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Study of the O-glycidylation of natural phenolic compounds. The relationship between the phenolic structure and the reaction mechanism

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ABSTRACT

The O-alkylation reaction by epichlorohydrin of some natural phenolic compounds such as 4-methylcatechol, gallic acid, protocatechuic acid, pyrogallol and resorcinol was investigated. Phenolic compounds reacted first with epichlorohydrin in the presence of benzyltriethylammonium chloride as phase transfer catalyst. Then, an aqueous solution of sodium hydroxide was added.

It was demonstrated that the two competitive mechanisms involved in the O-alkylation reaction were highly dependent of the starting material. The *O*-alkylated products obtained in this reaction could be further used as bisphenol A substitutes in the synthesis of epoxy resins pre-polymers.

1. Introduction

Bio-based polymer products derived from annually renewable agricultural and biomass feedstock have become increasingly important as sustainable and eco-efficient products, which will potentially replace the products based exclusively on petroleum feedstock.[1,2] Of all polymers produced, the thermosets represent an important class in the industry due to their high flexibility for tailoring desired ultimate properties, leading to their high modulus, strength, durability, and thermal and chemical resistances as provided by high cross-linking density.[3–7] Paradoxically, thermosets prepared from renewable resources have been the subject of limited investigations.[8]

Epoxy resins are some of the most important thermosetting resins, and are extensively used as coatings, adhesives, electronic materials, and for structural applications because of their outstanding mechanical properties ranging from extreme flexibility to high strength and hardness, high adhesion strength, good heat resistance and high electrical resistance.[9,10] Nowadays, almost 90% of the world production of epoxy resins is based on the reaction between bisphenol A (BPA) and epichlorohydrin, yielding diglycidyl ether of bisphenol A (DGEBA). Suspected of being hazardous to humans, concerns about the use of BPA in consumer products have been regularly reported in the news media since 2008 after several scientists and governments questioned its safety.[11–14] Therefore, there is a huge interest in developing a bio-based epoxy monomer or oligomer able to replace the traditional DGEBA by offering high performance materials.

In the manufacturing of sustainable epoxy resins, epoxidized plant oils (soybean oil, linseed oil, castor oil…) and fatty acids have been largely utilized as reported in the literature.[15–17]

However, these networks present disadvantages in heat resistance and mechanical properties due to the long aliphatic chains. Thus, this type of epoxy resin is applied only in limited fields of applications. Recently, the use of natural polysaccharides in the synthesis of bio-based epoxy resins retained industrial and scientific interest. Indeed, the conversion of maltitol, and sorbitol into multifunctional epoxy monomers has been reported.[18] Glycerol polyglycidyl ether, usually employed in textile and paper as processing agent and as reactive diluent, was reacted with curing agent to produce bio-based epoxy resin.[19] Isosorbide produced from the double dehydration of sorbitol was also used as a substitute of bisphenol A to produce epoxy material with good network properties.[20,21] Unfortunately, glycidyl ether derivatives of

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polysaccharide monomers are hygroscopic and the presence of water may deteriorate the properties of the networks.

The heat resistance and the mechanical and electrical performance properties of organic compounds are generally attributed to the aromatic ring structure. Most of the naturally occurring aromatic compounds are often believed to be originated from lignin. For this reason, many researchers have made their efforts to apply these macromolecular compounds to the production of epoxy resins. Until now, methods to synthesize lignin-based epoxy resin can be summarized into two categories as follows: (i) blending derivatives of lignin with epoxy resin directly;[22] (ii) modifying lignin derivatives (organosolv lignin) to improve their reactional ability, followed by epoxidation.[23,24] However, all lignins created problems with organic solvent—solubility, and thus required special solvent mixtures for formulation. Moreover their chemical structures, which are not yet entirely elucidated, could make the direct functionalization of this polymer difficult.

The other terrestrial source of phenolic compounds is tannins. Tannins are defined as water-soluble plant phenolic compounds having molecular weight ranging from 500 Da to 3000–4000 Da. Furthermore, the compounds should undergo the usual phenolic reactions and have the ability to precipitate some alkaloids, gelatin and other proteins from solutions.[25–27] They constitute an important group within the phenolic compounds and may be subdivided into hydrolyzable and condensed tannins. The former are esters of gallic acid (gallo- and ellagitannins), while the later (also known as proanthocyanidins) are polymers of polyhydroxyflavan-3-ol monomers. Another subdivision, the phlorotannins derived from the oligomerizing dehydrogenative coupling of phloroglucinol, have been isolated from several genera of red-brown algae.[26,28–30] Thus, tannins exhibit a wide structural diversity and their molecular structure is a key determinant of their chemical reactivity.

The objective of our ongoing research is to study the feasibility of replacing bisphenol A by such natural phenolic compounds in the synthesis of novel bio-based reactive pre-polymer systems.

