Use of Acyl Phosphonates for the Synthesis of Inulin Esters and Their Use as Emulsion Stabilizing Agents

Tina M. Rogge,[†] Christian V. Stevens,[†,*] Anton Colpaert,[†] Bart Levecke,[‡] and Karl Booten[‡]

SynBioC Research Group, Department of Organic Chemistry, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, B-9000 Gent, Belgium; and ORAFTI Bio Based Chemicals, Aandorenstraat 1, B-3300 Tienen, Belgium

Received June 20, 2006; Revised Manuscript Received October 18, 2006

Inulin, the polydisperse polyfructose, extracted from chicory, was modified via esterification with acyl phosphonates. The grafting of an acyl chain onto the inulin backbone under different conditions led to a highly efficient synthesis of a series of inulin esters, with interesting tensioactive properties. The derivatives were evaluated in oil-in-water (O/W) emulsions with isoparaffinic oil, Isopar M. Therefore, a 2% (w/v) aqueous solution of inulin-based surfactant was used in 50/50 O/W emulsions, in nonelectrolyte, and in electrolyte media, using 1 M $MgSO_4$. Longer acyl chains, e.g., dodecanoyl (C12), hexadecanoyl (C16), and octadecanoyl (C18), with degrees of substitution lower than 0.5, gave rise to the highest emulsion stabilities against coalescence.

Introduction

Polymeric surfactants attracted considerable attention as dispersants for solids in liquids and as emulsifiers.[1] Most of the copolymeric surfactants consist of a block (A-B and A-B-A) or graft structure (BA_n) whereby the B chain represents the anchor of the molecule (e.g., poly(methyl methacrylate)) and the A chains (e.g., poly(ethylene oxide)) remain in solution and are mostly referred to as the stabilizing part of the molecules.[2,3] In recent years, considerable attention was paid to polymeric or oligomeric surfactants, based on polysaccharides, because carbohydrate-based surfactants can be used in cosmetic, detergent, food, and pharmaceutical applications.[4] Via the introduction of acyl chains onto the polysaccharide backbone, the hydrophobic part is provided, which can be strongly adsorbed on hydrophobic surfaces such as carbon black or oil droplets.[5] The type of polysaccharide that is used as the water-soluble part has a big influence on the performance of the end-product; the difference in properties and applicability between modified starch, cellulose, inulin, and other oligosaccharides is therefore enormous. The low molecular weight carbohydrate esters, e.g., sucrose esters can be used as nonionic surfactants or as binders in paints,[6] plasticizers, or softeners, whereas the high molecular weight carbohydrate esters such as starch esters, are more preferentially used as sizing agents in the textile industry, as thickeners in the film and fiber industry,[7] and as substitutes for the purely synthetic grafted polymeric surfactants.

Inulin, the reserve polysaccharide of chicory (*Cichorium intybus*) has a nonbranched polyfructose structure, which can act as the stabilizing chain when grafted with hydrophobic acyl chains. Therefore, the interest in its chemical modification is increasing due to its interesting properties.[8] Inulin consists mainly of β(2-1) fructosyl fructose units (F_m), which are all present in the furanose form, with normally, but not always, a glucopyranose at the reducing end (GF_n).

In a previous study on the chemical modification of inulin for the development of inulin-based surfactants, very interesting properties could be attributed to carbamoylated inulin derivatives, which showed excellent emulsion stabilities even in high electrolyte concentrations.[9,10]

Considering these results, a number of inulin esters were synthesized via transesterification with fatty acid methyl esters (FAME).[11] However, this method was not suitable for the development of an industrially feasible process due to the moderate reaction efficiency caused by the low reactivity of the esters.

The most classical esterification method consists of the reaction of an alcohol with an acid chloride. This method has been described in dimethylformamide and pyridine for dextrin and in water for inulin.[13] When the esterification of inulin is performed in aqueous medium, with NaOH as catalyst, the reaction is very hard to reproduce and the purification of the crude reaction mixture is extremely difficult, since a lot of side products have to be removed.

The esterification of polysaccharides by alkylsuccinic anhydrides with sodium hydroxide was patented for the first time in 1953 and was initially described on starch.[14,15] Recently, a study was performed on the modification of several other polysaccharides, including inulin, using this esterification method in water. The disadvantage of water as a solvent, however, is the formation of several side products and the very difficult purification procedure.

