



A theoretical study on the reactivity of phenols and aldehydes: prospect of formaldehyde-free syntans

Yanan Wang, Wenhua Zhang^{*}, Shangzhi Pu, Xuepin Liao, Bi Shi^{*}

National Engineering Laboratory for Clean Technology of Leather Manufacture, Sichuan University, Chengdu, P. R. China, Phone: 86-28-85400356, Fax: 86-28-85400356, e-mail: zhangwh@scu.edu.cn, sibtannin@vip.163.com

Abstract

Phenolic syntans made from aromatic compounds and formaldehyde have been used in leather tanning process for almost one century. Nowadays, formaldehyde is considered as a probable human carcinogen and its application on leather industry is extremely restricted. Hence the development of formaldehyde-free phenolic syntans is necessary for the production of eco-friendly leather. In this study, the condensation reactions between phenols (phenol, bisphenol A and 4,4'-sulfonyldiphenol) and aldehydes (formaldehyde and glyoxal) were investigated by the approach of computational chemistry. The B3LYP functional with 6-31G(d) basis set was employed to obtain the geometric, electronic and vibrational properties of all the reactants and intermediates involved in the reactions. The results indicate that the *o*-carbon atom of phenolic hydroxyl group is the nucleophilic center that is susceptible to react with aldehyde to form condensate. Phenol-glyoxal condensation from phenol methylation to formation of dimer may not slow down in consideration of the decrease of HOMO-LUMO energy gap, which is in opposition to phenol-formaldehyde reaction. As a result, glyoxal exhibits relatively high reactivity in the interaction with phenols compared with formaldehyde.

1. Introduction

Formaldehyde exhibits great reactivity in crosslinking molecules together to form a polymeric structure. In leather industry, formaldehyde as well as various products based on it is widely used in tanning, retanning and finishing processes.¹ However, formaldehyde has been classified as a restricted chemical in recent years due to its probable carcinogenesis.² Meanwhile, the customer demand for ecological leather and leather goods is increasing, which imposes the constraint on the use of leather chemicals containing formaldehyde. Although it can be successfully replaced by other chemicals in tanning and finishing processes, formaldehyde is difficult to be eliminated from the production of synthetic tannins for both technical and cost reasons. Therefore, finding an alternative crosslinking agent is not only a necessity for environmental safety but a serious challenge for leather chemists.

Glyoxal is a dialdehyde that is non-volatile and low toxic (LD50 rat > 2960 mg/kg; LD50 mouse > 1280 mg/kg)³ compared with formaldehyde (LD50 rat > 100 mg/kg; LD50 mouse > 42 mg/kg).⁴ It is reported that glyoxal could be used as an effective crosslinking agent in condensation reaction. Pizzi A et al prepared lignin-based and tannin-based wood adhesives using glyoxal.⁵⁻⁷ Ramirez E C et al synthesized a glyoxal-phenol resin for composites.⁸ These researches indicate the adjacent carbonyl groups might provide high reactivity for glyoxal. So it is very interesting to explore the possibility of glyoxal as a suitable substitute for formaldehyde to prepare syntans used in leather processing. At this point of view, further research is needed to obtain the details of condensation between glyoxal and phenolic compounds.

In fact, the reactivity of aldehyde can be traced to its structure that can be best understood through quantum mechanics. Computational chemistry is also considered as an indispensable approach for



exploring mechanism of reactions.⁹ In this study, the condensation between glyoxal and phenolic compounds was modeled by quantum chemical calculations, and the reaction involving formaldehyde was also calculated for comparison.

2. Methods

Phenol, bisphenol A (BPA) and 4, 4'-sulfonyldiphenol (SDP) are commonly used raw materials in the production of phenolic syntans. In this study, they were used as the reactants involved in the phenol-aldehyde condensation. Formaldehyde and glyoxal were chosen as the model of aldehyde to link phenolic compounds together. The structures of these compounds are shown in Figure 1.

