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Research paper

Material and tablet properties of pregelatinized (thermally modified) *Dioscorea* starches

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Abstract

The material and tablet formation properties of pregelatinized (thermally modified) forms of four *Dioscorea* starches have been investigated. *Dioscorea* starches were pregelatinized followed by either oven drying (PS) or freeze drying (FD) and used as excipient in direct compression. The physicochemical, morphological and material properties of the pregelatinized starches have been investigated. The tablet formation properties were assessed using the 3-D modeling parameters, the Heckel equation and the force–displacement profiles. The tablet properties were evaluated using the elastic recovery, compactibility plots and the disintegration test. The results indicate that pregelatinization improved the compressibility and flowability of the *Dioscorea* starches. The high bulk and tap densities of PS coupled with their good flowability offer a unique possibility of the starches being used as filler in capsule formulations. The modified starches generally showed differences in their time and pressure dependent deformation behaviour. PS exhibited higher elasticity during tableting. FD Chinese and FD Bitter showed higher plasticity and low fast elastic deformation than the PS forms of the starches indicating that the FD starches undergo the highest plastic deformation. However, FD starches generally showed higher compactibility compared to the PS forms of the *Dioscorea* starches. While FD White and FD Water showed fast disintegration time and high compactibility, FD Chinese and FD Bitter were non-disintegrating and showed high compactibility. The high compactibility observed with the FD starches appears to be as a result of material change occurring during tableting probably due to the effect of temperature or pressure or a combination of both factors. Thus, FD White and FD Water starches could be useful when high crushing force and fast disintegration are of concern while FD Chinese and FD Bitter, which were non-disintegrating, could find application as excipients for controlled drug delivery.

Keywords: Pregelatinized starch; Material properties; Tableting; *Dioscorea* starches; Yam

1. Introduction

Starch in general plays a prominent role in the production of pharmaceutical tablets. Tropical yam tubers are another potential starch source that could be used in the food and pharmaceutical industries that have not been explored commercially [1]. Previous studies on the material and tablet properties of starches from four different tropical *Dioscorea* (yam) species, namely White yam (*Dioscorea rotundata*), Bitter yam (*D. dumetorum*), Chinese yam (*D. oppositifolia*) and Water yam (*D. alata*), have shown that the four starches varied considerably in their physicochemical and material properties. The amylose content of the starches was 28.8%, 21.6%, 18.8% and 23.3% for White, Bitter, Chinese and Water starches, respectively. Furthermore, Chinese and Bitter yam starches were highly compressible and formed tablets of acceptable crushing force while White and Water yam starches showed poor compression properties and formed weak tablets even at very high compression pressures [2]. When comparing native starches in their applicability for tablet compression

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purposes, yam starches provided much better compaction properties [2]. Moreover, the high starch (70–80% dry basis) content of yam tubers and cheap cost makes them good candidates for the production of industrial starch. However, native *Dioscore*a starches generally exhibited poor flow properties characteristic of other native starches [3].

Physical and chemical modifications have been used to improve the compaction properties of some native starches [4–11]. Typical physical modifications include pregelatinization, particle size and moisture adjustment. Starches from corn, waxy maize, wheat and potato with different amylose/amylopectin ratios have been thermally modified by extrusion [6,7], drum drying [6–8] and controlled pregelatinization-spray drying techniques [7]. The process of gelatinization causes substantial changes in both the chemical and the physical nature of granular starch due to the rearrangement of intra- and intermolecular hydrogen bonding between the water and starch molecules resulting in the collapse or disruption of molecular orders within the starch granule [3]. This results in irreversible changes in the starch properties [12]. Evidence of the loss of an organized structure includes irreversible granule swelling, loss of bifringence and crystallinity [13,14].

To date, most studies on the production of modified starches have been limited to widely available starches such as corn, potato, wheat, tapioca and rice [6–11]. Modified starches from other botanical sources may yield starches with special properties and offer a wide range of functional properties permitting numerous applications. So far, no work has been done to evaluate the usefulness of thermally modified yam starches as directly compressible excipients in tablet formulation. Thus the aim of the present work is to investigate the compaction properties of four *Dioscorea* starches which were modified by pregelatinization followed by either oven drying or freeze drying. The tablet formation properties were assessed using the 3-D modeling parameters, the Heckel equation and the force–displacement profiles, while the properties of the starch tablets were evaluated using the elastic recovery, compactibility plots and disintegration test. The physicochemical, morphological and material properties of the pregelatinized starches were also investigated.

2. Materials

Tubers of four different *Dioscorea* species namely White yam – *Dioscorea rotundata* L., Bitter yam – *D. dumetorum* Kunth, Chinese yam – *D. oppositifolia* L. and Water yam – *D. alata* L. DIAL2 were obtained from local farmers in Ibadan, Nigeria. The starches were extracted from the relevant tubers using established procedures [15]. In the following text only the abbreviations FD will be used for freeze-dried pregelatinized starch and PS will be used for pregelatinized oven dried starch while White, Bitter, Chinese and Water will be used for the starches, respectively. All materials and tablets were equilibrated, produced and stored at 22 ± 1 °C and 45 ± 2% relative humidity (RH).

3. Methods

3.1. Preparation of pregelatinized starches

The pregelatinized forms of the *Dioscorea* starches were prepared using established methods [7]. 20% w/v aqueous starch slurry was heated at 80 °C with stirring for 15 min. For the oven dried pregelatinized starch (PS), the resultant paste was dried in a hot air oven at 40 °C for 24 h and then powdered using a laboratory mill. All the starches were passed through a 125 μm mesh sieve.

Freeze-dried pregelatinized starch (FD) was prepared by freeze drying the pregelatinized starch in a freeze dryer (Christ GmbH, Osterode, Germany) at −84 °C and pressure of −0.371 bar for 24 h.

3.2. Swelling power and solubility

The swelling and solubility properties of the starches in cold water (22 ± 1 °C) and hot water (85 ± 1 °C) were assessed using established methods [16,17]. Starch suspensions (1% w/w) were prepared in a flask and heated to appropriate temperature for 30 min with shaking every 5 min and left to cool at room temperature and centrifuged for 15 min at 3000*g*. The supernatant was decanted and dried in an oven for 2 h at 130 °C. The residue obtained after drying was weighed to obtain the swelling of the starch [16]. The solubility was calculated as *g* per 100 g of sample on dry weight basis.

3.3. X-ray powder diffraction

The X-ray diffraction pattern was recorded with Co-Kα_1 X-ray radiation (STOE STADI-MP diffractometer, STOE & Cie GmbH, Darmstadt, Germany). The starch powders tightly packed in a sample holder were exposed to X-ray beam at 40 kV and 30 mA. The scanning region of the diffraction angle (2θ) was from 3° to 50°. The total run time was 100 min.

3.4. Scanning electron microscopy

The starch powders and tablets (upper surface and breaking surface) were analysed using scanning electron microscopy (ESEM 30, Philips, Kassel Germany) at an accelerating voltage of 5 keV.

3.5. Water content

The water content was determined by thermogravimetric analysis using TGA 209 in triplicate (Netzsch Gerätebau GmbH, Selb, Germany). The powder was heated with 10 K min^{-1} from 20 to 150 °C.

3.6. Sorption isotherms

The sorption isotherms were determined gravimetrically after equilibrating the samples over saturated salt solutions for 7 days in triplicate [18]. The powders were equilibrated at specific RH and after equilibration, the powders were weighed and transferred to the next higher RH starting at 32% RH and up to 90% RH. Desorption was performed by placing the powders in the next lower RH up to 0% RH (phosphorous pentoxide). The water content was calculated on the dry powder weight basis at 0% RH.

3.7. Particle size determination

Particle size distribution was determined by laser light diffraction using a dry powder feeder (Malvern instruments, Worcester, UK, Series 2600 c, 300 mm focal length, beam length 10 mm). The software from Malvern was used to calculate the median particle size (D_{50}), the particle size distribution (*v*/*v*) with parameters for 10% (D_{10}) and 90% (D_{90}) particle size. Determinations were done in quadruplicate and results are given as mean and standard deviation.

3.8. Apparent particle density

The apparent particle density of all equilibrated starches was determined by Helium pycnometry (Accupyc 1330; Micromeritics, Norcross, GA, USA) in triplicate [18,19].

3.9. Bulk and tap density

Bulk and tap density were determined in a 250 mL cylinder using a volumeter (Stampfvolumter STAV 2003, J. Engelsmann AG, Germany). Determinations were performed in triplicate according to the European Pharmacopoeia [20].

3.10. Powder flowability

The flowability of the starches was assessed using the Hausner ratio and the Carr-index [21]. The flow rate of the starch powders was determined using a steel funnel on a Pharmatest flow rate apparatus (Sartorius Pharmatest, Apparatebau GmbH, Hainburg, Germany) with an orifice of 15 mm.

