed at providing a survey of the available information on polystyrene based materials, their recycling and reuse.

Polystyrene (PS) is used in solid and expanded forms both of which can be recycled. Solid PS components such as coffee cups, trays, etc. can be recycled back into alternative applications such as videocassette cases, office equipments, etc. Expanded PS foam waste loses its foam characteristics as part of the recovery process. The recovered material can be re-gassed but the product becomes more expensive than virgin material. Instead it is used in solid form in standard molding applications. Both

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expanded and solid PS wastes have been successfully recycled in extruded plastic timber/lumber. Recycled PS is used to produce plant pots and desk items such as pen, pencils, etc. As with other types of plastic materials, PS recycling takes place after consideration by the industry of a number of issues including eco-efficiency, availability, corporate social responsibility, product quality/hygiene aspects, and traceability.

Polystyrene (PS) foam has been widely used as an insulator and in packaging. More than a thousand tonnes of this plastic worldwide is being disposed off into environment as municipal solid waste (MSWs). The amount is increasing every year. However, especially in the developing countries, most of the PS foam waste is discarded as solid pollutant. The booming development of electronic products has sharply increased the quantities of Waste from Electrical and Electronic Equipment (WEEE), amplifying the problem of their disposal. The solution can be found only through a modern Design For Environment (DFE) with a big attention to recycling and disassembly.

Packing of electronics products is done by the use of tape, reels, trays, and tubes. The reels are made of PS, which shows strength and durability to protect the products. Particular features in them allow them to be reused. Trays used to ship the products are generally made with thermoset plastics with heat resistance characteristics, such as carbon fiber modified polysulfone (MPSU). Similar to reels, the trays also show properties that allow for their reuse. Obviously, reuse of plastics will avoid waste from entering into landfills and prevent the creation of hazardous emissions from incineration. To reduce environmental impact, these should be reused or recycled.

Expanded PS can be used as substrates to obtain polyelectrolytes[1] which exhibit good flocculation properties comparable with that of commercial Praestol 2515. Recycled and virgin PS is being used to create a material with almost the same characteristics as wood. The new

material replicates wood in terms of density, matching look, feel, and structural characteristics, making it suitable for use as a replacement material in all areas of house building and furniture production. Windows systems, roof trusses, flooring, and other construction components have been employed in a small chalet made entirely of the extruded PS material.

2. TYPES OF POLYSTYRENE ACCEPTED FOR RECYCLING

Expanded polystyrene (EPS) foam packaging, which is the familiar white material, custom molded to cushion, insulate and protect all types of products during transportation and it can be recycled. EPS insulation boards used for housing and commercial construction, foodservice products like cups, plates, trays, etc. that are made of PS resin foamed to provide a unique insulating quality and loosefill packaging are accepted for recycling. Non-Foam Polystyrene products also called high impact polystyrene (HIPS), oriented polystyrene (OPS), post consumer products, post industrial products, and styrofoam (A Dow Chemical Company brand trademark for a PS foam thermal insulation product) have also been accepted for recycling[2].

3. RECYCLING METHODS FOR POLYSTYRENE PRODUCTS

Before recycling, the recyclable materials should be rinsed off for the removal of any food or dirt particles, the caps of the plastic bottles and glass jars should be thrown away and the oversized materials like cartons, milk jugs, etc. should be crushed so that they can fit into the bin and into the truck more easily.

The volume of EPS is reduced by methods such as solvent volume reduction (dissolved using solvent), heating volume reduction, and pulverizing volume reduction (pulverized). The processed expanded PS is used in its reduced state as an ingredient for recycled products or it is burnt to generate heat energy.

A large amount of expanded PS is discharged after use at wholesale markets, supermarkets, department stores, restaurants and shops, such as electrical appliances stores, as well as at factories of machinery manufacturers. It is collected through the in-house collection of companies or by resource recycling agents and becomes a recycled resource.

