PALLADIUM COMPLEX IMMOBILIZED ON SBA-15 AS AN EFFICIENT CATALYST FOR THE HECK REACTION OF ARYL IODIDES WITH STYRENE

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ABSTRACT

Highly ordered mesoporous silica SBA-15 was synthesized and functionalized via silane chemistry with N-[3-(trimethoxysilyl)propyl]ethylenediamine to create surface amino groups. The amino-functionalized SBA-15 was allowed to react with 2-acetyl pyridine to form an immobilized bidentate iminopyridine ligand, which was complexed with palladium acetate, affording the immobilized palladium complex catalyst with a palladium loading of 0.4 mmol/g (AAS). The catalyst was characterized by X-ray powder diffraction (XRD), scanning electron microscope (SEM), transmission electron microscope (TEM), thermogravimetric analysis (TGA), Fourier transform infrared (FT-IR), nitrogen physisorption measurements, and elemental analysis (EA). The immobilized palladium complex was used as an efficient heterogeneous catalyst for the Heck cross-coupling reaction of iodobenzene and styrene to form stilbene as the principal product. The reaction was carried out in dimethylformamide (DMF) at 140ºC, in the presence of triethylamine as a base, and at the catalyst concentration of 0.1 mol% palladium. Excellent conversions (more than 99%) were achieved after 5 hours. It was also observed that the modified SBA-15 catalyst could be facilely separated from the reaction mixture by centrifugation, and could be reused in subsequent reactions without significant degradation in activity.

I - INTRODUCTION

Transition metal-catalyzed cross-coupling reactions have gained popularity over the past thirty years in organic synthetic chemistry, as they represent key steps in the building of more complex molecules from simple precursors [1]. Their applications range from the synthesis of complex natural products to supramolecular chemistry and materials science, from fine chemical to the pharmaceutical industries [2]. A wide variety of cross-coupling methodologies have been developed to achieve the most powerful and useful tool for the elaboration of molecular architecture, in which the Heck coupling reactions appear to have advantages over other processes [3]. Catalysts used in the standard Heck processes are generally based on homogeneous palladium phosphine complexes, which are rarely recoverable without elaborate and wasteful procedures, and therefore commercially undesirable [4].

In this context, heterogeneous catalysis is emerging as an alternative to homogeneous processes so that catalysts can be recovered and reused [5]. At the same time, the catalyst recovery also decreases contamination of the desired products with hazardous or harmful heavy metals. Previously, palladium species immobilized on cross-linked polystyrene resins and silica gels have been used as catalysts for the Heck reactions [6 - 8]. However, the question of what is the best catalyst for the Heck

reactions still remains unanswered even for the simplest cases, though studied in hundreds of works [4]. SBA-15 has emerged as one of the most common mesoporous silica catalyst supports. It is known to be a well-defined, hexagonal mesoporous silica material with straight mesopores that are connected through small micropores [9]. In this paper, we wish to report *for the first time in Viet Nam*, to our best knowledge, the preparation of a palladium complex immobilized on SBA-15 and its application as an efficient catalyst for the Heck reaction of aryl halides with styrene to form stilbenes as principal products.

<div align="center">II - EXPERIMENTAL</div>

1. Materials and instrumentation

Chemicals were purchased from Sigma-Aldrich, Fisher, and Acros and used as received without further purification unless otherwise noted. The synthesis of SBA-15 and diamino-functionalized SBA-15 was carried out at the School of Chemical and Biomolecular Engineering, the Georgia Institute of Technology, USA.

Fourier transform infrared (FT-IR) spectra were obtained on a Bruker TENSOR37 instrument with samples being dispersed on potassium bromide pallets. Scanning electron microscope (SEM) studies were performed on a JSM 740. Transmission electron microscope (TEM) studies were performed using a JEOL JEM 1400, in which samples were dispersed on holey carbon grids for TEM observation. A Netzsch Thermoanalyzer STA 409 was used for simultaneous thermal analysis combining thermogravimetric analysis (TGA) and differential thermal analysis (DTA) with a heating rate of 10ºC/min under a nitrogen atmosphere. Nitrogen physisorption measurements were conducted using a Micromeritics Chem BET 3000 system. X-ray powder diffraction (XRD) patterns were recorded using Cu K radiation source on a D8 Advance Bruker powder diffractometer.