The condensation between phenolic compound and aldehyde was based on the generally accepted mechanism for the synthesis of novolac resin. As we know, novolac is produced using excess phenol and an acid catalyst to form a linear polymer. To simplify the calculation, only the initial two steps of condensation, i.e. methylation of phenolic compound and formation of dimer, were investigated. As an example, the mechanism of condensation between phenol and formaldehyde under acidic condition is shown in Figure 2. Firstly, protonated formaldehyde acts as an electrophile and substitutes for a hydrogen atom on the benzene ring in acid condition. Then the methylolated phenol (intermediate) links another phenol to form a dimer.¹⁰ The mechanisms involving other reactants all follow this model.

The density functional theory (DFT) method with B3LYP hybrid functional was used for computation, and the Gaussian basis set 6-31G(d) was chosen. All calculations were performed using Gaussian 03 program. The optimized structures and harmonic vibrational properties of all compounds involved in condensation were obtained, as well as atomic charges of typical atoms and HOMO-LUMO energy gap.

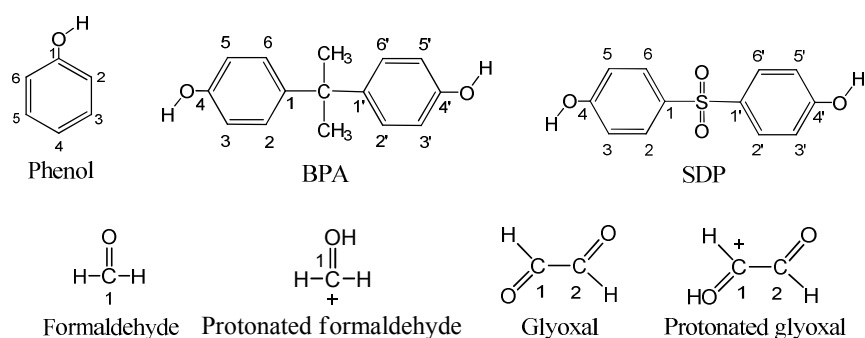


Figure 1. The structures of reactants

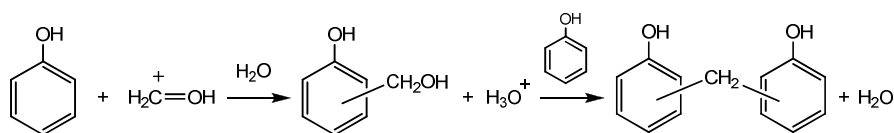


Figure 2. Condensation of phenol with formaldehyde in acid condition

3. Results and discussion

3.1 Atomic charges of reactants

In general, nucleophile attacks at molecular sites with positive charges and electrophile attacks at sites with negative charges. Therefore, the atomic charges can provide a quick summary of molecule feature and predict the probable reaction site.



The calculated charges on typical atoms of phenols and aldehydes are shown in Table 1. It is found that the carbon atoms on the *ortho* positions of phenolic hydroxyl group (C2 in phenol, C3 and C5' in BPA, C3 and C5' in SDP) possess more negative charges than others on the benzene ring, suggesting they should have higher reactivity. Electrophilic substitution of aldehyde will be performed on the *ortho*-C. This result has also been confirmed by NMR analysis.¹¹ In addition, the C3 and C5' in BPA have more negative charge than C2 in phenol, suggesting that *o*-C in BPA is more susceptible toward electrophilic substitution than that in phenol. However, it looks the other way around to SDP. This can be explained by the electronic effect of bridging group between phenolic rings. The electron donating effect of iso-propyl group in BPA results in the increase of negative charge in benzene ring. On the other hand, the sulphone group in SDP decreases the electron cloud density of benzene ring due to its electron attracting effect.