3.11. Tableting

Tableting was performed on an eccentric tableting machine instrumented for pressure and displacement measurement (EK0/DMS, No. 1.0083.92; Korsch GmbH, Germany with an inductive transducer W20 TK; Spectris GmbH, Germany). Displacement measurement was corrected for elastic deformation of the punches and machine. 11 mm diameter flat faced punches (Ritter GmbH, Germany) were used as tooling. Equal volumes of the substances based on apparent particle density were tableted to different graded maximum relative densities ($\rho_{\text{rel, max}}$) of the tablets (precision 0.001) between 0.75 and 0.95. No lubricant was used. The amount of material necessary for each tablet with a given $\rho_{\text{rel, max}}$ was calculated. The powder was manually filled into the die and one compaction cycle was performed. The minimum tablet height under load was held constant at 3 mm and the depth of filling at 13 mm. The production rate was set to 10 tablets per min.

Ten single tablets were produced at each condition and force, time and displacement of the upper punch were recorded for each compaction cycle. Data acquisition was performed by a DMC-plus system (Hottinger Baldwin Messtechnik) and data were stored by BEAM-Software (AMS, Flöha, Germany). Tableting was performed in a climate-controlled room, which was set to 23 ± 1 °C and 45% ± 2% RH.

3.12. Data analysis

For analysing tableting data, to distinguish from noise, only data > 1 MPa were used. For all compaction cycles of each material, normalized time, pressure and $\ln(1/1-D_{\text{rel}})$ according to Heckel [22] were calculated.

3.13. 3-D model

Using the 3-D modeling technique normalized time, pressure and $\ln(1/1-D_{\text{rel}})$ according to Heckel were presented in a 3-D data plot, to which a twisted plane was fitted by the least-squares method according to Levenberg–Marquardt (Matlab) [23]

$$z=\ln\left(\frac{1}{1-D_{\text{rel}}}\right)=((t-t_{\max})\cdot(d+\omega\cdot p_{\max}-p))+(e\cdot p)+(f+d\cdot t_{\max}) \quad (1)$$

where D_{rel} = relative density; t = time; p = pressure;

$$d=\frac{\delta\ln(1/(1-D_{\text{rel}}))}{\delta t},\quad e=\frac{\delta\ln(1/(1-D_{\text{rel}}))}{\delta p},$$

$$f=\ln\left(\frac{1}{1-D_{\text{rel}}}\right),$$

$t_{\max}$ = time at maximum pressure, $p_{\max}$ = the maximum pressure and ω = twisting angle at $t_{\max}$.

The plane is twisted at $t = t_{\max}$. Time plasticity (d), pressure plasticity (e), and fast elastic decompression, the inverse of ω, of the compaction cycles at each tableting condition (material and a given $\rho_{\text{rel, max}}$) were averaged, and means and standard deviations were calculated.

3.14. Heckel function

Heckel describes the decrease of porosity with pressure by first order kinetics [22]. The slope of the Heckel equation was calculated from the linear portion of the compression curve with a correlation coefficient $R \geqslant 0.999$ and the linear portion was determined by building the second deviation of the compression curve. The Heckel slope provides information on the total deformation of the starches during compression.

3.15. Force-displacement profiles

Force-displacement profiles are useful to calculate the different types of energy evolving during tableting [24]. The analysis is based on the compression and the decompression curves of the force–displacement plot. The area between compression and decompression curve is defined as the area of compaction energy ($E2$). The area between maximum displacement and decompression curve is defined as the area of elastic energy ($E3$). $E2$ and $E3$ values were calculated and normalized for tablet weight for 5 compaction cycles. The normalized energies $E2_{\mathrm{norm}}$ and $E3_{\mathrm{norm}}$ are presented.

3.16. Temperature measurement

The temperature at the surface of the tablet was measured from the time of ejection until cooling down to room temperature using an infrared sensor [25]. The infrared sensor (Sensytherm IR-C, ABB AG, Mannheim, Germany) was positioned with a special holder at the die holder of the tableting machine and allowed to collect thermographic sequences of the tablet directly from the moment of ejection of the tablet until cooling down to room temperature. The position of the infrared sensor was the same in all experiments. The temperature of the tablets was analysed as the mean value over the central circular area at the surface of the tablet.

3.17. FT-Raman spectroscopy

The modified starches and scrapped surface of the tablets were analysed using FT-Raman spectroscopy. The spectra were collected on a Bruker RFS 100/S FT-Raman spectrometer (Bruker Optik GmbH, Ettlingen, Germany) using a diode-pumped Nd:YAG with an operating wavelength of 1064 nm. Typical spectra were acquired with 200 scans and a laser power of 200 mW at the sample location. The interferograms were apodized with the Blackman–Harris four-term function and subjected to Fourier transformation to give spectra with a resolution of 4 cm^{-1}.

The effect of heat on the modified starch powders was also analysed. The powder sample was placed in a glass tube and heated up to various temperatures and the FT-Raman Spectra were collected.

3.18. Tablet properties

Elastic recovery after tableting was calculated using the equation of Armstrong and Haines-Hutt [26]:

$$\mathrm{ER}(\%) = 100\frac{H_1 - H_0}{H_0} \quad (2)$$

where ER, elastic recovery, H_1, height of the tablet after 10 days, and H_0, minimal height of the tablet under load. Ten tablets were analysed, and the means and standard deviations were calculated.

Table 1
Swelling and solubility properties of pregelatinized *Dioscorea* starches (Mean ± SD, $n = 3$)

Starch	Cold water (20 ± 1 °C)		Hot water (85 ± 1 °C)	
	Swelling (g/g)	Solubility (%)	Swelling (g/g)	Solubility (%)
PS White	3.90(0.22)	3.88(0.99)	9.79(0.29)	7.94(0.00)
PS Chinese	4.08(0.47)	4.59(0.60)	14.11(0.75)	18.77(0.86)
PS Bitter	5.45(0.69)	4.29(0.15)	11.33(0.13)	13.01(0.60)
PS Water	3.66(0.25)	4.15(0.44)	10.82(0.57)	11.56(1.24)
FD White	5.01(0.22)	1.89(0.30)	12.02(0.19)	6.64(0.18)
FD Chinese	7.94(0.65)	7.65(0.91)	20.70(0.53)	9.15(0.95)
FD Bitter	7.23(0.69)	1.22(0.19)	11.04(0.34)	10.15(0.90)
FD Water	5.32(0.16)	2.12(0.33)	10.98(0.32)	9.82(0.63)

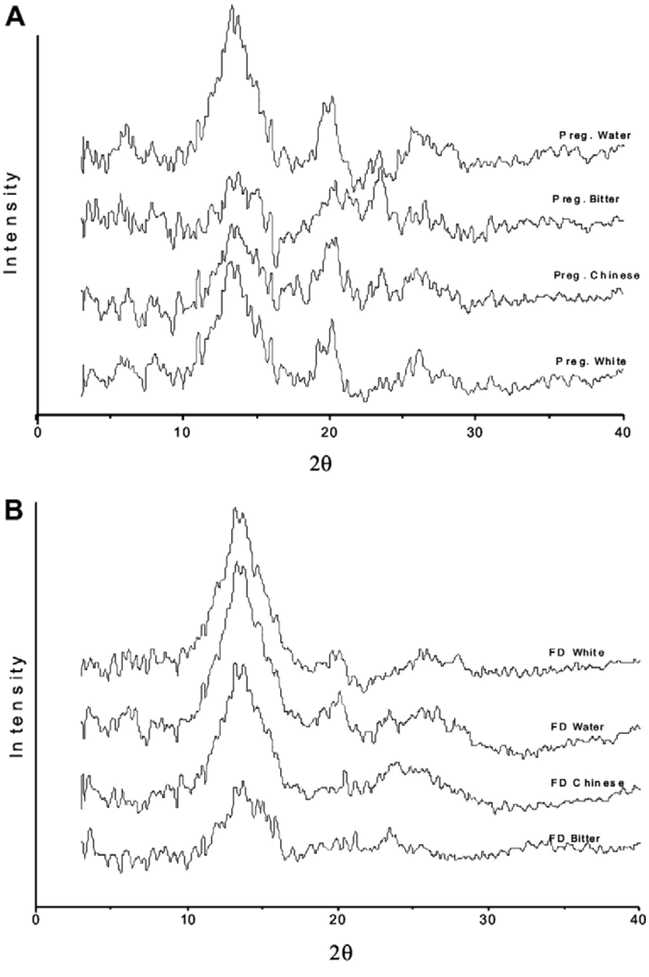

Fig. 1. X-ray powder diffraction pattern of pregelatinized (A) and freeze-dried pregelatinized (B) *Dioscorea* starches.