GC-MS analyses were performed using an Agilent GC-MS 6890. GC analyses were performed using a Shimadzu GC-17A equipped with a FID detector and a 30 m × 0.25 mm × 0.25 μm DB-5 column. The temperature program for GC analyses heated samples from 60ºC to 140ºC at 10ºC/min, held at 140ºC for 1 min, from 140ºC to 300ºC at 50ºC/min, and held at 300ºC for 3 min.

2. Synthesis of SBA-15 and amino-functionalized SBA-15

Mesoporous SBA-15 was synthesized using poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide) (EO-PO-EO), 1,3,5-trimethylbenzene (TMB), and tetraethyl orthosilica (TEOS), according to a previously reported literature procedure [10]. Prior to functionalization, the SBA-15 was dried under vacuum at 200ºC for 3h and stored in a dry box. Diamino-functionalized SBA-15 was synthesized by stirring a toluene (30 ml) suspension of SBA-15 (1 g) and *N*-[3-(trimethoxysilyl)propyl]ethylenediamine (1 g) at room temperature for 24 h under an argon atmosphere. The solid was then filtered and washed with copious amounts of toluene, hexanes, methanol, and ether in a dry nitrogen glove box and dried under vacuum at room temperature overnight, yielding approximately 1 g of diamino-functionalized SBA-15.

3. Synthesis of palladium catalyst immobilized on SBA-15

The diamino-functionalized SBA-15 (0.40 g) was added to a round-bottom flask containing ethanol (99.5 %, 25 ml) and 2-acetyl pyridine (7 ml, 61 mmol). The resulting mixture was then heated at reflux with rapid stirring for 30 hours. After that, the reaction mixture was cooled to room temperature, centrifuged, washed with copious amounts of ethanol and *n*-hexane, and dried under vacuum at room temperature to yield the immobilized Schiff base (0.31 g). The immobilized Schiff base (0.30 g) was then added to the round-bottom flask containing the solution of palladium acetate (0.0355 g, 0.158 mmol) in acetone (30 ml). The mixture was then stirred vigorously at room temperature for 30 hours. The solid was then separated by centrifugation, washed with copious amounts of

acetone and dried under vacuum at room temperature to yield the immobilized palladium catalyst (0.25 g).

4. Catalysis studies

Unless otherwise stated, a mixture of iodobenzene (0.12 ml, 1.08 mmol), styrene (0.2 ml, 1.62 mmol), triethylamine (0.45 ml, 3.24 mmol), and hexadecane (0.03 ml, 0.27 mmol) as the internal standard in dimethylformalmide (5 ml) were added to a round-bottom flask containing the required amount of the immobilized palladium catalyst. The flask was heated at the required temperature with magnetic stirring. Reaction conversions were monitored by withdrawing aliquots (0.1 ml) from the reaction mixture at different time intervals, and quenching with water. The organic components were extracted into diethylether, dried over Na_2SO_4 and analyzed by gas chromatography (GC) with reference to hexadecane. Product identity was also further confirmed by gas chromatography — mass spectroscopy (GC-MS), and also by using standard *trans*-stilbene and *cis*-stilbene (Sigma-Aldrich).

III - RESULTS AND DISCUSSION

Mesoporous SBA-15 was synthesized according to a literature procedure as previously reported, utilizing the triblock poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide) (EO-PO-EO) nonionic surfactant as the structure-directing agent and 1,3,5-trimethylbenzene (TMB) as a swelling cosolvent [10]. The as-synthesized silica was then functionalized *via* the reaction of these silanol groups with *N*-[3-(trimethoxysilyl)-propyl]ethylenediamine to create surface amino groups (Scheme 1). The amino-functionalized SBA-15 was allowed to react with 2-acetyl pyridine to form an immobilized bidentate iminopyridine ligand, which was complexed with palladium acetate using a literature procedure previously reported by Clark and co-workers, affording the immobilized palladium complex catalyst (Scheme 1) [11]. The modified SBA-15 was characterized by X-ray powder diffraction (XRD), scanning electron microscope (SEM), transmission electron microscope (TEM), thermogravimetric analysis (TGA), Fourier transform infrared (FT-IR), nitrogen physisorption measurements, and elemental analysis (EA), which were in good agreement with the literature [12].