3.1. Mechanical Recycling

A Japanese Patent invented by Toyomasa[3] suggests recycling of PS foam recovered as refuse by compressing and heated to melt to reduce its volume.

A process and apparatus for reclamation of waste polystyrene-type materials for reuse within the specification ranges of the input polystyrene-type material has been described by David et al.[4] The disclosed process and apparatus include dissolution of the waste polystyrene-type materials in a dissolve section utilizing a reusable solvent having a low boiling point and high vaporization rate, removal of solid contaminants in one or more filter sections, devolatilization of the dissolved PS, and recovery of the polystyrene-type material in a solid form in a recovery section. Preferably the process and apparatus provide a closed system and include recycling and reuse of the vaporized solvent. The maximum temperature in the recovery section is 190°C. The reusable solvent is preferably environmentally safe and has a low boiling point and high vaporization rate. Propyl bromide or environmentally safe mixtures thereof, including mixtures with isopropyl alcohol, is the preferred reusable solvent for this process.

Patent invented by Marcello et al.[5] suggested the use of dialkyl carbonates as solvent for expanded PS, the removal of the insoluble components by filtration, the selective precipitation of PS with a non-solvent or a blend of non-solvents, the separation, drying, and extrusion of the precipitated PS. This process allows the recovery of pure PS without altering its properties.

In a United States patent, Katz et al.[6] have described reduction of PS foams with dibasic esters. An aqueous solution comprising of dibasic ester selected from the group of dimethyl glutarate, dimethyl adipate and dimethyl succinate, and a surfactant when applied to PS foam form a gel-like substance which may be applied to an object as a waterproofing agent or recycled into PS foam.

One economic way of recovering PS[7] is via a new product being developed in the USA. The product uses a biodegradable solvent derived from citrus fruits that eliminate all air from the PS, making it economic to transport. Plastics waste is chewed up and then sprayed with the biodegradable solvent. This dissolves all the PS, turning it into a jelly-like substance with a much greater density than squashed PS waste. It is this high density and the consequent ability to transport much larger quantities of material per truck that makes the recovery process economic.

At this stage, the material can also be land filled economically, or it can be reprocessed by the precipitation of the PS from the suspension. Because the solvent reduces only PS to a liquid form, it is possible to force the solution through screen filters that remove most of the contaminants, such as waste made from other plastics. This also means that for the first time it will be economic to reprocess PS from food and horticultural uses. Other sources of recyclable PS are of course the white and brown goods industries and fisheries. From the packagers point of view there is now a legal requirement to do this and the new solvent can reduce the economic impact of large-scale recovery. Following the filtration stage, another solvent is added to the mixture that precipitates out the PS. Centrifuging separates the three components, allowing the solvents to be recovered for reuse and the PS to be used for subsequent processing.

3.2. Chemical Recycling

Koji et al.[7] have explained to obtain a PS foam, which can be recycled into styrene by mixing a PS with a basic metal oxide being a catalytic decomposition catalyst and foaming the mixture with an inert blowing agent. When it is wasted, it can be recycled into styrene by decomposing it by heating to 300–450°C in a nonoxidizing atmosphere. The basic oxide is Na_2O, MgO, CaO or the like and among them CaO is desirable. When the basic metal oxide carried by porous inorganic filler is used, it can exhibit improved effectiveness desirably. The blowing agent used is a nitrogen gas, a chlorofluorocarbon, propane or the like.

One of the attractive chemical recycling processes is the catalytic degradation[8] of polystyrene (PS). This process enables to get styrene monomer (SM) at relatively low temperature with a high selectivity. In this study, the modified Fe-based catalysts were employed for the catalytic degradation of EPSW (expandable PS waste), where carbanion may lead to high selectivity of SM in the catalytic degradation of PS. The yield of oil (Y_{Oil}) and SM (Y_{SM}) were increased in the presence of Fe-based catalysts and with increasing reaction temperature. Y_{Oil} and Y_{SM} were obtained over Fe–K/Al_2O_3 at the relative low reaction temperature (400°C) 92.2 and 65.8 wt. %, respectively. The value of E_a (activation energy) is obtained as 194 kJ/mol for the thermal degradation of EPSW. However, the E_a was decreased considerably from 194 to 138 kJ/mol in the presence of the catalysts (Fe–K/Al_2O_3).