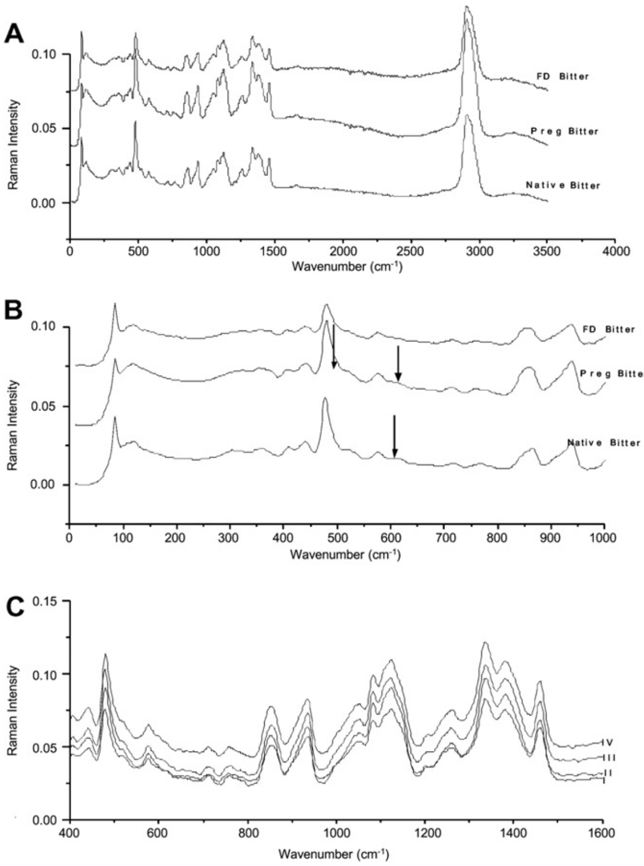

Fig. 2. FT-Raman spectroscopy pattern of native and modified Bitter yam starches (A and B) and FD *Dioscorea* starches (C) I, FD Water; II, FD White; III, FD Chinese; IV, FD Bitter.

3.19. Crushing force

The crushing force of the tablets was determined with the crushing force tester (TBH 30; Erweka GmbH, Germany). Five tablets were analysed 10 days after tableting in all cases, and the means and standard deviations were calculated.

3.20. Disintegration

The disintegration times of the tablets were determined using an Erweka ZT 2 disintegration tester (Erweka Apparatebau GmbH, Heusenstamm, Germany) coupled with a water bath (GFL GmbH, Burgwedel, Germany). Determination was performed for 6 tablets according to the European Pharmacopoeia [20].

3.21. Statistical analysis

Statistical analysis was carried out using analysis of variance (ANOVA) using a computer software GraphPad Prism® 4 (GraphPad Software Inc. San Diego, USA). Tukey–Kramers multiple comparison tests were used to compare the material and tablet properties of the various starches. Values of p less than or equal to 0.05 were considered significant.

4. Results and discussion

4.1. Physicochemical properties

The swelling and solubility properties of the starches in cold water (22.0 ± 1.0 °C) and hot water (85.0 ± 1.0 °C) are given in Table 1. The swelling and solubility of the

Table 3
Particle size distribution (v/v) of pregelatinized *Dioscorea* starches (Mean and SD, $n = 4$)

Starch	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
PS White	42.90(0.54)	104.68(0.26)	144.91(0.32)
PS Chinese	32.63(1.14)	95.19(0.08)	140.21(0.44)
PS Bitter	19.52(0.48)	88.89(0.58)	138.47(3.15)
PS Water	27.19(0.77)	96.76(0.67)	140.14(0.14)
FD White	33.67(0.98)	104.05(0.98)	207.66(0.98)
FD Chinese	5.89(1.57)	32.56(6.40)	206.92(0.90)
FD Bitter	8.42(0.16)	45.49(0.49)	180.03(0.17)
FD Water	22.65(0.36)	54.46(0.26)	166.46(1.01)

Table 2
Raman bands of native and modified Bitter yam starch

Assignment	Native starch	PS starch	FD starch	Scraped tablet surface	At 90 °C
Skeletal modes of pyranose ring	440	442	440	440	442
	477	479	480	480	480
	577	575	575	577	577
	614	–	–	–	–
CH and CH_2 deformation	864	858	852	853	852
Skeletal mode involving -1,4-glycosidic linkage (COC)	940	939	938	936	937
COH deformation	1126	1125	1127	1123	1123
CH_2OH (side chain) related mode	1262	1262	1258	1264	1255
CH_2 twist, COH bending	1339	1337	1339	1337	1336
CH_2 scissoring, CH and COH deformation	1387	1395	1387	1385	1381
CH_2 sym. deformation	1460	1460	1458	1459	1459
CH stretching modes	2910	2909	2910	2906	2908
OH modes				3000–3500	

starches was generally low at low temperatures but increased significantly ($p < 0.01$) at 85 °C. Despite being pregelatinized, the materials retained their capillary activity, and swell to some degree when in contact with water which is in contrast to other modified starches [27]. FD starches showed significantly ($p < 0.01$) higher cold water swellability but lower solubility than PS starches except FD Chinese which showed significantly ($p < 0.01$) higher cold water solubility. However, at 85 °C, there were no significant differences in the swelling properties of the modified starches except for FD White and FD Chinese which showed significantly ($p < 0.01$) higher swelling than the PS forms of the starches. PS forms of the starches generally showed significantly ($p < 0.05$) higher hot water solubility.

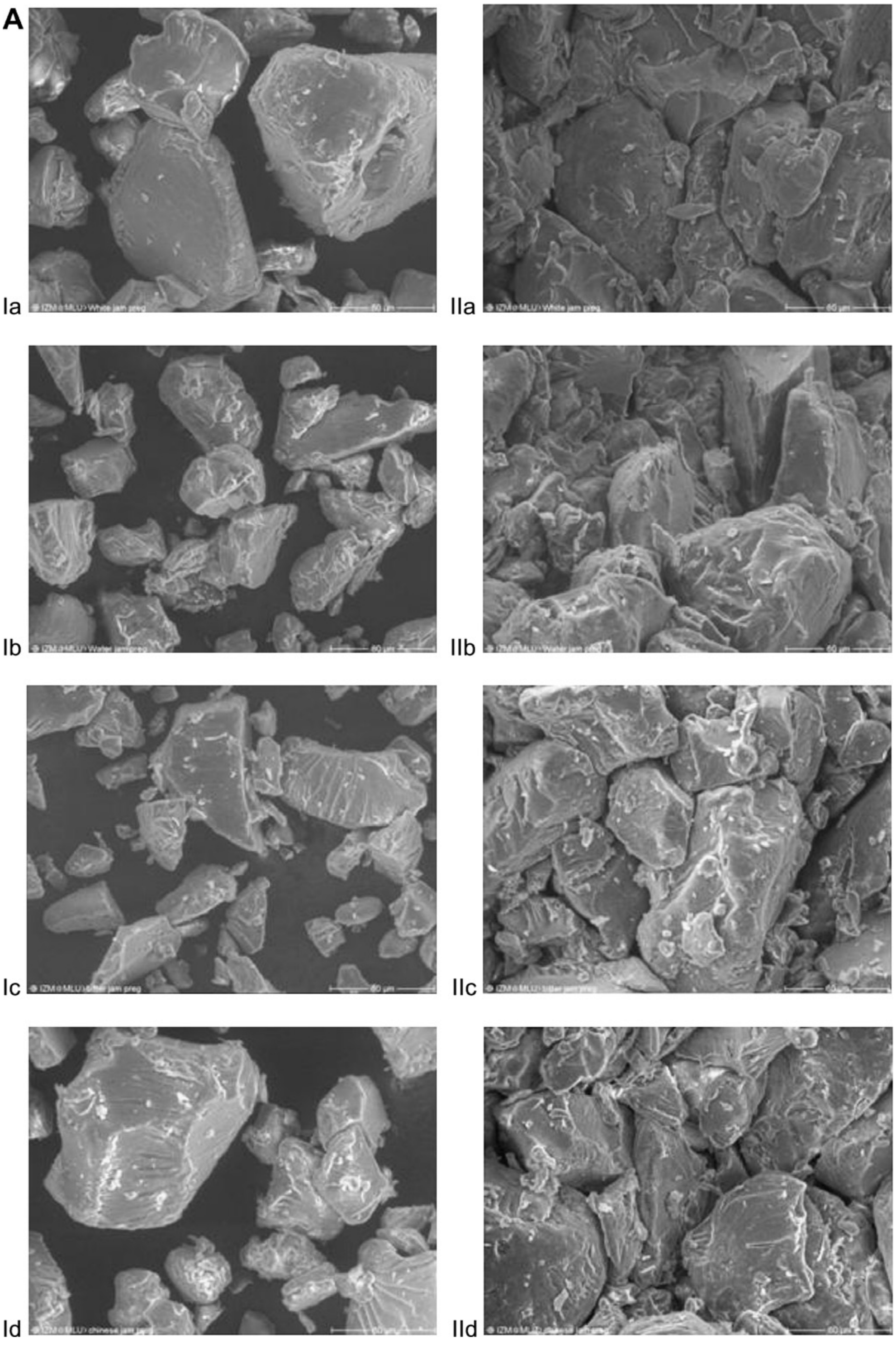

Fig. 3. SEM of modified *Dioscorea* starches (A) – PS starch (i) and tablet (ii), (B) – FD starch (i) and tablet (ii) (a, White; b, Water; c, Bitter; d, Chinese, respectively) and (C) – tablets at $\rho_{\text{rel, max}}$ of 0.90 (i), FD Bitter and (ii) FD Chinese tablets (magnification 1000×).