In our previous paper,[31] one of the building blocks of polymeric condensed tannins, namely catechin, was reacted with epichlorohydrin in alkaline medium to lead to the expected tetraglycidylether of catechin along with a benzodioxane derivative (Scheme 1). The formation of this cyclic by-product seemed to be directly related to the *ortho*-positions of the two phenolic OH groups carried by the B-ring of catechin.[31]

In 1985, the glycidylation of gallic acid (building block of gallotannins) had been claimed in a patent from Haruo Tomita et al.[32] The use of a phase transfer catalyst (PTC) and a two step-procedure in Tomita's protocol make the noticeable differences compared to the protocol that we used for the catechin glycidylation. The O-alkylation product obtained by the experimental conditions given in the patent is reported as being the product of substitution reaction of epichlorohydrin onto the carboxyl group and at least onto one phenolic hydroxyl group. The formation of side-products such as the benzodioxane derivative that we obtained with catechin was not mentioned in this work in spite of the presence of three hydroxyls groups in *ortho*-position on the aromatic ring of gallic acid.

Although the experimental conditions of the reaction are not totally the same between the work that we reported earlier on catechin and those of the Haruo Tomita's patent on gallic acid, the products obtained after reaction suggest a difference in reactivity between the two phenolic compounds towards epichlorohydrin. Therefore, we decided to investigate further the role of the phase transfer catalyst (PTC) on one hand, and, on the other hand, the glycidylation of model phenolic compounds by epichlorohydrin in order to ultimately optimize the functionalization reactions of natural tannins. For this purpose, some characteristic mononuclear aromatic phenolic compounds, bearing two or three phenolic hydroxyls in *ortho*- or *meta*-positions, with or without additional carboxylic group, were reacted with epichlorohydrin. The structures of the glycidylated products were determined, mainly from NMR experiments. The glycidylation mechanism was then discussed on the basis of the structural characterizations.

The model phenolic compounds studied in the present work are: 4-methylcatechol, gallic acid, protocatechuic acid, pyrogallol and resorcinol.

2. Results and discussion

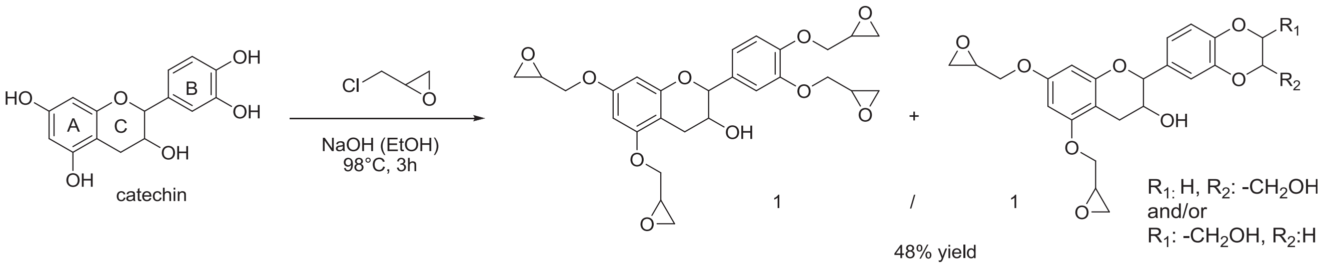
2.1. Confirmation of the benzodioxane structure in the glycidylation of 4-methylcatechol

In our previous work related to the functionalization of catechin,[31] the reaction of 4-methylcatechol **1** (as representative of the B-ring of catechin) with epichlorohydrin in alkaline medium revealed the formation of the benzodioxane derivative **3** besides the expected glycidylation product (Scheme 2). This cyclic by-product was tentatively identified by NMR analyses among a mixture of other impurities.

In order to unequivocally establish the chemical structure of the hypothetical benzodioxane derivative, the glycidylation reaction of 4-methylcatechol **1** was repeated in the same reaction conditions mentioned in our anterior work.[31] The crude product was purified by silica gel chromatography allowing the isolation of products **2** and **3** in equal amount. These products definitely correspond, respectively, to the diglycidylether and the benzodioxane derivative of 4-methylcatechol, (Scheme 2).

Detailed structure characterization of product **3** was performed by NMR spectroscopy. The ^{1}H NMR spectrum (Fig. 1) displays resonance signals easily attributed using both their chemical shifts and coupling pattern. The 6.6–6.8 ppm region contains an ABX system corresponding to the **3** aromatic ring protons whereas the aliphatic signals in the 3.5–5.1 ppm range arise from the dioxane group. The dioxane hydroxyl group gives a characteristic signal at 5.03 ppm, the methylene proton Ha and Ha′ resonance signals are located at 3.96 and 4.27 ppm while the signal at 4.09 ppm is assigned to the methyne proton Hb.

The HMBC spectrum of product **3** (Fig. 1) allows to attribute the quaternary carbons of the aromatic ring C1, C2 and C3 from their correlations with both the aromatic, the methyne and the methyl



Scheme 1. Glycidylation of catechin.