Bajdur et al.[1] have synthesized sulfonated derivatives of expanded PS wastes, which may be used as polyelectrolytes. Modification was conducted by means of known methods and products having various contents of sulfogroups in polymer chain were obtained. They have found that the polyelectrolytes have good flocculation properties similar to those of anionic commercial polyelectrolytes.

The effect of a base catalyst, MgO, on the decomposition of PS was studied through degradation of both a monodisperse polymer (number average molecular weight = 50,500 g/mol) and a PS mimic, 1,3,5-triphenylhexane (TPH), to determine the potential of applying base catalysts as an effective means of polymer recycling[9]. The presence of the catalyst increased the decomposition rate of the model compound but decreased the degradation rate of PS as measured by evolution of low molecular weight products. Although the model compound results suggest that the rate of initiation was enhanced in both cases by the addition of catalyst, this effect is overshadowed for the polymer by a decrease in the 'zip length' during depropagation due to termination reactions facilitated by the catalyst. Due to the small size of the model compound, this effect does not impact its observed conversion since premature termination still affords a quantifiable low molecular weight product. A decrease in the selectivity to styrene monomer in the presence of MgO was observed for both PS and TPH. They have discussed the reconciliation of their results with those of Zhang et al.[10] based on differences in the reactor configuration used.

Degradation of PS into styrene, including monomer and dimer, was studied by Ukei et al.[11] using solid acids and bases viz. MgO, CaO, BaO, K_2O, SiO_2/Al_2O_3, HZSM5 and active carbonas catalysts. They have found that solid bases were more effective catalysts than solid acids for the degradation of PS into styrene. This was attributed to differences in the degradation mechanisms of PS over solid acids and bases. Among the solid bases employed, BaO was found to be the most effective catalyst and about 90 wt. % of PS was converted into styrene when thermally degraded PS was admitted to BaO powder at 350°C.

Ke et al.[12] has studied the degradation of PS in various supercritical solvents like benzene, toluene, xylene, etc. at 310–370°C and 6.0 MPa pressure. It was found that PS has been successfully depolymerized into monomer, dimmer, and other products in a very short reaction time with high conversion. Toluene used as supercritical solvent was more effective than other solvents such as benzene, ethylbenzene, and p-xylene for the recovery of styrene from PS, though the conversions of PS were similar in all the above solvents. The highest yield of styrene obtained from PS in supercritical toluene at 360°C for 20 min reached 77 wt.%.

Lee et al.[13] have studied several solid acids such as silica-alumina, HZSM-5, HY, mordenite, and clinoptilolite (natural and synthesized) as catalyst and screened their performances in the catalytic degradation of polystyrene (PS). The clinoptilolites showed good catalytic activity for the degradation of PS with very high selectivity to aromatic liquids. They have discussed the effects of catalyst acidity, reaction temperature, and contact time on the distribution of aromatics. The increase of contact time and surface acidity enhanced the production of ethylbenzene. High degradation temperature favored the selectivity to styrene monomer. The clinoptilolite catalysts (HNZ, HSCLZ) showed good catalytic performance for the degradation of PS with selectivity to aromatics more than 99%. Styrene is the major product and ethylbenzene is the second most abundant one in the liquid product. The increase of acidity favored the production of ethylbenzene by promoting the hydrogenation reaction of styrene. Higher selectivity to styrene is observed at higher temperatures. An increase of contact time by reducing nitrogen gas flow rate enhanced the selectivity to ethylbenzene. Thus a designed operation including acidity of catalyst, reaction temperature, and contact time will be necessary to control the product distribution between styrene monomer and ethylbenzene.