Thus, the modified starches could be useful for the preparation of various products depending on the desired properties.

The X-ray diffraction patterns of the thermally modified *Dioscorea* starches are presented in Fig. 1. The modified *Dioscorea* starches showed strong reflections at 2θ of 13° and between 22° and 24° 2θ. Native *Dioscorea* starches have been shown to exhibit the C-type diffraction pattern [1,2]. The PS starches, however, showed sharper diffraction peaks than the FD starches. This diffraction pattern is associated with a slight increase in the crystalline region and loss in the amorphous fraction [12]. Thus the PS starches appear to be more crystalline in nature than the FD starches.

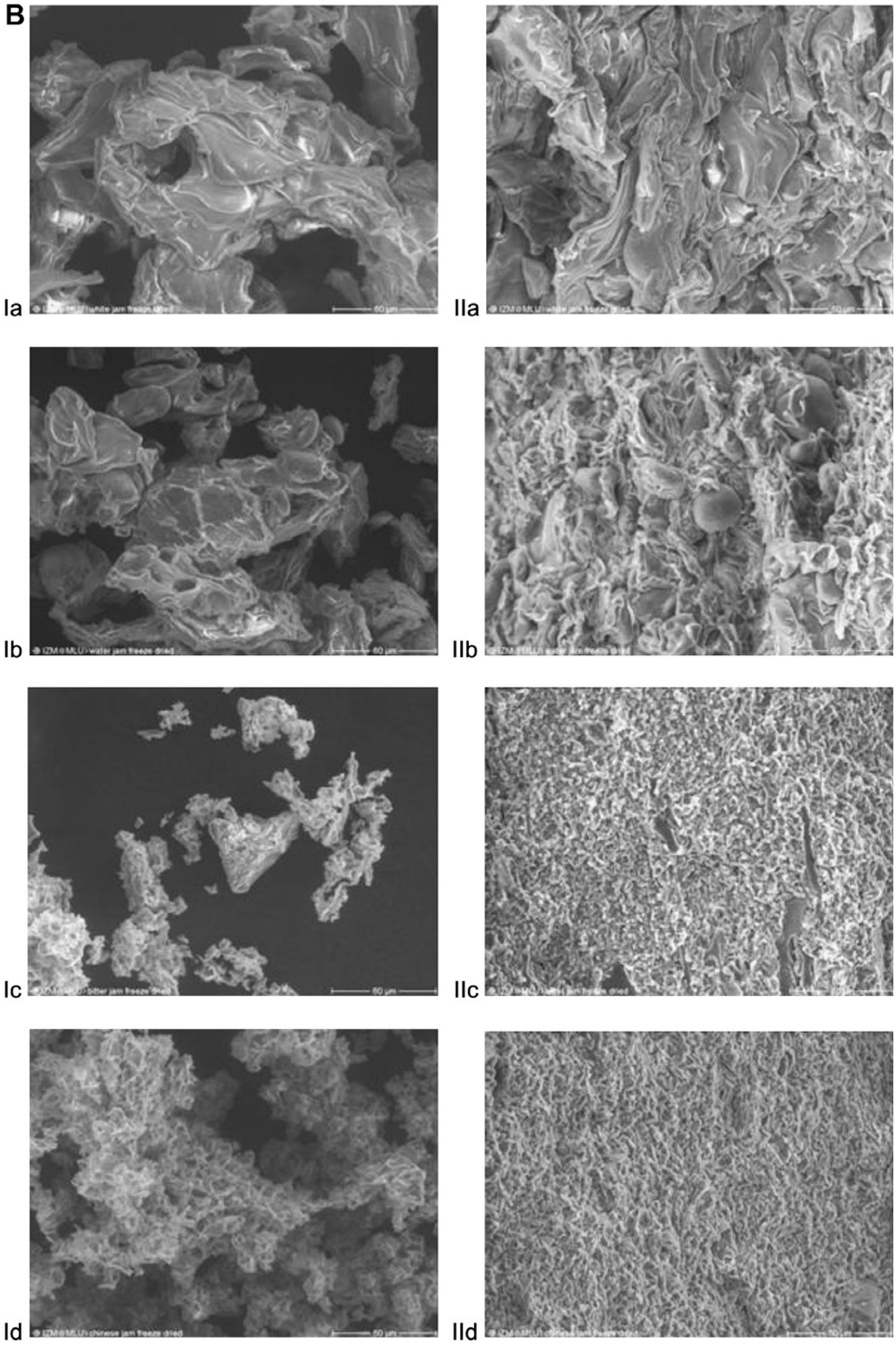

Fig. 3 (*continued*)

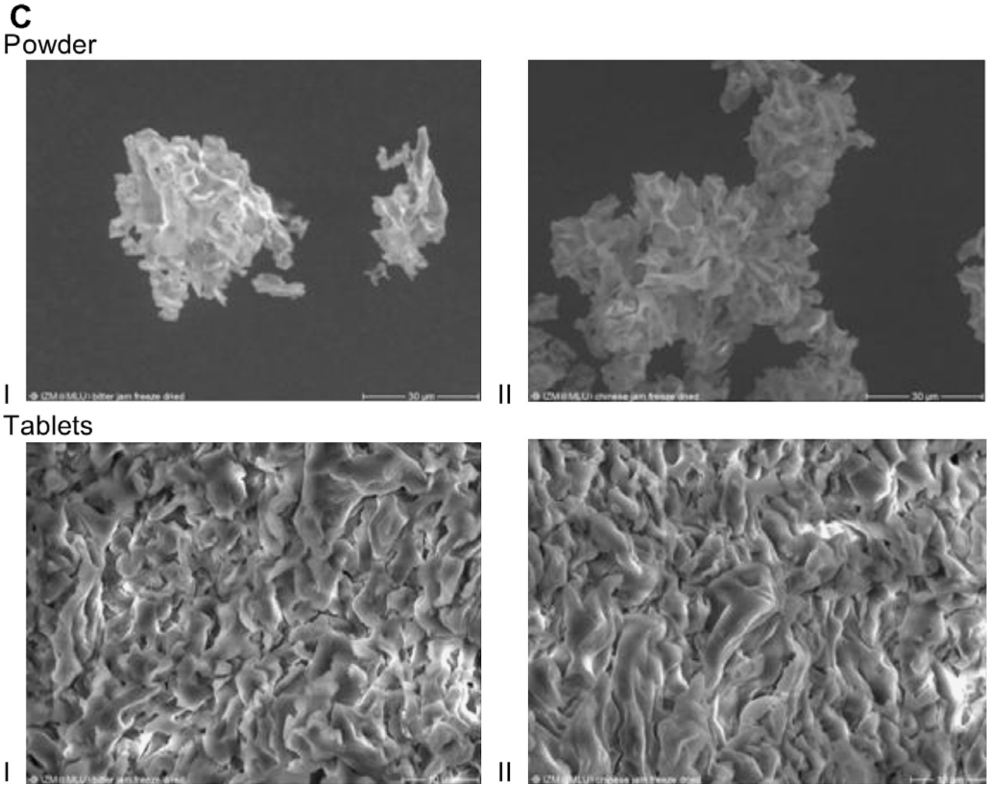

Fig. 3 (*continued*)

The Raman spectra of native and modified forms of Bitter are shown in Fig. 2. Native and modified forms of Bitter showed typical Raman spectra for starches although there were increased intensity observed with the PS starches (Fig. 2A) [2,28]. The Raman bands are shown in Table 2. Physical modifications such as gelatinization causes typical changes in the Raman bands positions and in band shape [28]. The most important difference between the native and modified starches can be observed in the skeletal vibrations below 600 cm^{-1}. Pregelatinization causes typical changes in the Raman bands position and shape. The native starch exhibited a sharp band at 477 cm^{-1} which shifted to 478 cm^{-1} in PS and 480 cm^{-1} in FD starches. Furthermore, the native starch also showed two sharp peaks at about 600 cm^{-1} (Fig. 2B) but a single band was observed for the modified starches. This is similar to previous result by Fechner et al. [28] on other modified starches. Fig. 2C shows the Raman spectra of the FD forms of the various *Dioscorea* starches. The Raman spectra of the starches were similar indicating a similarity in their molecular structure.