Similarly, Südzucker described the esterification of inulin with the C4−C7 anhydrides in pyridine and reported the properties of the derivatives formed. The speed of the reaction could be increased using alkaline catalysts such as 4-(dimethylamino)-pyridine, potassium carbonate, or an ion-exchange resin in its acid or in its alkaline form.[16] Again, the major disadvantage of this reaction is the formation of an equivalent amount of free fatty acid that has to be removed. Further, the use of pyridine is undesirable for an industrial process because of its toxicity profile. Apart from the chemical esterification, it is also possible to perform the esterification enzymatically, using lipases, with a fatty acid ester such as vinyl or ethyl dodecanoate as acylating agents in a mixture of organic solvents such as dimethyl sulfoxide (DMSO) and 2-methyl-2-butanol.[17] Major drawbacks for enzymatic esterifications are the cost of the enzyme and the

* Corresponding author.
[†] Ghent University.
[‡] ORAFTI Bio Based Chemicals.

10.1021/bm060592z CCC: $37.00
Published on Web 12/22/2006

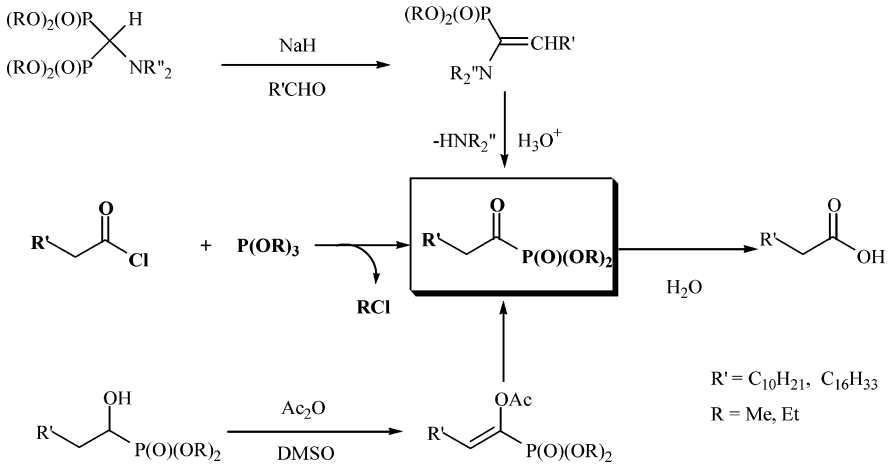

Figure 1. Synthesis of acyl phosphonates.

need of very diluted reaction conditions, which are both undesirable for industrial applications. Furthermore, some organic solvents that are suitable to dissolve polysaccharides (e.g., DMF) will deactivate the expensive enzyme; therefore, most reactions are still performed in diluted aqueous media.[18] The esterification of inulin using fatty acid methyl esters (FAME) in dimethylacetamide (DMA) was patented recently;[19] however, the described reaction conditions were very stringent, with reactions at 160 °C for 6 h. These reactions were repeated in our lab but could not be reproduced.

Therefore, we studied the transesterification in depth to develop a more elegant and less stringent method, which ensures a very good reproducibility in a wide range of organic solvents. From that point of view, acyl phosphonates were evaluated in this work as acylating agents. Acyl phosphonates show an ambivalent character in their behavior toward nucleophiles, since they can act as ketones toward some nucleophiles, such as hydroxylamine, with the formation of the corresponding oximes. Toward most nucleophiles however, they act as activated carboxylic acid derivatives, with the phosphonyl group as the leaving group. For the esterification of inulin, the acylating property will be exploited.

Acyl phosphonates are generally prepared by reaction of an acid chloride and a trialkyl phosphite, which can be performed easily in a solvent-free medium in larger scale. The length of the acyl chain does not affect the reaction kinetics dramatically.[20,21]

Besides the well-known Arbusov-like reaction, acyl phosphonates can also be synthesized via a mild hydrolysis of α-phosphono enamines, which can be formed via a Horner−Wittig−Emmons reaction of a *N*, *N*-dialkylaminomethane bisphosphonate with an aldehyde in the presence of a base. Normally the hydrolysis leads to the formation of the carboxylic acid, but when the reaction (Figure 1) is performed using benzaldehyde in the presence of NaH, the acyl phosphonates can be isolated.[22]