Low angle X-ray powder diffraction (XRD) profiles of the modified SBA-15 exhibited reflections in the 2θ range of 0.7 — 2° attributable to 2D hexagonal symmetry (figure 1). The patterns were consistent with the literature with no impurity peak being observed in the XRD diffractogram [13]. Nitrogen physisorption measurements of the modified SBA-15 showed BET surface areas of 449 m^2/g. Being in good agreement with the literature, the TEM micrograph of the modified SBA-15 showed the honey-comb like structure, typical of an hexagonal array with highly regular parallel layers [14] (figure 2). The SEM micrograph revealed that the modified SBA-15 consisted of several rod-like domains with relatively uniform sizes of 2 — 3μm, which were aggregated into wheat-like macrostructures (figure 2). FT-IR spectra of the immobilized palladium catalyst showed an O-H stretching vibration due to physisorbed water and potentially surface hydroxyls near 3436 cm^{-1}, an O-H deformation vibration near 1636 cm^{-1}, and an Si-O stretching vibration near 1076 cm^{-1}, respectively. The significant feature was the appearance of the peaks near 2950 - 3050 cm^{-1} due to the -CH_2 and aromatic C-H stretching vibrations, and the presence of the imine C=N stretching vibration near 1558 cm^{-1}. There also existed the contribution of the -NH_2 group for the band near 3300 cm^{-1}, which was overlapped by the O-H stretching vibration [12] (Figure 3). However, the FT-IR spectra exhibited little meaningful data due to the low loading of the ligand and the palladium complex on the SBA-15.

TGA analyses of the amino-functionalized SBA-15 and the immobilized bidentate iminopyridine ligand showed that 1.30 mmol /g of the diamine and 0.64 mmol/g (figure 4) of the Schiff base, respectively, were supported on the SBA-15. This indicated that approximately 50% of the surface amino groups were converted to
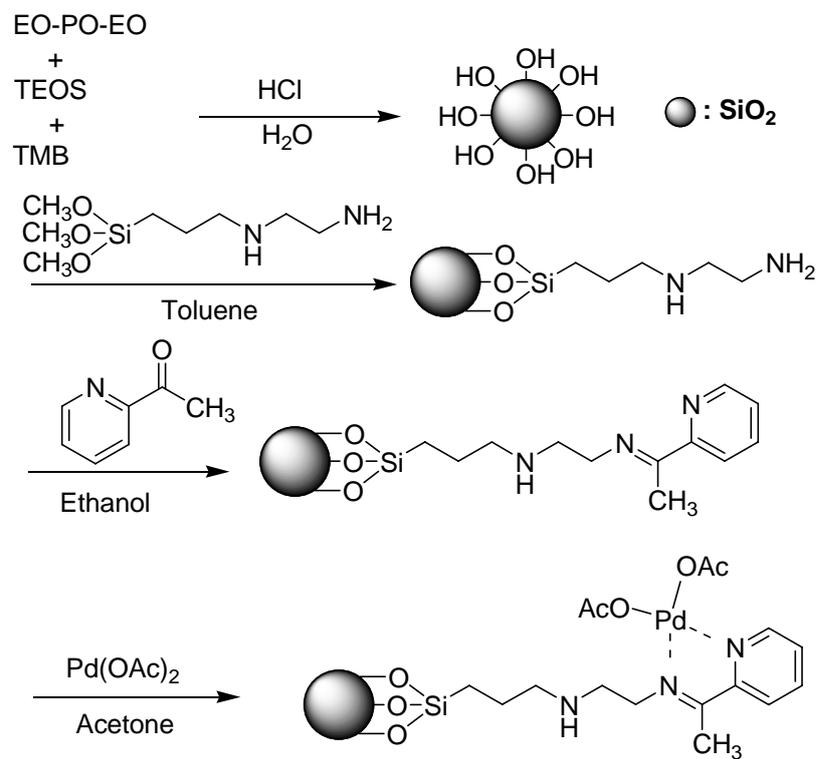
Scheme 1: Synthesis of the immobilized palladium catalyst on SBA-15
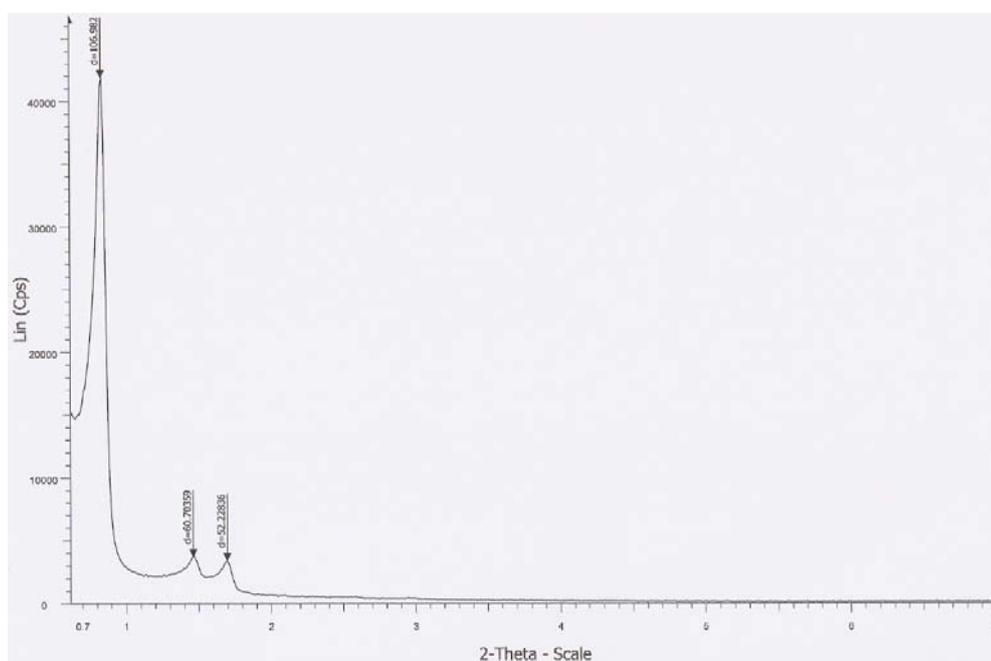
Figure 1: X-ray powder diffractogram of the modified SBA-15