4.2. Material properties

The parameters D_{10}, D_{50} (median particle size), and D_{90} are given in Table 3. The SEMs of the modified starches are shown in Fig. 3. The micrographs showed no evidence of the presence of starch granules earlier reported for the native forms of the various species of *Dioscorea* starches [2]. The process of gelatinization causes substantial changes in both the chemical and physical nature of granular starch due to the rearrangement of intra- and intermolecular

Table 4
Powder properties of pregelatinized *Dioscorea* starches (Mean and SD, $n = 3$)

Starch	Moisture content (%)	Apparent particle density (g cm^{-3})	Bulk density (g cm^{-3})	Tap density (g cm^{-3})	Carr Index (%)	Flow rate (s)
PS White	11.64(0.02)	1.515(0.003)	0.664(0.005)	0.833(0.000)	20.35(0.00)	3.60(0.26)
PS Chinese	11.19(0.08)	1.517(0.001)	0.667(0.000)	0.855(0.006)	22.00(0.00)	3.63(0.42)
PS Bitter	10.69(0.10)	1.508(0.001)	0.670(0.005)	0.855(0.007)	21.65(0.00)	4.17(0.76)
PS Water	11.85(0.03)	1.515(0.000)	0.667(0.007)	0.853(0.010)	21.78(0.00)	3.57(0.25)
FD White	12.22(0.08)	1.564(0.003)	0.239(0.005)	0.339(0.000)	29.62(0.00)	–
FD Chinese	10.92(0.12)	1.584(0.003)	0.153(0.001)	0.216(0.000)	29.31(0.00)	–
FD Bitter	10.25(0.02)	1.595(0.010)	0.162(0.001)	0.240(0.001)	32.62(0.00)	–
FD Water	11.31(0.06)	1.545(0.003)	0.193(0.001)	0.275(0.002)	29.66(0.00)	–

–, Not measurable.

hydrogen bonding between water and starch molecules leading to collapse, deformation and loss of granule structure as it has been reported for other starches [3,12].

Thermogravimetric analysis showed that the equilibrated starches had water contents of 10–12% (w/w) (Table 4). There were generally no significant ($p > 0.05$) differences in the water content of the modified starches prepared by both methods. The maximum water content prescribed for safe storage by most starch producing countries is 13% w/w [24]. Higher levels of water have been known to affect the flow and mechanical properties of starches and can lead to microbial spoilage and subsequent deterioration in starch quality [24]. However, pregelatinized starch as an excipient is more consistent in its average water content than unprocessed starch [1]. The sorption isotherms of the starches show that the water content increased with the relative humidity (RH) (Fig. 4) and the water content corresponds with the results from thermogravimetric analysis.

The apparent particle density of the FD starches was generally higher than that of the PS starches. On the other hand, the bulk and tap densities of the PS were significantly ($p < 0.001$) higher than those for the FD starches. The particle size and shape of the modified starches may be responsible for the differences in the density values. The Carr index, which is a measure of the flowability and compressibility of a powder, was significantly ($p < 0.001$) lower for the PS and is characteristic of fairly free flowing material (Table 4) and its flowability is worse than, e.g. for StarLac and better than, e.g. for maize starch [29]. PS flowed through a 15 mm funnel with the flow rate ranging between 3.6 and 4.2 s. FD starches on the other hand did not flow through the funnel and the Carr index indicates poor flow properties. However, the lower the Carr index of a material, the better the flowability, but the poorer the compressibility [21]. Thus, FD starches showed better compressibility than PS. However, FD starches were more loosely packed and showed very low bulk density values. Thus, in tablet production, this may result in problems during die filling. On the other hand, the high bulk and tap densities of PS coupled with their good flowability offer a unique advantage of being used as filler in capsule formulations.

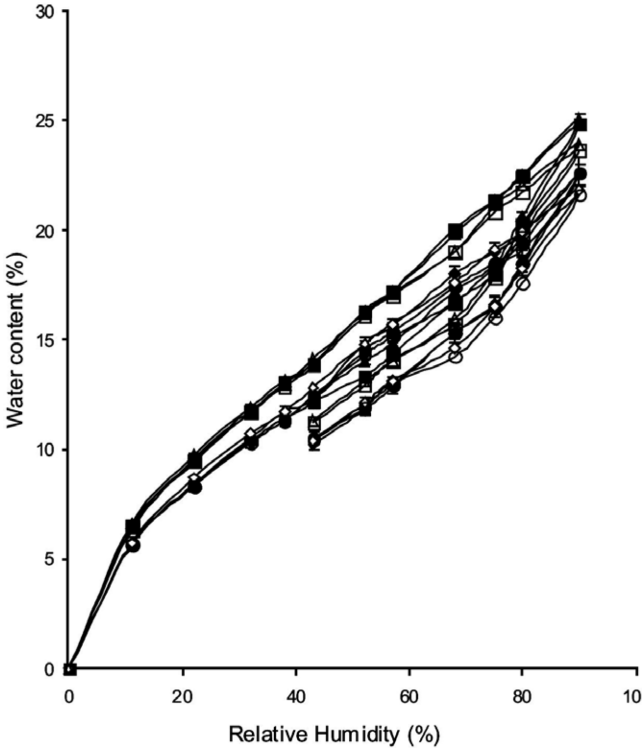

Fig. 4. Sorption Isotherm of pregelatinized (open) and freeze-dried pregelatinized (closed) *Dioscorea* starches: ▲, Water yam; ◆, Chinese yam; ●, Bitter yam; ■, White yam (Mean and SD, $n = 3$).

4.3. Tableting properties

The tableting behaviour of the modified starches was characterized by 3D modeling which allows the simultaneous evaluation of the three most important tableting process variables (normalized time, pressure and density) [30]. The 3-D parameter plots for the starches are given in

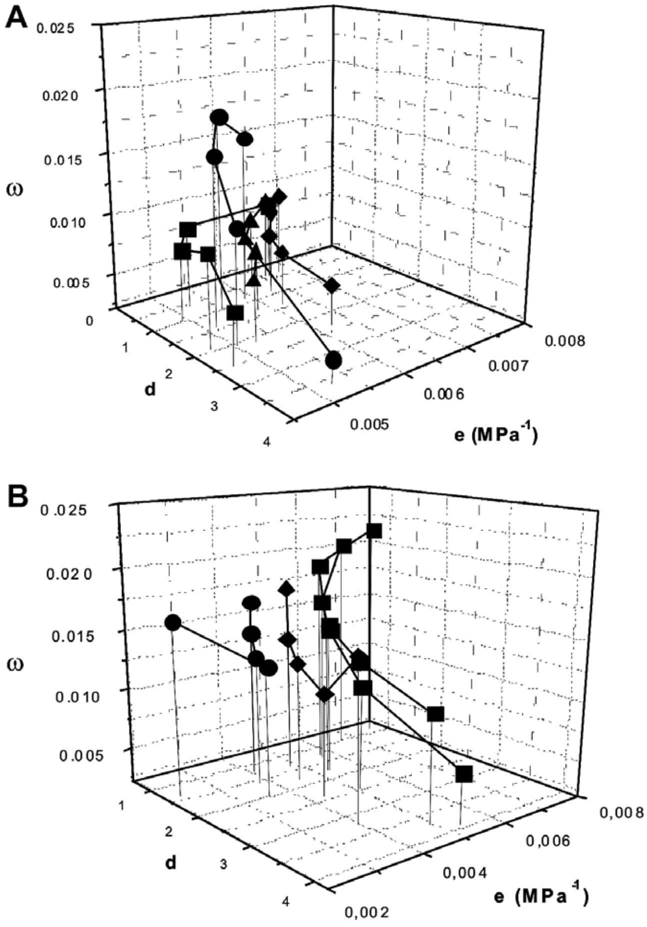

Fig. 5. 3-D parameter plot of pregelatinized oven dried (A) and freeze-dried pregelatinized (B) *Dioscorea* starches: ▲, Water yam; ◆, Chinese yam; ●, Bitter yam; ■, White yam.