Carbonyl oxygen of aldehyde can be protonated under high acidic condition, which leads to significant increase of the positive charge of carbonyl carbon (Table 1). This means the electrophilicity of formaldehyde and glyoxal is further enhanced by protonation. Actually, the condensation between phenol and aldehyde is favored by acid catalysts.¹⁰

Table 1. Atomic charges of typical atoms of phenols and aldehydes

Compound	Atom	Atomic charge
Phenol	C2	-0.0780
	C6	-0.0194
	C4	-0.0094
BPA	C3, C5'	-0.0828
	C2, C6'	-0.0792
	C6, C2'	-0.0498
	C5, C3'	-0.0225
SDP	C3, C5'	-0.0577
	C5, C3'	-0.0005
Formaldehyde	C1	0.3230
Protonated formaldehyde	C1	0.7635
Glyoxal	C1, C2	0.3440
Protonated glyoxal	C1	0.5495
	C2	0.4952

3.2 Frontier molecular orbital of reactants

Frontier orbital theory can illustrate the potential sites of nucleophilic or electrophilic reaction. The nucleophilic attack usually occurs in the region of lowest unoccupied molecular orbit (LUMO) of an electrophile, whereas the region of highest occupied molecular orbit (HOMO) of a nucleophile is the site of electrophilic reaction.¹² Therefore, the reaction position can be confirmed by the combination of atomic charges of typical atoms and component of frontier molecular orbits. Figure 3 is the frontier molecular orbits of reactants in phenol-aldehyde condensation. HOMO of phenol, BPA and SDP are all distributed on the whole benzene rings, that is to say, electrophilic substitution of aldehyde can proceed on their *ortho*-C atoms. This deduction is consistent with atomic charge analysis. Similarly, the electrophilic centers in formaldehyde and glyoxal, i.e. carbonium ions are covered with LUMO as shown in Figure 3, indicating the feasibility of reaction.

The energy difference between HOMO of phenolic compound and LUMO of aldehyde can estimate the reaction rate of methylation. A lower energy gap leads to a higher reaction rate.¹³ It can be seen from Table 2 that the LUMO energies of formaldehyde and glyoxal are -10.2650 eV and -10.6610 eV, respectively. Therefore, the HOMO-LUMO gap involving formaldehyde is approximately 0.4 eV

lower than that with glyoxal for the same phenolic compound. But the difference of the energy gap is quite slight, indicating similar reactivity of both formaldehyde and glyoxal with phenols. From the point of HOMO-LUMO energy gap, the order of reactivity of phenols is SDP > phenol > BPA. It should be pointed that hindering effect is not concerned in HOMO-LUMO energy gap.

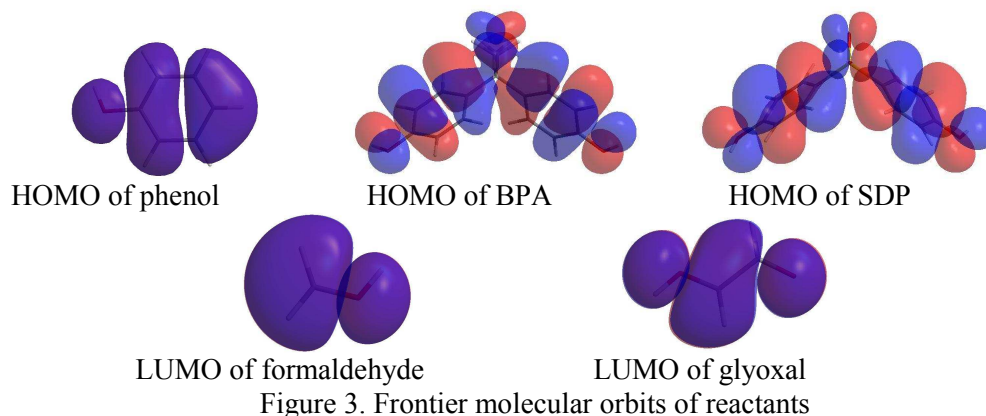


Table 2. HOMO-LUMO energy gap (ΔE) between phenols and aldehydes

	E_{HOMO} (eV)		E_{LUMO} (eV)	ΔE^* (eV)
Phenol	-5.9583	Formaldehyde	-10.2650	4.3067
Phenol	-5.9583	Glyoxal	-10.6610	4.7027
BPA	-5.5950	Formaldehyde	-10.2650	4.6700
BPA	-5.5950	Glyoxal	-10.6610	5.0660
SDP	-6.3553	Formaldehyde	-10.2650	3.9097
SDP	-6.3553	Glyoxal	-10.6610	4.3057