Also α-hydroxyphosphonates can lead to acyl phosphonates, via an oxidation using DMSO in acetic acid anhydride as oxidizing agent from which the acyl phosphonate is isolated as the enol acetate.[23] These α-hydroxyphosphonates are synthesized via the addition of a dialkyl phosphite to an aldehyde or a ketone (Abramov reaction).[17,24,25]

Acyl phosphonates are not only very sensitive to hydrolysis,[26] the phosphorus−carbon (P−C) bond is also easily cleaved by a multitude of nucleophiles such as amines,[27] alcohols,[28] and thiols,[29] resulting in the expulsion of phosphite. This property will be utilized for the esterification of inulin.

Materials and Methods

Materials. Inulin (INUTECN25) and INUTECSP1 were supplied by ORAFTI (Tienen, Belgium) and were used without purification. The average degree of polymerization of INUTECN25 was approximately 25 and was determined by HPLC analysis after enzymatic hydrolysis.[30] *N*-Methylpyrrolidinone (NMP) was purchased from Aldrich and was used without prior purification.

The emulsions were prepared using a high-speed stirrer (CAT X620). The oil phase consisted of Isopar M isoparaffinic oil obtained from Exxon. The water phase comprised demineralized water or 1 M $MgSO_4$ solution, which was prepared with $MgSO_4 \cdot 7H_2O$ p.a. obtained from Merck.

Methods. *General Synthesis of Dodecanoyl Phosphonate (C12*). A dried round-bottom flask of 50 mL was charged with nitrogen, and 13.65 g (0.1 mol; 1.1 equiv) of trimethyl phosphite was added dropwise to 21.87 g (0.1 mol) of dodecanoyl chloride (C12) at room temperature. After the reaction was stirred for 3 h at room temperature, the excess of trimethyl phosphite was removed under high vacuum from the reaction mixture. The dodecanoyl phosphonate (C12) was obtained in quantitative yields, and no additional purification step was needed for further use. ^{1}H NMR δ (ppm, 300 MHz, $CDCl_3$, 16 scans): 0.88 (3H, t, $J = 6.6$ Hz, CH_3); 1.26 (16H, br.m., $(CH_2)_8$); 1.63 (2H, m, $(CH_2)_\beta$); 2.82 (2H, t, $J = 7.3$ Hz, $(CH_2)_\alpha$); 3.87 (6H, d, $J_{P-H} = 10.5$ Hz, $(OCH_3)_2$). ^{13}C NMR δ (ppm, 75 MHz, $CDCl_3$): 13.81 (CH_3); 22.07 (CH_2); 22.45 (CH_2); 28.68 (CH_2); 29.11 ($(CH_2)_2$); 29.20 (CH_2); 29.38 ($(CH_2)_2$); 31.69 (CH_2); 43.35 (2C, d, $J_{P-C} = 54.2$ Hz, $(OCH_3)_2$); 53.51 $(CH_2)_\alpha$); 210.26 (1C, d, $J_P-C = 163.8$ Hz, CO). ^{31}P NMR δ (ppm, 109 MHz, $CDCl_3$): −0.21.

General Esterification of Inulin with Et3N as Base. Inulin (6.0 g, 37.0 mmol of fructose equivalents) was dissolved in 20 g of *N*-methylpyrrolidinone (NMP) at 50 °C. The solution of inulin in NMP was evaporated under high vacuum up to a 40% (w/w) solution in order to remove moisture that was present in the inulin−NMP system. After stripping of the water, the inulin solution was transferred to a round-bottom flask of 100 mL under a nitrogen atmosphere and heated at 60 °C. Et_3N (1.23 g, 0.33 equiv based on fructose equivalents) was then added. The temperature was raised to 85 °C, and the reaction was continued for 1 h at 85 °C. Then 3.55 g (0.3 equiv) of tetradecanoyl phosphonate (C14) was added, in order to obtain a DS of 0.29.

After the reaction was heated for 24 h, it was poured into 200 mL of dry dichloromethane under vigorous stirring. The inulin derivative crystallized immediately and was filtered over a sintered glass filter. The modified inulin was washed with dichloromethane and acetone to remove the NMP and some remaining acyl phosphonate. The resulting powder was dried under high vacuum (crystallization yield: 84%).