Fig. 5, while the parameters and their standard deviations are shown in Table 5. For all modified starches, the time plasticity (d) increased with increasing $\rho_{\text{rel, max}}$ while the pressure plasticity (e) and angle of torsion (ω) decreased except for FD Chinese and FD Bitter which showed minima at $\rho_{\text{rel, max}}$ of 0.90. Increasing time plasticity indicates faster deformation during tableting while decreasing pressure plasticity indicates less pressure-dependent deformation. Furthermore, elasticity is high at low ω-values and strongly decreasing ω-values indicate brittleness [23]. For example, maize starch exhibits ω-values in between 0.000 and 0.005, lactose exhibits decreasing ω-values from 0.022 to 0.003 [29]. Thus, the modified starches exhibit high elasticity combined with some brittleness. Except for FD Chinese and FD Bitter, the elasticity increased with increasing pressure for all the starches. FD Chinese and FD Bitter exhibited a strong increase in ω between $\rho_{\text{rel, max}}$ of 0.90 and 0.95 while the d value increased for FD Chinese and decreased for FD Bitter. This indicates a change in deformation properties of these starches, possibly due to a change in material properties: At increasing pressures starch acts in the beginning elastically, then the particles break and finally the starch deforms more plastically. A similar behaviour has been reported for StarLac [29] and also for Starch 1500 to a less extent [31]. The d values were generally lower for the PS especially at low $\rho_{\text{rel, max}}$ indicating that there were differences in the time dependent deformation of the modified starches. This indicates that PS slowly deform while FD deform faster probably due to their low bulk density. The pressure plasticity (e) was higher for FD White and FD Water than for the PS forms of the starches but lower for FD Chinese and FD Bitter than for the PS forms of the starches. This indicates that FD White and FD Water deform more easily without a lot of pressure than the PS forms of the starches while FD Chinese and FD Bitter would require more pressure to deform than the PS forms. The fast elastic deformation, the inverse of ω, was higher for FD, which indicates that PS exhibits the higher elasticity during tableting [29]. Furthermore, FD Chinese and FD Bitter showed higher plasticity and lower fast elastic deformation (high ω value) than the PS forms of the starches. This is similar to reports in which pregelatinized starch has been stated to have good compression properties and deforms mainly plastically [13,14].

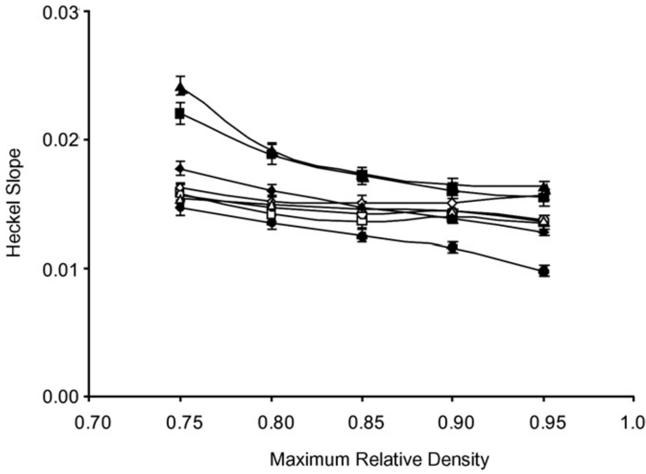

Fig. 6. Heckel slope at different maximum relative densities of pregelatinized (open) and freeze-dried pregelatinized (closed) *Dioscorea* starches: ▲, Water yam; ◆, Chinese yam; ●, Bitter yam; ■, White yam.

The shape of the 3-D plots (Fig. 5) shows that (except for PS Bitter) PS generally had flat plots with decrease in ω values compared to the FD starches. This indicates a

Table 5
The 3-D modeling parameter of pregelatinized *Dioscorea* starches (Mean and SD, $n = 5$)

Starch	$\rho_{\text{rel.max}}$	d	e	ω	Starch	$\rho_{\text{rel.max}}$	d	e	ω
PS White	0.75	0.4009(0.0031)	0.0066(0.0002)	0.0087(0.0004)	FD White	0.75	0.9903(0.0482)	0.0067(0.0005)	0.0204(0.0006)
	0.80	0.6276(0.0102)	0.0052(0.0001)	0.0089(0.0002)		0.80	1.3273(0.0291)	0.0057(0.0001)	0.0163(0.0003)
	0.85	0.9407(0.0078)	0.0049(0.0001)	0.0079(0.0001)		0.85	1.7497(0.0044)	0.0053(0.0000)	0.0146(0.0004)
	0.90	1.9373(0.1162)	0.0047(0.0001)	0.0076(0.0006)		0.90	2.4865(0.0099)	0.0051(0.0000)	0.0109(0.0001)
	0.95	2.5667(0.2590)	0.0047(0.0001)	0.0064(0.0010)		0.95	3.9289(0.0588)	0.0053(0.0001)	0.0062(0.0007)
PS Chinese	0.75	0.3555(0.0020)	0.0068(0.0000)	0.0091(0.0002)	FD Chinese	0.75	1.0627(0.0083)	0.0052(0.0001)	0.0172(0.0004)
	0.80	0.5601(0.0068)	0.0065(0.0001)	0.0082(0.0002)		0.80	1.3728(0.0159)	0.0048(0.0001)	0.0135(0.0001)
	0.85	0.8906(0.0110)	0.0063(0.0000)	0.0070(0.0001)		0.85	1.7592(0.0120)	0.0045(0.0000)	0.0121(0.0001)
	0.90	1.3602(0.0086)	0.0062(0.0001)	0.0064(0.0001)		0.90	2.3681(0.0668)	0.0044(0.0002)	0.0107(0.0012)
	0.95	2.3503(0.0337)	0.0062(0.0000)	0.0053(0.0000)		0.95	3.2421(0.1040)	0.0039(0.0001)	0.0153(0.0009)
PS Bitter	0.75	0.4972(0.2052)	0.0061(0.0001)	0.0152 (0.0064)	FD Bitter	0.75	0.9676(0.0062)	0.0044(0.0001)	0.0166(0.0002)
	0.80	0.9770(0.0244)	0.0055(0.0001)	0.0181(0.0009)		0.80	1.2332(0.0160)	0.0041(0.0001)	0.0144(0.0003)
	0.85	1.4291(0.0425)	0.0051(0.0001)	0.0159(0.0007)		0.85	1.5843(0.0214)	0.0038(0.0001)	0.0129(0.0002)
	0.90	2.0896(0.2020)	0.0050(0.0000)	0.0134(0.0017)		0.90	1.9986(0.0163)	0.0035(0.0001)	0.0129(0.0003)
	0.95	3.6336(0.3062)	0.0053(0.0001)	0.0039(0.0002)		0.95	1.3134 (0.0326)	0.0023(0.0000)	0.0165(0.0003)
PS Water	0.75	0.3723(0.0043)	0.0066(0.0001)	0.0088(0.0001)	FD Water	0.75	0.8943(0.0392)	0.0077(0.0001)	0.0213(0.0011)
	0.80	0.5813(0.0049)	0.0062(0.0001)	0.0080(0.0001)		0.80	1.2505(0.0284)	0.0057(0.0001)	0.0193(0.0007)
	0.85	0.8883(0.0065)	0.0059(0.0001)	0.0071(0.0001)		0.85	1.7418(0.0149)	0.0052(0.0001)	0.0150(0.0005)
	0.90	1.3346(0.0189)	0.0058(0.0000)	0.0070(0.0005)		0.90	2.4050(0.0265)	0.0051(0.0001)	0.0128(0.0006)
	0.95	2.1181(0.0364)	0.0052(0.0002)	0.0069(0.0005)		0.95	3.7265(0.0215)	0.0049(0.0002)	0.0109(0.0029)

more homogeneous bonding facilitating deformation and is similar to the behaviour of other materials such as microcrystalline cellulose. PS Bitter at higher densification showed strongly decreasing ω values while the d and e values remained similar, which is typical for crushing and brittle deformation behaviour [23]. The plot of FD starches also showed a strong decrease in ω values indicating brittle fracture of the material which enhances the formation of new surfaces and thus enhances the formation of bonds between particles [32].

The slope of the Heckel equation indicates the total deformation of a material, and deformation increases with increasing slope of the Heckel equation [22]. The Heckel slopes of the modified starches are shown in Fig. 6. The Heckel slope of the PS and the FD was at a $\rho_{\mathrm{rel,\ max}}$ of 0.85 was similar. It stayed almost constant for all the PS at all $\rho_{\mathrm{rel,\ max}}$. The Heckel slope decreased with increase in $\rho_{\mathrm{rel,\ max}}$ in the rank order of FD Water > FD White > FD Chinese > FD Bitter for the FD starches from about 0.025–0.010. Thus, FD Water showed the highest deformation while FD Bitter exhibited the lowest values. This order is the same as for pressure plasticity (e).

The normalized compaction and elastic energy determined by force–displacement profiles are shown in Fig. 7. The normalized compaction energy, $E2_{\mathrm{norm}}$, was higher for FD than PS starches which indicates that more compaction energy was involved in tablet formation for FD than for PS. The normalized elastic energy, $E3_{\mathrm{norm}}$, was higher for PS than for FD except for FD Bitter at $\rho_{\mathrm{rel,\ max}}$ of 0.95, which indicates that in the tablet formation of PS, more elastic energy was involved. This correlates with the result obtained from the 3-D modeling which indicates that PS deform more elastically compared to FD starches.