the Schiff base. As expected, EA analysis of the immobilized palladium complex catalyst exhibited a palladium loading of 0.44 mmol/g (AAS). It should be noted that the metal loading of several immobilized palladium complex catalysts for cross-coupling reactions was reported to be in the range of 0.1 - 0.5 mmol/g [4]. It was previously found that higher palladium loading was unnecessary as increasing the catalyst loading on the solid support to over 0.5 mmol/g could make a number of active sites inaccessible to the reactants [15]. As the catalyst was designed for Heck reaction where a base was required, it was unnecessary to block the free amino groups on the surface of the catalyst. Indeed, it was previously reported that the presence of an amine could increase the stability of the palladium catalyst in the Heck and the Suzuki reactions [15]. However, the effect of free amino groups on the activity of the catalyst still needs further investigation.
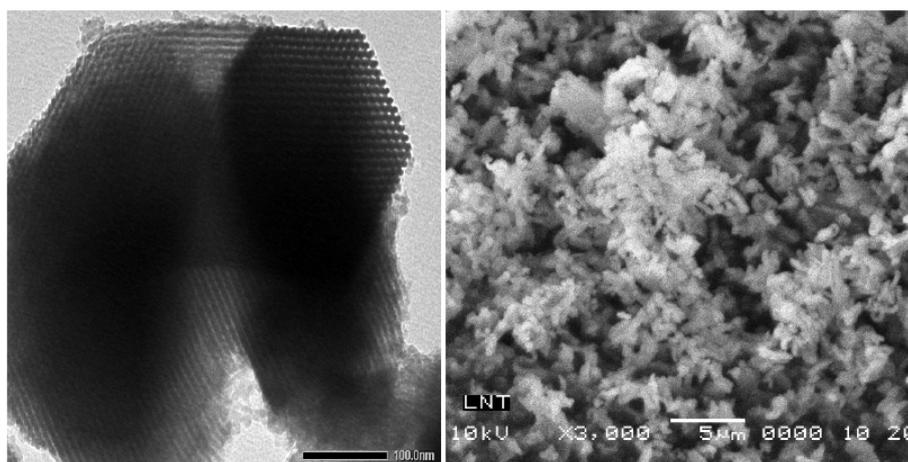
Figure 2: TEM (left) and SEM (right) micrographs of the modified SBA-15
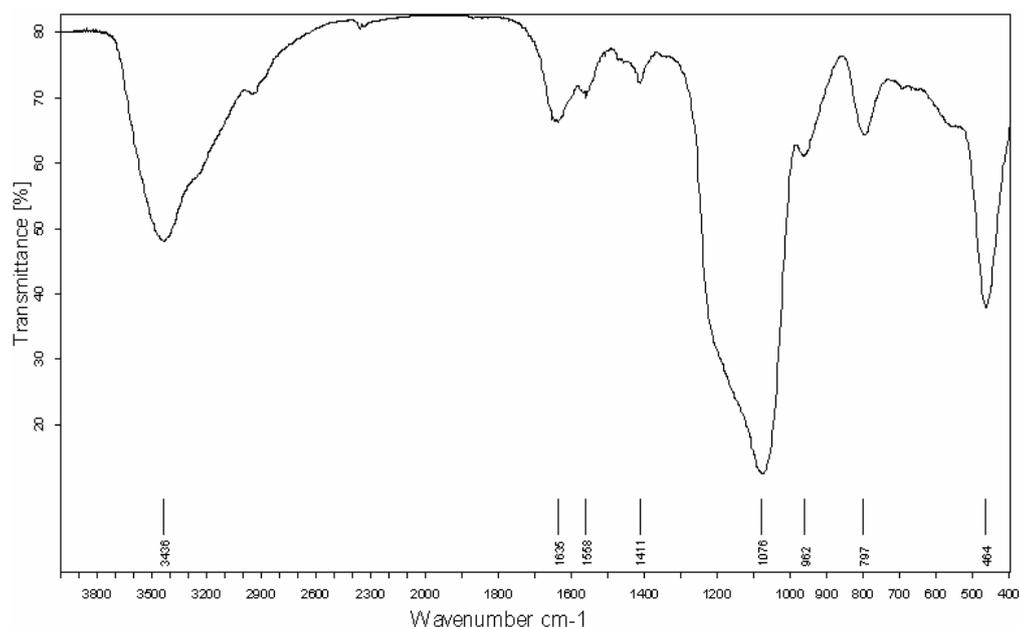
Figure 3: FT-IR spectrum of the immobilized palladium complex catalyst
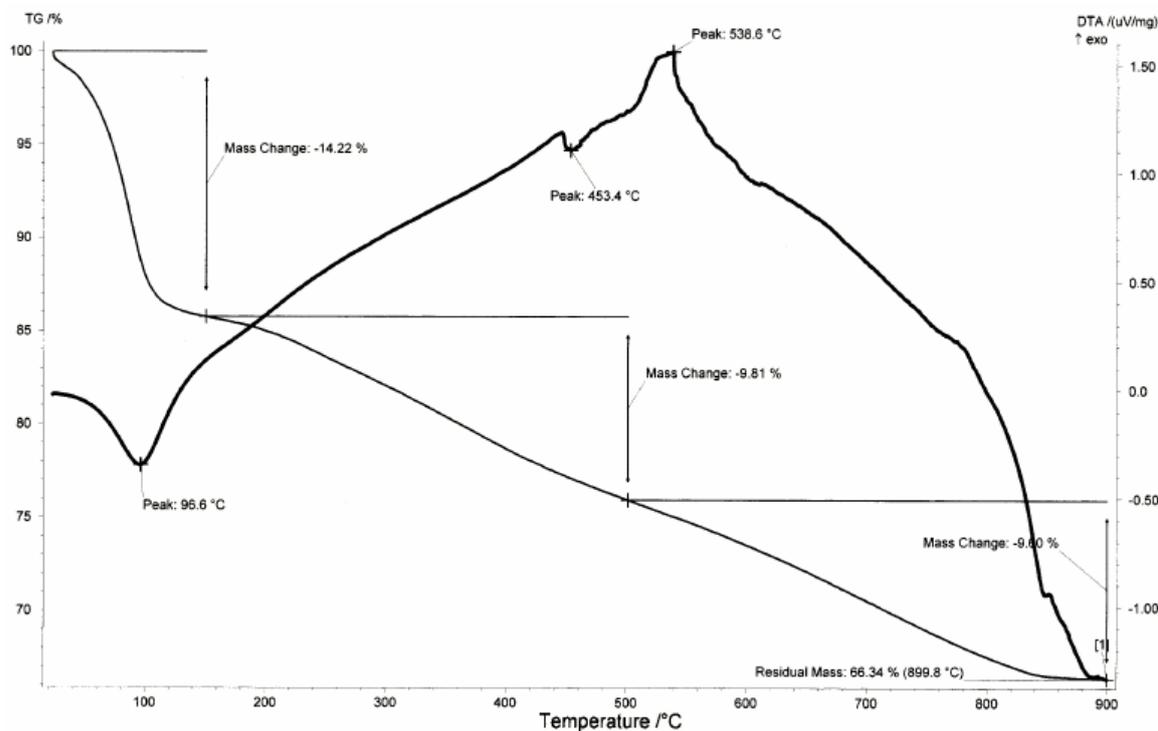
Figure 4: TGA graph of the immobilized bidentate iminopyridine ligand