General Esterification of Inulin with NaH as Base. Inulin (6.0 g, 37.0 mmol of fructose equivalents) was dissolved in 20 g of *N*-methylpyrrolidinone at 50 °C. The solution of inulin in NMP was

evaporated under high vacuum up to a 40% (w/w) solution in order to remove moisture that is present in the inulin−NMP system. After stripping of the water, the inulin solution was transferred to a round-bottom flask of 100 mL under a nitrogen atmosphere and heated at 60 °C. NaH (0.2 g, 0.22 equiv based on fructose equivalents) was then added. The temperature was raised to 85 °C. After stirring until the reaction mixture became homogeneous, 2.89 g (0.2 equiv) of octadecanoyl phosphonate (C18) was added, in order to obtain a DS of 0.19.

After the reaction was heated for 7 h, it was poured into 200 mL of dry dichloromethane under vigorous stirring. The inulin derivative crystallized immediately and was filtered over a sintered glass filter. The modified inulin was washed with dichloromethane and acetone to remove the NMP and some remaining acyl phosphonate. The resulting powder was dried under high vacuum (crystallization yield: 96%).

Spectroscopic data for a representative dodecanoyl inulin (C12) are presented: ^{1}H NMR: δ (ppm, 300 MHz, DMSO-d_6, 20 °C, 16 scans): 0.83 (3H, br.t., CH_3); 1.00−1.21 (16H, br.s., $(CH_2)_8$); 1.30−1.55 (2H, br.s., $(CH_2)_\beta$); 2.2−2.4 (2H, br.t., $(CH_2)_\alpha$); 3.3−3.6 (5H, br.m., CH_2 at pos. 6 and 1 and CH at pos. 5), 3.70−3.85 (1H, br.s., CH at pos. 4); 3.9−4.0 (1H, br.s., CH at pos. 3); 4.5−5.5 (3H, m, 3OH).

Only the integrations of the peaks are changing with a changing degree of substitution (DS) of the sample and an increase or a decrease in the length of the acyl chain. The DS was determined using ^{1}H NMR and was calculated from the ratio of the integration of the CH_3 signal of the acyl side chain and the integration of the inulin signals.

^{13}C NMR δ (ppm, 75 MHz, DMSO-d_6, 50 °C, 4000 scans): 14.48 (CH_3); 22.68 (CH_2); 24.94 (CH_2); 29−31 ($(CH_2)_6$); 31.90 (CH_2); 33.84 (CH_2); 62.1−62.3 (CH_2 at pos. 1 and at pos. 6); 74.4−74.8 (CH at pos. 4); 77.3−77.7 (CH at pos. 3); 82.38 (CH at pos. 5); 103.6−103.9 (C_{quat} at pos. 2); 173.58 (C═O).

From these spectroscopic data no conclusions could be drawn regarding the regioselectivity toward a certain hydroxyl group of the inulin backbone. It is, however, known that the C3 and C4 hydroxyl groups are more reactive compared to the C6 hydroxymethyl group. The degree of substitution (low DS) can be calculated as follows: DS = integration(CH_3_sidechain)/integration(3OH_inulin). IR (cm^{-1}, KBr): 3385 (OH); 2930 (CH); 1710 (C═O).

Emulsion Preparation. Oil-in-water emulsions with a 50/50 (v/v) ratio were prepared on a 50 mL scale. Therefore, 0.5 g of the inulin surfactant (2%) was dissolved in 25 mL of demineralized water or 1 M $MgSO_4$ to which 25 mL of Isopar M oil was added. The emulsions were prepared using a high speed mixer in a multistep mixing procedure: 2 min at 9500 rpm followed by 1 min at 13500 rpm, 45 s at 20500 rpm, and a final step of 1 min at 24000 rpm. During the first mixing step, the oil phase was added slowly to the water phase that contained the inulin-based surfactant. Then, the emulsion was poured from a 50 mL beaker into a 100 mL beaker, and the mixing procedure was continued. The resulting emulsion was divided into two bottles: one-half was stored at room temperature, while the other one was kept in an oven at 50 °C.

Results and Discussion

NMP was chosen as solvent for the esterification of inulin with acyl phosphonates, because of the major malodor when DMSO or DMSO/NaH were used for the modification of inulin, which was reported for the esterification using methyl esters.[11] For the evaluation of the method, inulin was dissolved in NMP as a 40% solution and heated up to 80 °C. Stirring was continued at elevated temperature for 24 h, and the end product was purified via nonsolvent crystallization in, for example, acetone.