* $\Delta E = |E_{\text{HOMO}} - E_{\text{LUMO}}|$

3.3 Structures of intermediates

The optimized structures of intermediates—methylolated phenols are shown in Figure 4. The results of harmonic vibration frequency show that imaginary frequency does not appear in any of the structures, which means all the intermediates are stable.

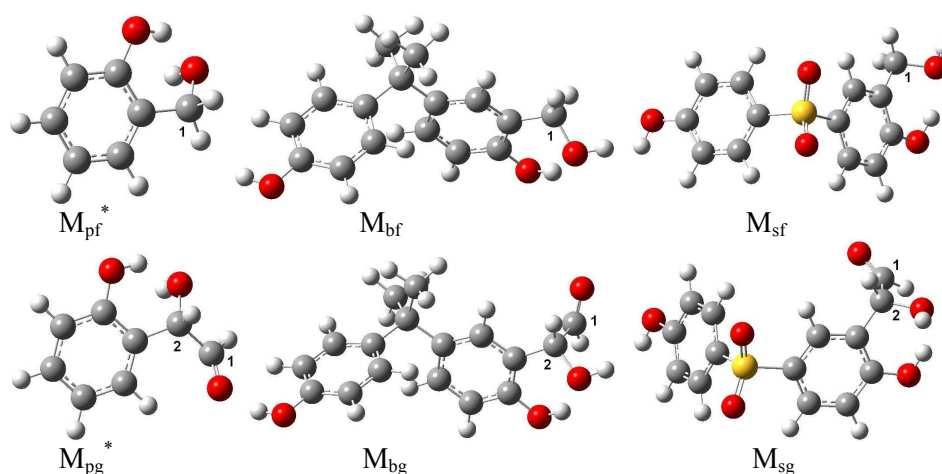


Figure 4. Optimized structures of intermediates

* p, b, s, f, g denote phenol, BPA, SDP, formaldehyde and glyoxal, respectively. M means intermediate formed by phenolic compound and aldehyde described as subscripts.



3.4 Atomic charges of intermediates

The charges of typical atoms of intermediates are listed in Table 3 (The typical atoms have been labeled in Figure 4). All the carbon atoms derived from formaldehyde and glyoxal in intermediates have positive charges, suggesting they still keep in electrophilic state and could continue reacting with phenols. The decrease in positive charges of C1 (methylol carbon) in M_{pf} , M_{bf} and M_{sf} is almost 0.6 compared with that in protonated formaldehyde (Table 1 and Table 3). This means dimer is more difficult to form than methylolated phenols. However, the carbonyl carbon atoms (C1) in M_{pg} , M_{bg} and M_{bg} maintain relatively high positive charge, and relatively strong electrophilicity. So the further condensation between these intermediates and phenols should be easy. Moreover, C2 in M_{pg} , M_{bg} and M_{bg} are also possible to react from perspective of atomic charge, but the preferential site should be the aldehyde group.