The immobilized palladium complex catalyst was assessed for its activity initially in the Heck reaction between iodobenzene and styrene to form *trans*-stilbene as the principal product and *cis*-stilbene as the minor product (Scheme 2). Indeed, Clark and co-workers previously immobilized these palladium complexes on silica gel and investigated their activity in the Heck reactions of several aryl halides and vinylic olefins [11]. However, the immobilization of these palladium complexes on SBA-15 was not previously reported. As DMF is normally the solvent of choice for cross-coupling reactions [4], it was decided to carry out the Heck reaction in DMF at 120 °C, using 0.1 mol% of the immobilized palladium catalyst. It is generally accepted that a base is obviously necessary to neutralize the HI produced, and regenerate the active species to complete the catalytic cycle of the Heck reaction [4, 15]. Therefore, the effect of base on the reaction conversion was investigated, using four bases including Na_2CO_3, K_3PO_4, CH_3COONa, and triethylamine (figure 5). The most commonly used base in the Heck reaction is Na_2CO_3, but stronger bases such as NaOH, K_3PO_4 and $Ba(OH)_2$ were previously reported to give better results in some cases. In this research, however, the Heck reaction using Na_2CO_3 afforded the coupling product in a significantly lower conversion than reactions using CH_3COONa and K_3PO_4 as bases. After 7 hours, a conversion of only 5% was obtained for the case of Na_2CO_3, while reactions using K_3PO_4, CH_3COONa, and triethylamine proceeded with up to 27%, 54%, and 77% conversions, respectively, being achieved under the same conditions. Indeed, triethylamine was previously employed as the base for several Heck cross-coupling reactions [4].