During the reaction (Figure 2), phosphite is expelled and is removed during the crystallization in acetone or dichloromethane. After that, any remaining phosphite is removed by means of high vacuum evaporation. ^{31}P NMR confirmed the absence of any phosphorus containing compound in the purified end products.

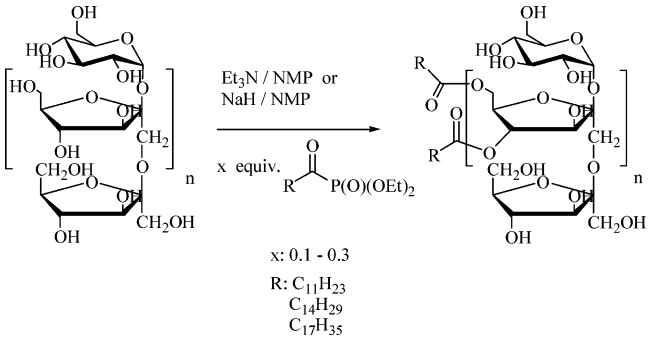

Figure 2. Esterification of inulin using acyl phosphonates.

In the absence of base, a typical reaction efficiency of 30% could be obtained, which could be increased up to 97% upon addition of Et_3N (1.1 equiv based on acyl phosphonate). Therefore, this reaction was studied into detail using long chain acyl phosphonates C12−C18 (Table 1). Several derivatives, with varying degrees of substitution and chain lengths, were synthesized for their evaluation in emulsion stabilization.

It is clear from Table 1 that the efficiency of the esterification of inulin with acyl phosphonates is much higher using less stringent conditions than the reaction with methyl esters described before. For all the derivatives, the reaction time was initially kept at 20 h and the reaction temperature at 80 °C.

Also NaH was evaluated as base for the esterification in order to realize a reduction of the reaction time. When performing the reaction in NMP with 1.1 equiv of NaH, again a typical reaction efficiency of 96%, calculated on the amount of acyl phosphonates (Table 2), was reached. In addition, the reaction time could be reduced to 2 h.

In order to evaluate the inulin esters in 50/50 (v/v) oil-in-water (O/W) emulsions, 2% (w/v) of inulin-based surfactant was used, since previous research indicated that this was the best surfactant concentration for hydrophobized inulin derivatives. The emulsion stability was checked using a microscope and visually, looking for small oil droplets on the surface, which indicates coalescence and hence instability. Emulsions were not only prepared with demineralized water, but also using 1 M $MgSO_4$ in order to study the influence of electrolytes. NaCl could also have been used, but bivalent ions have a more significant influence on the emulsion stability than monovalent ions.

For the evaluation and the comparison of their properties, the inulin esters were synthesized via two different methods: using methyl esters and using acylphosphonates. Using methyl esters, again 2 methods were used: NaOMe in NMP or NaH in DMSO. The influence of the method of preparation on the emulsion stability was distinct, which can be explained by impurities, which could influence the emulsion stability. The method in DMSO, using NaH as a base, resulted in inulin derivatives with moderate to good emulsifying properties. The emulsions prepared with this type of inulin ester were stable for less than 1 year, while the derivatives prepared with NaOMe led to more stable emulsions (Table 1 vs Table 2). From a synthetic point of view, the method with NaOMe was already considered as the better method, regarding reaction efficiency and applicability on larger scale.[11] Not only the purification method, but also the length of the acyl chain has a big influence on the emulsion stability. The emulsions prepared with inulin hexanoate were only stable for a couple of days, while some of

Table 1. Esterification of Inulin with Acyl Phosphonates, Using Et_3N as Base

	targeted DS		
acyl chain	0.1	0.2	0.3
yield of C_{12} **15c** (obt ained DS[a])	99% (DS = 0.10)	90% (DS = 0.20)	75% (DS = 0.30)
yield of C_{14} **15d** (obtained DS[a])	95% (DS = 0.09)	99% (DS = 0.20)	84% (DS = 0.30)
yield of C_{18} **15e** (obt ained DS[a])	98% (DS = 0.10)	95% (DS = 0.16)	98% (DS = 0.30)

[a] The DS was determined using ^{1}H NMR and was calculated from the ratio of the integration of the CH_3 signal of the acyl side chain and the integration of the inulin signals.