The plot of compression pressure versus the $\rho_{\mathrm{rel,\ max}}$ for the various starch tablets is shown in Fig. 8. The plots indicate that there were differences in the compression pressures required to achieve the same $\rho_{\mathrm{rel,\ max}}$ for the various starch tablets. Higher compression pressures were required for FD starches than for PS starches. This results correlate with the compaction energy involved in the tablet formation.

4.4. Tablet properties

The elastic recovery of the tablets was determined at various times and the results are shown in Table 6. The elastic recovery is much higher than for, e.g. maize starch [29] or the native forms [2], however, similar to pregelatinized ones [8]. The fast elastic recovery (FER) increased with increasing $\rho_{\mathrm{rel,\ max}}$. The FER was higher for PS than for FD starches, which is similar to the order of Elastic energy. The elastic recovery of the starch tablets increased with storage with FD White and FD Water showing higher ER after 10 days than the PS forms of the starches. FD Chinese and FD Bitter showed lower ER than PS forms of the starches.

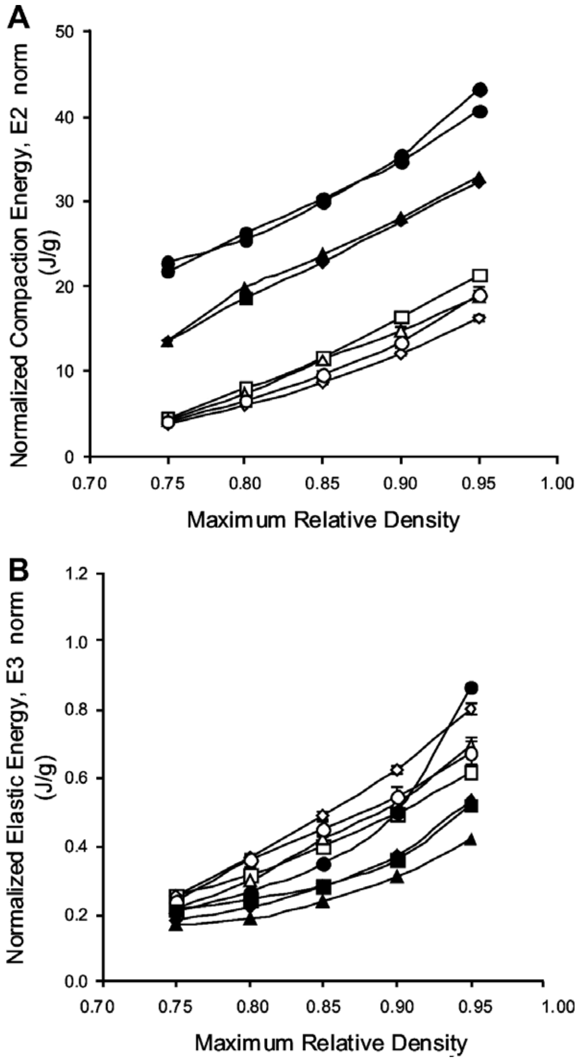

Fig. 7. Normalized Compaction Energy, $E2$, (A) and Normalized Elastic Energy, $E3$, (B) calculated from force–displacement profiles at different Maximum Relative densities for pregelatinized (open) and freeze-dried pregelatinized (closed) *Dioscorea* starches: ▲, Water yam; ◆, Chinese yam; ●, Bitter yam; ■, White yam.

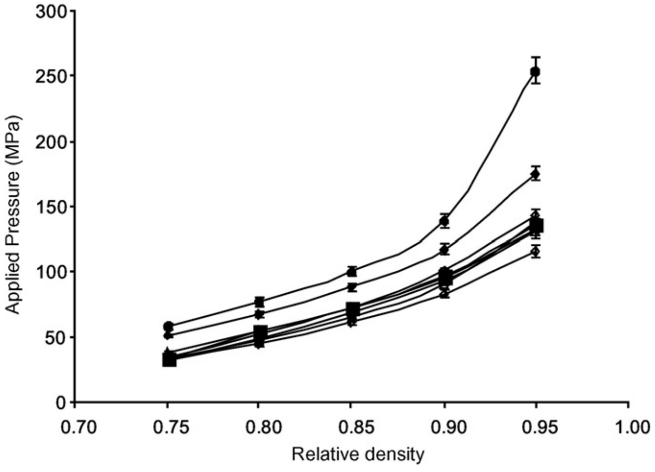

Fig. 8. Applied Pressure (MPa) versus Relative densities for pregelatinized (open) and freeze-dried pregelatinized (closed) *Dioscorea* starches: ▲, Water yam; ◆, Chinese yam; ●, Bitter yam; ■, White yam.

Table 6
Elastic Recovery (ER) at different $\rho_{\mathrm{rel,\ max}}$ of pregelatinized *Dioscorea* starches (Mean and SD, $n = 10$)

Starch	$P_{\mathrm{rel.max}}$	Fast ER (%)	ER after ejection (%)	ER after 1 h (%)	ER after 10 days (%)	Starch	$P_{\mathrm{rel.max}}$	Fast ER (%)	ER after ejection (%)	ER after 1 h (%)	ER after 10 days (%)
PS White	0.75	3.78(0.03)	14.93(0.29)	17.46(0.36)	19.25(0.47)	FD White	0.75	3.08(0.08)	19.64(0.37)	24.00(0.30)	25.91(0.46)
	0.80	3.79(0.01)	15.35(0.16)	17.98(0.27)	19.95(0.07)		0.80	2.78(0.19)	18.41(0.18)	21.88(0.29)	23.38(0.36)
	0.85	3.95(0.02)	15.62(0.26)	18.15(0.17)	20.26(0.45)		0.85	2.68(0.02)	16.80(0.16)	19.55(0.19)	20.89(0.18)
	0.90	4.04(0.01)	15.65(0.27)	18.12(0.41)	19.84(0.30)		0.90	2.76(0.02)	15.54(0.25)	17.81(0.27)	18.98(0.12)
	0.95	3.76(0.01)	14.89(0.16)	17.02(0.17)	18.62(0.30)		0.95	3.01(0.01)	14.84(0.25)	16.59(0.24)	17.61(0.31)
PS Chinese	0.75	3.99(0.02)	16.53(0.23)	18.39(0.29)	–	FD Chinese	0.75	2.36(0.05)	12.15(0.24)	13.78(0.17)	14.54(0.11)
	0.80	4.54(0.01)	17.79 (0.23)	20.16(0.09)	21.90(0.31)		0.80	2.40(0.02)	11.85(0.24)	13.28(0.28)	13.77(0.24)
	0.85	4.98(0.01)	18.38(0.21)	21.16(0.19)	23.41(0.29)		0.85	2.40(0.01)	11.11(0.24)	12.27(0.19)	12.86(0.27)
	0.90	5.20(0.01)	18.12(0.16)	21.13(0.28)	23.64(0.45)		0.90	2.43(0.02)	10.46(0.37)	11.37(0.28)	12.01(0.33)
	0.95	5.15(0.01)	17.56(0.16)	20.18(0.18)	22.83(0.32)		0.95	2.28(0.01)	9.86(0.24)	10.47(0.26)	11.15(0.26)
PS Bitter	0.75	3.52(0.03)	14.42(0.21)	16.52(0.30)	17.75(0.39)	FD Bitter	0.75	2.43(0.03)	11.32(0.54)	12.60(0.31)	13.23(0.16)
	0.80	3.80(0.01)	15.78(0.32)	18.01(0.33)	19.92(0.38)		0.80	2.46(0.03)	10.50(0.23)	11.55(0.36)	12.14(0.18)
	0.85	4.28(0.01)	16.10(0.22)	18.67(0.15)	20.73(0.40)		0.85	2.47(0.02)	10.25(0.10)	10.75(0.35)	11.53(0.74)
	0.90	4.51(0.02)	16.50(0.21)	19.29(0.27)	21.09(0.37)		0.90	2.54(0.05)	9.27(0.38)	10.12(0.41)	10.59(0.37)
	0.95	4.72(0.01)	16.79(0.40)	19.28(0.25)	20.83(0.51)		0.95	2.31(0.04)	8.85(0.18)	9.49(0.22)	10.07(0.58)
PS Water	0.75	3.52(0.01)	14.05(0.22)	15.80(0.16)	17.27(0.23)	FD Water	0.75	2.77(0.13)	15.85(0.20)	18.22(0.24)	18.72(0.20)
	0.80	4.11(0.02)	14.72(0.10)	16.96(0.14)	18.69(0.52)		0.80	2.38(0.01)	14.85(0.17)	17.03(0.17)	17.30(0.12)
	0.85	4.28(0.02)	14.78(0.29)	17.01(0.29)	18.78(0.24)		0.85	2.35(0.02)	14.20(0.24)	15.93(0.24)	16.04(0.16)
	0.90	4.20(0.01)	14.36(0.14)	16.56(0.19)	18.54(0.73)		0.90	2.39(0.03)	13.01(0.32)	14.54(0.26)	14.81(0.30)
	0.95	3.64(0.01)	13.69(0.15)	15.63(0.18)	17.51(0.24)		0.95	2.46(0.03)	12.14(0.25)	13.48(0.33)	13.90(0.26)

–, Not measurable.