Table 3. Atomic charges of typical atoms of intermediates

Intermediate	Atom	Atomic charge
M_{pf}	C1	0.1914
M_{bf}	C1	0.1568
M_{sf}	C1	0.1819
M_{pg}	C1	0.3552
	C2	0.1757
M_{bg}	C1	0.3626
	C2	0.1457
M_{sg}	C1	0.4085
	C2	0.1435

3.5 Frontier molecular orbital of intermediates

The frontier molecular orbits of intermediates are shown in Figure 5. All the electrophilic sites identified by the atomic charges are included in the LUMO of the intermediates except M_{sf} . So LUMO+1 (the unoccupied molecular orbit whose energy is higher than LUMO but lower than any other unoccupied molecular orbits) of M_{sf} is used for analysis. Table 4 gives the HOMO-LUMO energy gap between intermediates and phenolic compounds. The intermediates formed by glyoxal are found to be more reactive in linking another phenol than those formed by formaldehyde due to the lower HOMO-LUMO energy gap. In combination of the energy gaps in Table 2 and Table 4, we can deduce that the reaction of glyoxal with phenols would not be retarded by further linkage of phenols. For example, the HOMO-LUMO gap between glyoxal and BPA is 5.0660 eV, more than that between M_{bg} and BPA, which is only 4.2118 eV. That is to say, the second step—formation of dimer is even faster than the initial methylation. In fact, the high reactivity of glyoxal has been observed in our synthetic experiment, and our current study is focused on control of the reaction rate. In contrast, the reaction between formaldehyde and phenolic compound is a deceleration process, which is in agreement with the result of atomic charge investigation.

4. Conclusions

The condensation processes between phenols and aldehydes are calculated by using B3LYP functional with 6-31G(d) basis set. The atomic charges analysis and frontier molecular orbits distribution show that the site of electrophilic attack of aldehyde is the *ortho* position of phenolic hydroxyl group in phenols. According to the calculation of HOMO-LUMO energy gap, glyoxal may have similar or even higher reactivity to phenols compared with formaldehyde. From this point, glyoxal is a potential alternative to formaldehyde used as bridging agent in the condensation of phenolic syntans.

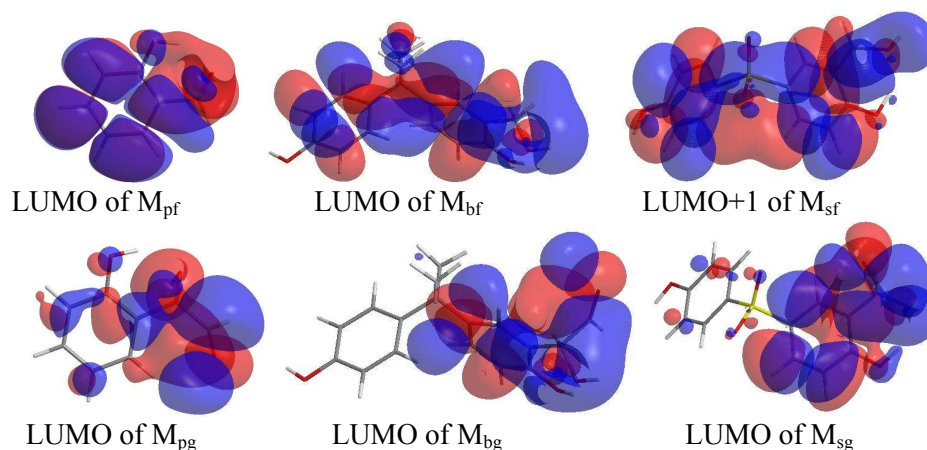


Figure 5. Frontier molecular orbitals of intermediates

Table 4. HOMO-LUMO energy gap (ΔE) between phenols and intermediates

	E_{HOMO} (eV)		E_{LUMO} (eV)	ΔE (eV)
Phenol	-5.9583	M_{pf}	-0.1720	5.7863
Phenol	-5.9583	M_{pg}	-1.3312	4.6271
BPA	-5.5950	M_{bf}	-0.0792	5.5158
BPA	-5.5950	M_{bg}	-1.3832	4.2118
SDP	-6.3553	M_{sf}	-0.6515*	5.7038
SDP	-6.3553	M_{sg}	-1.5889	4.7664

* E_{LUMO+1} of M_{sf}

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