Table 2. Esterification with Acyl Phosphonates, Using NaH as Base

	targeted DS		
acyl chain	0.1	0.2	0.3
yield of C_{12} **15c** (obtained DS[a])	98% (DS = 0.10)	91% (DS = 0.19)	98% (DS = 0.28)
yield of C_{14} **15d** (obtained DS[a])	96% (DS = 0.10)	99% (DS = 0.20)	84% (DS = 0.30)
yield of C_{18} **15e** (obtained DS[a])	99% (DS = 0.10)	95% (DS = 0.19)	98% (DS = 0.26)

[a] The DS was determined using ^{1}H NMR and was calculated from the ratio of the integration of the CH_3 signal of the acyl side chain and the integration of the inulin signals.

Table 3. Emulsion Stabilities of Inulin Esters, Prepared with Fatty Acid Methyl Esters, Using NaOMe in NMP

side chain	additive (to water phase)	stability at 50 °C (days)[a]
hexanoyl	-	6
octanoyl	-	480
dodecanoyl	-	490
hexadecanoyl	-	490
octadecanoyl	-	480
octanoyl	1 M $MgSO_4$	170
dodecanoyl	1 M $MgSO_4$	150
hexadecanoyl	1 M $MgSO_4$	175
octadecanoyl	1 M $MgSO_4$	170

[a] The stability of the emulsion was determined by the occurrence of coalescence of oil in the samples.

Table 4. Emulsion Stabilities of Inulin Esters, Prepared with Fatty Acid Methyl Esters, Using NaH/DMSO

acyl chain	additive (to water phase)	stability at 50 °C (days)[a]
octanoyl	-	130
dodecanoyl	-	300
octadecanoyl	-	190
octanoyl	1 M $MgSO_4$	135
dodecanoyl	1 M $MgSO_4$	135
octadecanoyl	1 M $MgSO_4$	0

[a] The stability of the emulsion was determined by the occurrence of coalescence of oil in the samples.

the derivatives with longer acyl chains were stable for over more than 1 year at 50 °C. When the inulin stability in electrolyte medium was evaluated, the stability decreased considerably (Table 3). The most stable compounds in 1 M $MgSO_4$ showed no oil separation when stored at 50 °C for 6 months.For the method using NaOMe, the difference between the various chain lengths is not that significant, but in general and based on the appearance of the emulsions, it can be concluded that the best results were obtained when methyl dodecanoate, methyl hexanoate, or methyl octadecanoate were used as acylating agents. When higher degrees of substitution (>0.3) were produced, the appearance of the emulsions deteriorated and flocculation became more and more significant. The most stable emulsion was obtained with octadecanoyl inulin (with a DS < 0.3) and resulted in a stability of 490 days with demineralized water and of 175 days with 1 M $MgSO_4$ (Table 4).

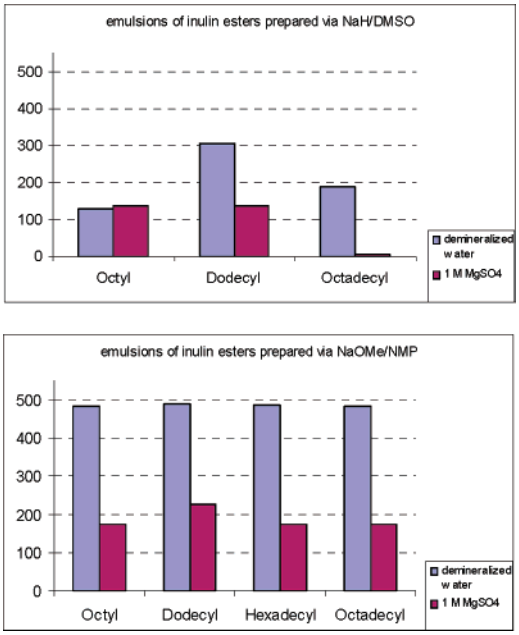

Figure 3. Comparison of emulsion stabilities (in days) in demineralized water and 1 M $MgSO_4$ (inulin esters prepared using the fatty acid methyl ester method).