3.3. Thermal Recycling

The thermal degradation of real municipal waste plastics (MWP) obtained from Sapporo, Japan and model mixed plastics was carried out at 430°C in atmospheric pressure by batch operation[14]. The resources and environmental effects assessed over the life of each of the packaging, includes fossil fuel consumption, greenhouse gas emissions, and photochemical oxidant precursors. The results[15] demonstrate that recycle and reuse strategies for plastic based products can yield significant environmental benefits.

The thermal recycling of post-consumer plastic wastes[16] has been studied most extensively for high-value petrochemical or fuel feedstock. The technology for thermal cracking that has been more widely studied and that has been tested at larger scale is that based on a fluidized bed, in which the plastics are fed in the solid state and sand is used for helping fluidization[17–22]. The design of fluidized beds used at laboratory or pilot plant scale has been carried out on an empirical basis, due to the fact that the kinetics of pyrolysis of plastics is subjected to great uncertainty caused by factors such as heterogeneity of the material, synergy in the cracking of different constituents, and limitations to heat and mass transfer. These factors prevent obtaining kinetics that is reliable for the design of the reactor at temperatures of industrial interest (above 450°C)[23]. The use of acid catalysts (the more widely studied are amorphous silica-aluminas, HY cracking zeolites, HZSM-5 zeolites, and mesoporous zeolites as the MCM-41) allows for lowering the cracking temperature (with the subsequent energy saving) and the selective obtaining of products of industrial interest[24–32].

Furthermore, this strategy is suitable for its development in a refinery by using the existing equipment and by optimizing the possibilities of incorporating the products either into the market (subsequent to fuel reformulation) or into the production process itself (subsequent to monomer purification). The selection of the solvent for dissolving the plastic may be established on the basis of market requirements. Several authors have studied the catalytic cracking of polyolefins[33–35] on different acid catalysts and using different solvents. In general, the interpretation of the results is faced with the difficulty of separating the effect of thermal cracking from the role of Bronsted and Lewis sites of the catalyst. Furthermore, an additional problem in the cracking of polystyrene (PS) is the rapid deactivation of the catalyst caused by the coke formed on the acid sites[10], which is favored by the aromatic nature of styrene and its high C/H ratio.

Arandes et al.[36] have studied the thermal cracking of PS and polystyrene-butadiene (PS-BD) on a mesoporous silica which has no measurable acidity. Although the content of PS in domestic plastic wastes is approximately 10 wt.%, less attention has been paid to the cracking of dissolved PS than to the cracking of dissolved polyolefins[32–34]. The kinetic characteristics of PS cracking described by Arandes et al. are different to those of polyolefins[22,35] and the ideal aim of its valorization is the recovery of the styrene monomer. Bockhorn et al.[37] and Kruse et al.[38] made an analysis of the reactions involved in the mechanism of PS cracking.

One possible process for recovering valuable chemical and petrochemical products from plastic waste is the stepwise thermal degradation of polymer mixtures. This potentially allows the step-by-step simultaneous separation of the different product fractions generated by the polymers of the blend.

In order to properly predict the kinetic interactions typical of the mixed phases, it was necessary to extend the detailed kinetic model already developed and validated for the single polymers. The resulting two-phase model gives a satisfactory explanation of several experimental data from the thermal degradation of PE-PS mixtures[39].

A conical spouted bed reactor (CSBR) has been used for the kinetic study of PS pyrolysis in the 450–550° range[40] and the results have been compared with those obtained by thermogravimetry (TGA) and in a microreactor (MR) of very high sample heating rate. The comparison proves the advantages of the gas–solid contact of this new reactor for the kinetic study of pyrolysis of plastics at high temperature, which stem from the high heat transfer rate between gas and solid and from the fact that particle agglomeration, is avoided.