It should be emphasized that among basic types of palladium-catalyzed transformations, the Heck reaction and related chemistry occupy a special place. Indeed, most organic reactions, particularly catalytic ones, are well defined and specific and require some particular reagents and catalysts, to operate within a confined domain. The definition of this includes a more

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or less limited scope and optimal conditions. Yields for similar substrates can be extrapolated. Nothing like that, however, is true for Heck chemistry. A small variation of substrate, structure, nature of base, ligands, temperature, pressure, *etc.* often leads to unpredictable results. Trends in reactivity and selectivity are uneven and often break when would not be expected. Brand name precious ligands which worked miraculously for some sophisticated transformations often fail in the simplest cases. An obvious question of what is the best catalyst and procedure for the Heck reaction still remains unanswered even for the simplest cases, though studied in hundreds of works [4, 15].

R: H, CH$_3$, COCH$_3$

cis-stilbenes

trans-stilbenes
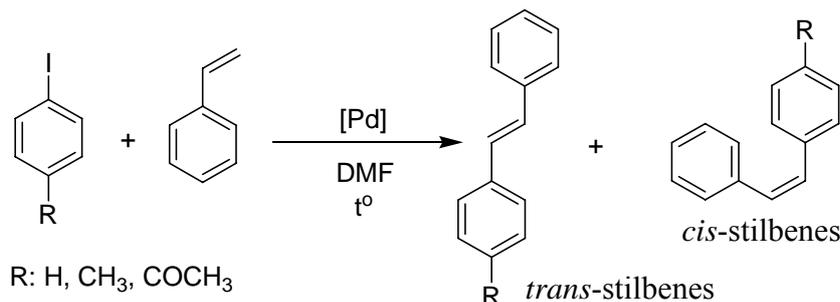
Scheme 2: The Heck reaction of aryl iodides and styrene using the immobilized palladium complex catalyst
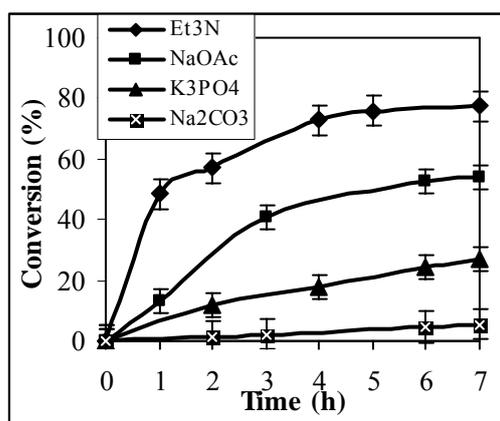
Figure 5: Effect of bases on reaction conversions