Table 5. Emulsion Stabilities of Inulin Esters, Prepared with Acyl Phosphonates

	stability at 50 °C (days)	
acyl chain	prepared with NaH	prepared with Et_3N
dodecanoyl	120	90
tetradecanoyl	300	140
octadecanoyl	300	140

For the NaH/DMSO method, the emulsions were less stable. The most stable emulsions were obtained with the dodecanoyl and the octadecanoyl inulin derivatives. In the presence of the electrolyte $MgSO_4$, however, only the octanoyl inulin and the dodecanoyl inulin resulted in emulsions with stabilities of 6 months (Figure 3). Using the inulin esters, prepared with the acyl phosphonates as acylating agents, again emulsion stabilities of several weeks up to several months were not exceptional. The most stable emulsions were obtained with longer acyl chains on the inulin backbone. In general, it has to be mentioned that all the emulsions were very coarse and showed a large droplet size under the microscope; however, previous research showed

that the droplet size could be easily reduced using an oil soluble cosurfactant, like 0.4 (w/v)% Span 20, due to the significant reduction in surface tension. Droplet sizes of 10 μm are not unusual using inulin-based surfactants; however, addition of Span 20 reduces the droplets to less than 4 μm. These findings show that the inulin-based surfactants should be considered to be emulsion-stabilizing agents rather than actual emulsifying agents. This can also be deduced from the fairly large molecular structure of inulin and its derivatives, because heavier molecules migrate more difficult to the interface of the oil-in-water emulsion. All emulsions also showed severe flocculation and creaming (the appearance of a small water layer at the bottom of the emulsions) within the first days.

In general, the method using NaH instead of Et_3N to produce inulin esters resulted in products with better emulsifying properties. It was concluded that the derivatives prepared with octadecanoyl and tetradecanoyl phosphonates, with a DS of 0.2 and 0.3, showed the best emulsifying properties.

Conclusion

In summary, the esterification of inulin using acyl phosphonates in the presence of sodium hydride results in a better and more efficient method using milder reaction conditions than the methods described previously by our group using fatty acid methyl esters (FAME) and thus proves to be a superior method. Within the FAME methods, the method using NaOMe in NMP proved to be better from a synthetic point of view than the methods using DMSO in relation to reaction efficiency and applicability on large scale.

Since the emulsion stabilities of the esterified inulin derivatives (by the FAME method as well as the acylphosphonate method) were not known up to know, an initial comparative study has been made to screen interesting derivatives rapidly. Although the chain length of the grafted acyl chains (FAME methods) is influencing the stability, it does not affect the stability significantly; derivatives with longer acyl chains, such as the dodecanoyl, hexadecanoyl, or octadecanoyl derivatives, with degrees of substitution less than 0.5 are preferred. These inulin-based surfactants can give rise to emulsions, which are stable for over 1 year at 50 °C in the absence of electrolytes and for over 6 months in 1 M $MgSO_4$.

Using acyl phosphonates and NaH to prepare the esters, the emulsions were more stable than those prepared with the inulin esters, synthesized with Et_3N. In general there is no distinct difference in emulsion-stabilizing capacity between inulin esters, prepared with methyl esters or with acyl phosphonates, although the esters prepared with methyl esters tend to result in slightly more stable emulsions.

Inulin-based surfactants lead to emulsions with rather large droplets, which can be reduced by the addition of an oil soluble cosurfactant. Furthermore, all the emulsions showed creaming and severe flocculation. Creaming can easily be solved when adding a thickening agent. The flocculation, however, is a more important problem for the introduction of new inulin esters onto the market.

References and Notes

(1) Tadros, T. F. Polymeric Surfactants: Stabilization of Emulsions and Dispersions. In *Principles of Polymer Science and Technology in Cosmetics and Personal Care*; Goddard, E. D., Gruber, J. V., Eds.; Marcel Dekker: New York, 1999.

(2) Tadros, Th. F., Vandamme, A.; Levecke, B.; Booten, K.; Stevens, C. V. *Adv. Colloid Interface Sci.* **2004**, 108−109, 207−226.

(3) Pirma, I. *Polymeric Surfactants*; Marcel Dekker: New York, 1982.

(4) Douglas, A. K.; Bernard, Y. T. *J. Surfactants Deterg.* **1999**, *2* (3), 383−390.

(5) Menger, F. M.; Mbadugha, B. N. A. *J. Am. Chem. Soc.* **2001**, *123*, 875−885.