A swirling fluidized-bed reactor (0.0508 m ID and 1.5 m in height) has been developed to recover the styrene monomer[41] and valuable chemicals effectively from the PS waste, since it can control the residence time of the feed materials and enhance the uniformity of the temperature distribution. To increase the selectivity and yield of styrene monomer in the product, catalyst such as Fe_2O_3, BaO, or HZSM-5 (Si/Al = 30) have been used. Effects of temperature, volume flow rate of gas, pyrolysis time, and the ratio of swirling gas to the amount of primary fluidizing gas on the yields of oil product as well as styrene monomer have been determined. Effects of operating variables on the temperature distributions and their fluctuations in the radial as well as axial directions have been also examined to analyze the effects of temperature distributions and their fluctuations on the catalytic pyrolysis of PS waste in the swirling fluidized-bed reactor. It has been found that the reaction time and temperature can be reduced profoundly by adding the solid catalyst. The swirling fluidization mode makes the temperature fluctuations more periodic and persistent, which can increase the uniformity of temperature distribution by reducing the temperature gradient in the reactor. The yields of styrene monomer as well as oil products have increased with increasing the ratio of swirling gas (V_2/V_1),

but exhibited their maximum values with increasing the total volume flow rate of gas.

Recently, as a part of thermal recycling, in order to reduce the consumption of energy and get oligostyrene of several thousands of molecular weight, which can be used as a kind of fuel oil, the thermal decomposition of expanded polystyrene (EPS) with α-methylstyrene[42] as a chain-transfer agent was studied at a temperature about 200°C. Three kinds of organic peroxides were used as radical accelerators in the thermal decomposition of EPS with α-methylstyrene. They found that the addition of dicumyl peroxide (DCP) enhanced the thermal decomposition of EPS even at lower temperature, about 140°C, but the addition of tert-butylcumyl peroxide (BCP) was less effective than DCP. On the other hand, di-tert-butyl peroxide had almost no effect on the thermal decomposition of EPS. The activation energy, determined from the rate coefficients, were 66.6 and 70.5 kJ/mol for DCP and BCP, respectively.

A general model for polymer degradation by concurrent random and chain-end processes was developed using continuous distribution kinetics[43]. Population balance equations based on fundamental, mechanistic free radical reactions were solved analytically by the moment method. The model, applicable to any molecular weight distribution (MWD), reduces to the cases of independent random or chain-end scission. Polystyrene degradation experiments in mineral oil solution at 275–350°C supported the model and determined reaction rate parameters. The degradation proceeded to moderate extents requiring a MW-dependent random scission rate coefficient. Throughout the experiments, the polymer MWD, which was measured by GPC, maintained the exponential form, so that the logarithm of MWD varies linearly with MW, with slope directly related to the number-average MW. Polystyrene random scission activation energy was 7.0 kcal mol^{-1}, which agrees well with other thermolysis investigations, but is lower than that found by pyrolysis due to fundamental differences between the processes. Magnesium oxide, added as a heterogeneous catalyst in solution, was found to have no effect on PS degradation rate.

Pyrolysis for the simultaneous generation of oils and gases can be convenient to obtain hydrocarbons and even to recover crude petrochemicals or to generate energy from waste plastics. A Gray-King apparatus has been used to pyrolyze polystyrene (PS) with different compositions[44]. Thermogravimetric analysis of waste plastics indicated the critical temperatures, which should be effective for pyrolysis. The chosen heating rate was low in order to achieve higher liquid yields. The results showed that waste PS yielded higher liquid. The dominant liquid product of PS waste was styrene.

Thermal and thermo-oxidative degradation of polystyrene (PS) in the presence of ammonium sulfate[45] was studied with thermogravimetry (TG) and infrared spectroscopy (IR). Thermogravimetry results indicated that ammonium sulfate accelerated thermal degradation in nitrogen but delayed thermo-oxidative degradation of PS in air. IR analysis of tetrahydrofuran extracts, from the samples degraded at 340°C and of residues after thermal treatment at 340°C in a furnace, showed that the acceleration of thermal degradation and the suppression of thermo-oxidative degradation were due to sulfonation and oxidation of ammonium sulfate and its decomposition products, and formation of unsaturated structures in the PS chain.