It was then decided to use triethylamine as the base for the Heck reaction in further studies. The effect of the reaction temperature was then investigated varying from 100°C to 140°C, using 0.1 mol% palladium catalyst in DMF, and in the presence of triethylamine as the base. As expected, experimental results showed that the higher the reaction temperature, the higher the reaction rate (figure 6). Increasing the temperature to 140°C, more than 99%

conversion was achieved after 5 hours. It was observed that the Heck reaction carried out at 100°C proceeded with slower rate, with 73% conversion being obtained after 7 hours. Indeed, the temperature range of 80°C to 140°C has been the most commonly used for Heck transformation using different types of palladium catalysts [3]. It should also be noted that DMF could decompose at its normal boiling point, therefore, Heck reactions in DMF should not be carried out at the temperature higher than 140°C.

With these results in mind, we therefore studied the effect of catalyst concentration on reaction conversions, using DMF as the solvent and triethylamine as the base at 140°C. As with previous reports, the higher the catalyst concentration was used, the higher the reaction rate was observed. Almost quantitative conversion of iodobenzene to stilbenes was achieved after 4 hours at the palladium concentration of 0.2 mol% relative to iodobenzene. Decreasing the catalyst concentration resulted in a drop in reaction rate, with 97% and 91% conversions being obtained after 4 hours at palladium concentrations of 0.1 mol% and 0.05 mol% respectively (figure 7).

The catalyst concentrations used in this study were comparable to those of several previous reports covering different aspects of the Heck reaction, where the palladium concentrations varied from less than 0.01 mol% to more than 1 mol%, depending on the nature of the catalysts as well as the substrates [3, 4, 15].

In order to investigate the effect of different substituents on reaction conversions, the study was then extended to the reaction of substituted iodobenzenes containing electron-donating (*i.e.* 4-iodotoluene) and electron-withdrawing (*i.e.* 4-iodoacetophenone) groups. It was observed that the reaction of 4-iodotoluene with styrene proceeded with slower rate than the Heck reaction of iodobenzene, though a total conversion of 99% was still achieved after 7 hours (Figure 8). As expected, the reaction rate of the Heck cross-coupling between 4-iodoacetophenone and styrene was higher than

the case of iodobenzene, affording a total conversion of more than 99% after 1 hours. As expected, the selectivity of the *trans*-isomer to the *cis*-isomer was around 90% of *trans*-isomer for the case of iodobenzene and 4-iodotoluene, while the selectivity for the case of 4-iodoacetophenone was slightly higher (Figure 8). This result indicated that the Heck reaction using the immobilized palladium catalyst was favoured by electron-withdrawing groups on benzene ring, while electron-donating groups slowed down the cross-coupling processes. It was also previously reported that the use of electron-withdrawing ring substituents normally lead to enhanced reactivity in palladium-catalyzed cross-coupling reactions [4, 14, 16]. The effect of substituents on reaction conversions of iodobenzene derivatives observed in this research was therefore in good agreement with the literature.
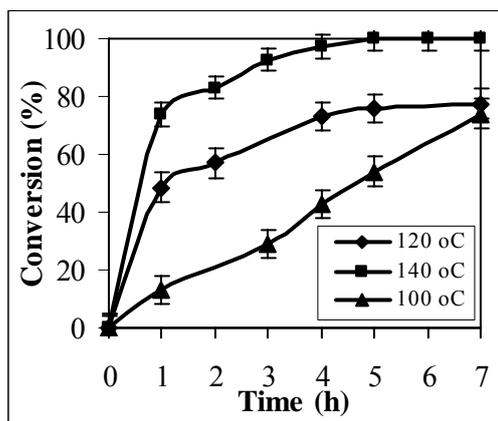
Figure 6: Effect of temperature on reaction conversions
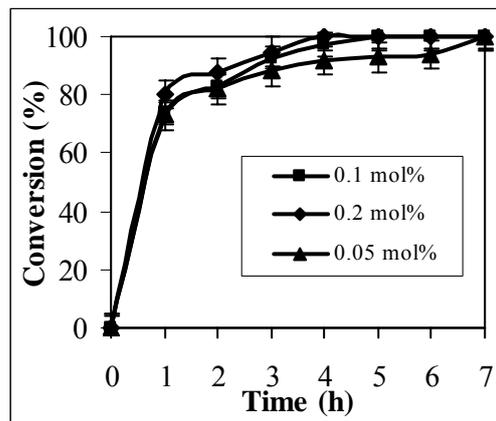
Figure 7: Effect of catalyst concentration on reaction conversions