(6) Oostveen, E. A.; Weijnen, J.; Van Haveren, J.; Gillard, M. PCT WO 03064498, 2003; *Chem. Abstr.* **2003**, *139*, 165937.

(7) Bognolo, G.; Gunstone, F. D.; Padley, F. B.; Eds. In *Lipid Technologies and Applications*; Marcel Dekker: New York, 1997; p 633.

(8) Stevens, C. V.; Meriggi, A.; Booten K. *Biomacromolecules* **2001**, *2*, 1−16.

(9) Booten, K.; Levecke, B.; Stevens, C. V. PCT WO 03031043, 2003; *Chem. Abstr.* **2003**, *138*, 323336.

(10) Stevens, C. V.; Meriggi, A.; Peristeropoulou, M.; Christov, P. P.; Booten, K.; Levecke, B.; Vandamme, A.; Pittevils N.; Tadros, T. F. *Biomacromolecules* **2001**, *2*, 1256−1259.

(11) Rogge, T. M.; Stevens, C. V. *Biomacromolecules* **2004**, *5*, 1799−1803.

(12) Suzuki, T.; Amano, I.; Chiba, K.; Tofukuji, R. Eur. Patent 0736545, 1996; *Chem. Abstr.* **1996**. Cruces, M. A.; Plou, F. J.; Ferrer, M.; Bernabe, M.; Ballesteros, A. *J. Am. Oil Chem. Soc.* **2001**, *78*, 541−546.

(13) Ward, F. M. WO PCT 02069981, 2002; *Chem. Abstr.* **2002**, *137*, 237723.

(14) Wurzburg, O. B.; Caldwell, C. G. US Patent 2661349, 1953; *Chem. Abstr.* **1954**, *48*, 9428.

(15) Wurzburg, O. B.; Caldwell, C. G. US Patent 2654836, 1953; *Chem. Abstr.* **1954**, *48*, 5626.

(16) Erhardt, S.; Haji, Begli, A.; Kunz, M.; Sheiwe, L. US Patent 5877144, 1999; *Chem. Abstr.* **1997**, *127*, 249640.

(17) Ferrer, M.; Cruces, M. A.; Bernabe, M.; Ballesteros, A.; Plou, F. *J. Biotechnol. Bioeng.* **1999**, *65*, 10−16.

(18) Cruces, M. A.; Plou, F. J.; Ferrer, M.; Bernabe, M.; Ballesteros, A. *J. Am. Oil Chem. Soc.* **2001**, *78*, 541−546.

(19) Oostveen, E. A.; Weijnen, J.; Van Haveren, J.; Gillard, M. PCT WO 03064498; *Chem. Abstr.* **2003**, *139*, 165937.

(20) Berlin, K. D.; Hellwege, D. M.; Nagablushaman, M. *J. Org. Chem.* **1965**, *30*, 1265−1267.

(21) Ackerman, B.; Jordan, T. A.; Eddy, C. R.; Swern, D. *J. Am. Chem. Soc.* **1956**, *78*, 4444−4447.

(22) Costisella, B.; Keitel, I.; Gross, H. *Tetrahedron* **1981**, *37*, 1227−1232.

(23) Glebova, Z. I.; Uzlova, L. A.; Zhdanov, Y. A. *Zh. Obshch. Khim.* **1985**, *55*, 1435−1437.

(24) Abramov, V. S. *J. Gen. Chem. USSR* **1952**, *22*, 709−713.

(25) Pudovik, A. N.; Kitaev, Y. P. *J. Gen. Chem USSR* **1952**, *22*, 531−535.

(26) Afarinkia, K.; Echenique, J.; Nyburg, S. C. *Tetrahedron Lett.* **1997**, *38*, 1663−1666.

(27) Sekine, M.; Satoh, M.; Yamagata, H.; Hata, T. *J. Org. Chem.* **1980**, *45*, 4162−4167.

(28) Sekine, M.; Kume, A.; Hata, T. *Tetrahedron Lett.* **1981**, *22*, 3617−3620.

(29) Breuer, E. Acyl phosphonates and their derivatives. In *The Chemistry of Organophosphorous Compounds*; Hartley, F. R., Ed.; Wiley: New York, 1996; Vol. 4, pp 653−729.

(30) Hubrechts, AOACS methods no. 997.08. *J. AOAC Int.* **1997**, *80*, 1029.

BM060592Z