Thermal degradation of PS has been investigated in the presence of water[46] under subcritical conditions (hydrous pyrolysis). The experiments were carried out in closed systems under inert atmosphere, in the temperature range 300–350°C, at pressures up to 18 MPa, for 1–120 h. The products obtained, separated as gases, volatiles, and heavy compounds, were analyzed qualitatively and quantitatively by gas chromatography, gas chromatography/mass spectrometry, and size exclusion chromatography. The results showed that the presence of water increases the yields of the volatile products, mainly in the first steps of the pyrolytic process, and leads to higher yields of monomer. This latter observation suggests a lowering of the secondary reactions extent.

A newly designed experimental apparatus[47] has been developed to effectively depress the secondary reactions of volatiles, which are the primary products of thermal degradation of polymers. In this communication, they have reported that controlled thermal degradation of polystyrenes and polypropylenes leads to effective preparation of novel macromonomer-like oligomers and telechelic oligomers.

The catalytic degradation of waste plastics such as polyethylene (HDPE, LDPE), polypropylene (PP), and polystyrene (PS) over spent fluid catalytic cracking (FCC) catalyst was carried out at atmospheric pressure with a stirred semi-batch operation at 400°C using the same reaction temperature programming[48]. The objective was to investigate the influence of plastic types on the yield, liquid product rate, and liquid product distribution for catalytic degradation. The catalytic degradation of waste PE and PP with polyolefinic structure exhibited the liquid yield of 80–85% and the solid yield of below 1%, whereas that of waste PS with polycyclic structure produced much more liquid, solid products, and much less gas products. Accumulative liquid product weight by catalytic degradation strongly depended on the degradation temperature of the plastics.

In accordance with the option of recycling plastics into fuels by dissolving them in standard feedstocks[49] for the process of catalytic cracking of hydrocarbons, FCC, and various acidic catalysts (zeolites ZSM-5, mordenite, Y,

and a sulfur-promoted zirconia) were tested in the conversion of PS dissolved into inert benzene at 550°C in a fluidized-bed batch reactor. Experiments were performed with very short contact times of up to 12 sec. Main products were in the gasoline range, including benzene, toluene, ethylbenzene, styrene, and minor amounts of C_{9-12} aromatics and light C_{5-} compounds. Coke was always produced in very significant amounts. All the products can be justified on the basis of properties of each catalyst and the various possible catalytic reaction pathways: cracking after protolytic attack on the polymer fragments, styrene oligomerization and subsequent cracking, or hydrogen transfer to styrene. Styrene would be mainly produced in this system from thermal cracking of the polymer as the initial step. If present, shape selectivity effects due to catalyst structure can influence significantly the prevalence of the various reactions, because they would interfere with those undergoing bulky transition states, like styrene oligomerization or hydrogen transfer. Even though sulfur-promoted zirconia is highly acidic, the low proportion of Bronsted-type acid sites does not allow the occurrence of secondary styrene reactions. It was shown that most favorable product distributions (higher yields of desirable products) are obtained on equilibrium commercial FCC catalysts. PS can be recycled into styrene monomer in association with some other aromatics, from which styrene can be converted to biodegradable plastic like PHA. Recently scientists have achieved 10% yield of PHA from PS[50]. It has also been studied that the chain length of PHA is ≤10.