An important point concerning the use of a heterogeneous catalyst is its lifetime, particularly for industrial and pharmaceutical applications of the palladium-catalyzed Heck reaction. In the best case the catalyst can be recovered and reused before it eventually deactivates completely. At the same time, the catalyst recovery can also reduce the environmental pollution caused by heavy metals used in the catalyst system [17]. The immobilized palladium complex catalyst was therefore investigated for recoverability and

reusability in the Heck reaction of iodobenzene and styrene. After the reaction, the catalyst was separated from the reaction mixture by centrifugation, washed several times with toluene, DMF, water and ethanol to remove any physisorbed reagents. The recovered catalyst was then dried and reused in further reaction under identical condition to the first run. Experimental results showed that the modified SBA-15 catalyst could be reused in further reaction without significant degradation in activity. A conversion of

more than 99% was still achieved after 7 hours for the second run.
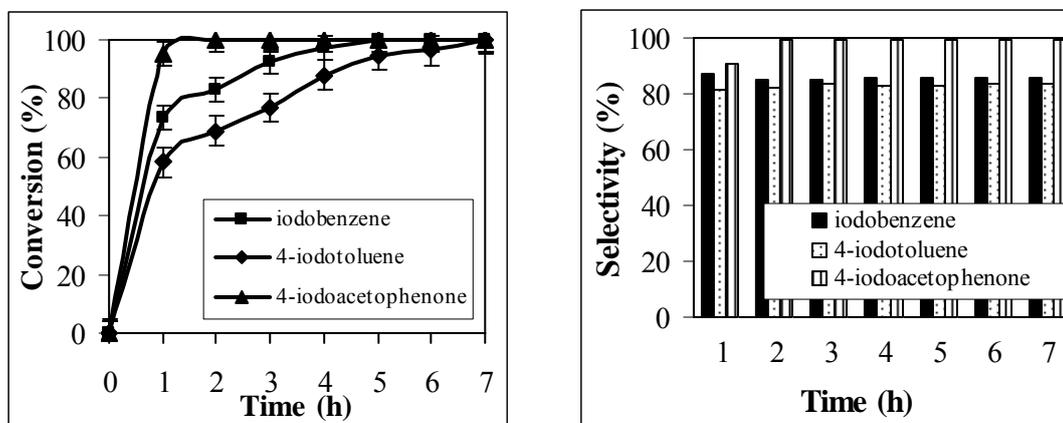
Figure 8: Effect of substituents on reaction conversions (left)
and selectivity of *trans*-isomer (right) of iodobenzene derivatives

IV - CONCLUSIONS

In summary, highly ordered mesoporous silica SBA-15 was synthesized and functionalized *via* silane chemistry with *N*-[3-(trimethoxysilyl)propyl]ethylenediamine to create surface amino groups. The amino-functionalized SBA-15 was allowed to react with 2-acetyl pyridine to form an immobilized bidentate iminopyridine ligand, which was complexed with palladium acetate, affording the immobilized palladium complex catalyst with a palladium loading of 0.4 mmol/g (AAS). The catalyst was characterized by X-ray powder diffraction (XRD), scanning electron microscope (SEM), transmission electron microscope (TEM), thermogravimetric analysis (TGA), Fourier transform infrared (FT-IR), nitrogen physisorption measurements , and elemental analysis (EA). The immobilized palladium complex was used as an efficient heterogeneous catalyst for the Heck cross-coupling reaction of iodobenzene and its derivatives with styrene to form stilbenes as the principal products. The Heck reaction of iodobenzene derivatives containing electron-donating and electron-withdrawing substituents with styrene could afford more than 99% conversions in the presence of triethylamine at 140ºC, and at the palladium loading of as low as 0.1 mol%. It was also observed that the modified SBA-15 catalyst could be facilely separated from the reaction mixture by centrifugation, and could be reused in subsequent reactions without significant degradation in activity. Current research in our laboratory has been directed to the design and immobilization of several homogeneous catalysts on SBA-15 for a wide range of organic transformations, and results will be published in due course.

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