The yield and composition of oils and gases derived from the pyrolysis and catalytic pyrolysis of PS has been investigated. The pyrolysis and catalytic pyrolysis was carried out in a fixed bed reactor. Two catalysts were used, zeolite ZSM-5 and Y-zeolite and the influence of the temperature of the catalyst, the amount of catalyst loading, and the use of a mixture of the two catalysts was investigated. The main product from the uncatalyzed pyrolysis of PS was oil consisting mostly of styrene and other aromatic hydrocarbons like toluene and ethylbenzene. The gases were found to consist of methane, ethane, ethene, propane, propene, butane, and butene. In the presence of either catalyst an increase in the yield of gas and decrease in the amount of oil production was found, but there was significant formation of carbonaceous coke on the catalyst. Increasing the temperature of the Y-zeolite catalyst and also the amount of catalyst in the catalyst bed resulted in a decrease in the yield of oil and increase in the yield of gas. Oil derived from the catalytic pyrolysis of PS contain aromatic compounds such as single ring compounds like benzene, toluene, styrene, *m*-xylene, *o*-xylene, *p*-xylene, ethylmethylbenzene, propenylbenzene, methylstyrene; two ring compounds like indene, methylindene, naphthalene, 2-methylnaphthalene, 1-methylnaphthalene, biphenyl,

methylbiphenyl, dimethylnaphthalene, trimethylnaphthalene, tetramethylnaphthalene, ethylbiphenyl; three ring compounds like phenanthrene, methylphenanthrene, dimethylphenanthrene, trimethylphenanthrene, and four ring compounds like pyrene, methypyrene, dimethylpyrene, chrysene, and methylchrysene.

3.4. Mechanism of Thermal Degradation of Polystyrene

During the thermal degradation of foamed PS various physical transitions may occur. Mehta et al.[23] have determined the various physical transitions using scanning electron microscopy, differential scanning calorimetry, and thermogravimetric analysis. They have also investigated the effect of polymer density and bead structure on the degradation characteristics. They have shown that the polymer beads collapse at about 110–120°C when exposed to elevated temperature. The collapsed beads melt at 160°C and start to vaporize at temperatures greater than about 275°C whereas complete volatilization occurs in the temperature range 460–500°C.

4. CONCLUSION

Mechanical recycling gives solid PS and also liquid PS in a pure form without altering its properties, which can be used again. Chemical recycling of PS using catalysts like clinoptilolite (HNZ, HSCLZ) gives 99% aromatics like styrene and ethylbenzene as the major products. Use of catalysts is highly selective for styrene monomer production. Solid bases were found to be more effective catalyst than solid acids for the degradation of PS into styrene. Controlled thermal degradation of PSs leads to effective preparation of novel macromonomer-like oligomers and telechelic oligomers. Conical spouted bed reactor has proven to be more advantageous in comparison to thermogravimetry (TGA) and microreactor (MR) for kinetic study of pyrolysis of plastics at high temperatures. Catalytic degradation of waste PE and PP with polyolefinic structure exhibited the liquid yield of 80–85% and the solid yield of below 1%, whereas that of waste PS with polycyclic structure produced much more liquid, solid products and much less gas products. Weight of liquid products obtained by catalytic degradation strongly depends on the degradation temperature of the plastics. Main products of cracking were in the gasoline range, including benzene, toluene, ethylbenzene, styrene, and minor amounts of C_{9-12} aromatics and slight C_5 compounds. It has been observed that yields of most favorable products are obtained on equilibrium commercial FCC catalysts. Thermal cracking without using catalysts is more efficient than using catalysts as in the former case production of styrene monomer is more than the gaseous products. PS can be recycled into styrene monomer in association with some other aromatics, from which styrene can be converted to biodegradable plastic like PHA. Recently scientists have achieved 10% yield of

PHA from PS. It has also been studied that the chain length of PHA is ≤ 10. Further research can be done to improve this yield by taking other bacteria or by designing specialized fermenter. We can also incorporate enzymatic catalyst to the fermenter to support polymerization of PHA.

5. FUTURE PROSPECTUS

1. Thermal recycling of PS yields higher percentage of styrene monomer, which can be fermented by bacteria to produce PHA—the starting material for the synthesis of biodegradable polymers.
2. The waste PS can be blended with biodegradable polymers to produce biodegradable polymers.
3. Styrene monomer produced by recycling can be grafted onto biodegradable polymers to give biodegradable polymers.

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