The SEMs of particles of the interior of the starch tablets at $\rho_{\mathrm{rel,\ max}}$ of 0.90 shown in Fig. 3, indicate that the particles of the PS starches were in contact with each other but there appears to be no strong bonding between the particles (Fig. 3A). FD starches on the other hand showed complete deformation of the particles and the formation of a gel-like network (Fig. 3B). Partially amorphous materials have been shown to be more easily compactable [32]. Moreover, the high specific surface area of the FD starches will facilitate more contact between the particles and the formation of more solid bond. At higher magnification (Fig. 3C), FD Chinese and FD Bitter exhibited a completely new network-like structure and the particles are strongly deformed and appear to be 'fused' together.

Visual examination of the tablets showed that there was darkening of the upper surface in of the FD starch tablets especially at higher $\rho_{\mathrm{rel,\ max}}$ while there were no such changes for PS tablets. The ranking of the intensity of the changes is Water > Bitter > Chinese > White. Temperature and pressure have been shown to influence the molecular structure and tableting behaviour of materials [23]. The applied pressure is partially transformed into heat, and the temperature increase is caused either by friction of particle [33], friction between particles and machine component or by material stress in the tablet [34]. The temperature changes at the surface of the tablet immediately after ejection from the die have been measured using infrared sensors although the temperatures actually reached inside the tablet can be assumed to be much higher [25]. The maximum temperature reached at the surface of the modified starch tablets is presented in Table 7. The maximum temperature at the surface of all the PS starches was 26.4 °C while the temperatures were higher (30.5 °C) for the FD starches. The ranking of temperature for the FD starches was Chinese > Bitter > Water > White. Thus, except for FD Water, the intensity of colour changes follows the same order. However, the colour changes in FD Water could be as a result of other factors. This finding correlates with the 'fusion' seen in the SEM of FD Bitter and Chinese tablets (Fig. 3C). The changes observed in the tablets could probably be due to temperature or pressure or a combination of both factors.

Table 7
Maximum temperature measured at the surface of the tablets produced at $\rho_{\mathrm{rel,\ max}}$ of 0.90 and disintegration time (min) for the modified *Dioscorea* starches (Mean ± SD, $n = 5$)

Starch	Temperature (°C)	DT (min)
PS White	26.4 ± 0.1	4.74 ± 0.17
PS Chinese	26.2 ± 0.1	3.53 ± 0.11
PS Bitter	26.1 ± 0.0	9.02 ± 0.20
PS Water	26.3 ± 0.1	4.03 ± 0.13
FD White	28.6 ± 0.1	6.75 ± 0.28
FD Chinese	30.5 ± 0.1	–
FD Bitter	30.0 ± 0.1	–
FD Water	29.2 ± 0.1	8.33 ± 0.17

–, Non-disintegrating.

In order to evaluate if the temperature increase causes structural changes in the materials which could be responsible for the darkening of the upper surface of the tablets, the FD starch powder and the powder scrapped from the tablets surface were analysed using FT-Raman spectroscopy. The FT-Raman spectra of the FD starches, of the powder scrapped from the tablets surface, and of the starch powders subjected to heating at 90 °C are shown in Fig. 9

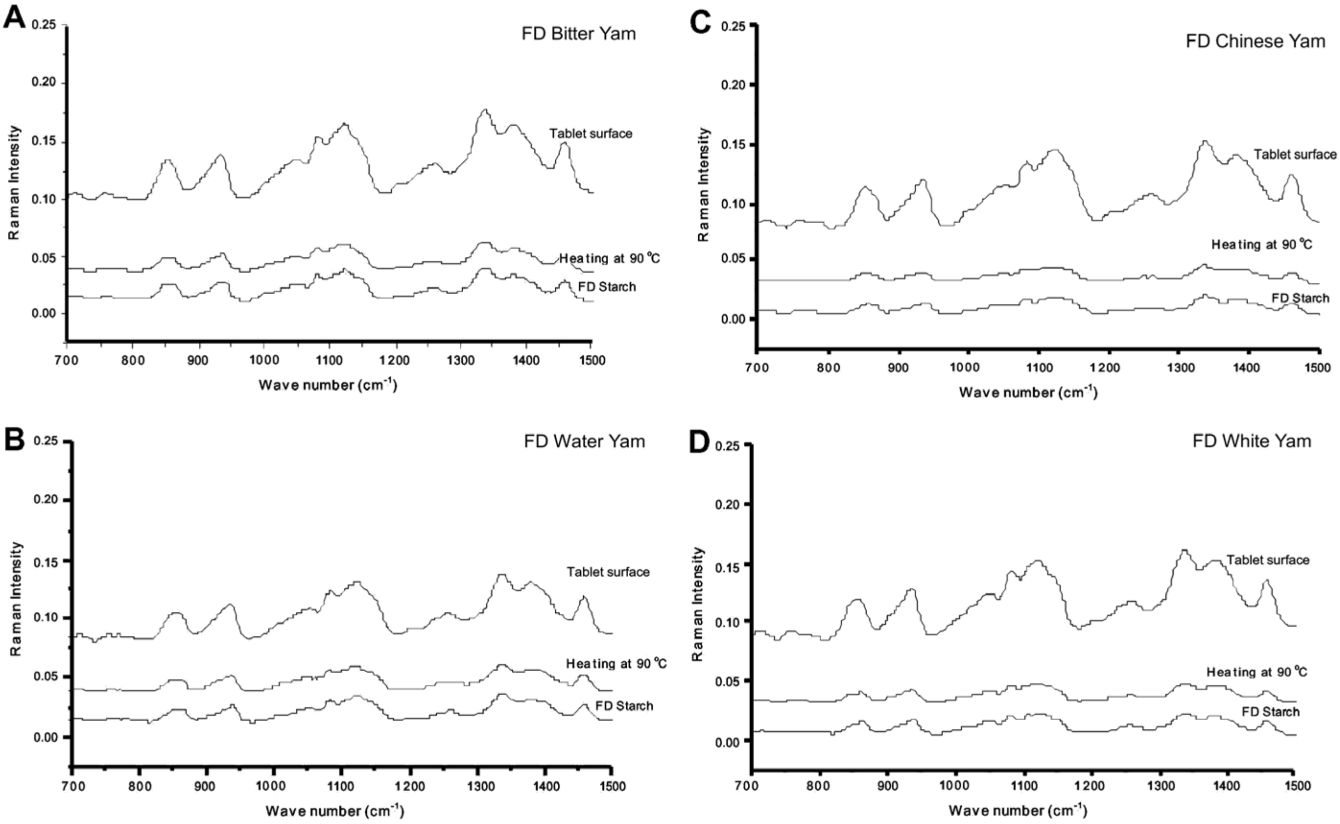

Fig. 9. The FT-Raman spectra of the FD starches, the scraped surface of the tablets and the starch powders subjected to heating and the Raman spectra at 90 °C (A – FD Bitter, B – FD Water, C – FD Chinese, D – FD White).

and the major bands are shown in Table 2. A decrease of 4–10 cm^{-1} was observed in the CH and CH_2 deformation at 852 cm^{-1} for the FD starches due to heating. The Raman bands indicate that there was a shift in the Raman band with the spectra of the powder scrapped from the tablets surface being similar to the shift obtained at 90 °C. This indicates that the temperature generated during tableting probably caused a change in the structure of the starches which could be responsible for the darkening observed at the tablet surface.

The compactibility profiles of the starch tablets are shown in Fig. 10. The results show that the crushing force is higher than for native starches [2,29] and it increased with compression pressure. FD starches exhibited significantly ($p < 0.01$) higher compactibility than the PS starches. The crushing force of the PS starches was generally less than 60 N indicating that the tablets were generally weak. On the other hand, FD White and FD Water exhibited crushing force greater than 100 N at all compression pressures and at $\rho_{\text{rel, max}}$ of 0.95, FD Water has crushing force greater than 500 N. FD Chinese and FD Bitter exhibited crushing force values higher than 500 N at $\rho_{\text{rel, max}}$ of 0.85 and above. Crushing force above 500 N was not shown because the maximum pressure recordable using the tester was 500 N. The tablets did not break into clean halves after the application of 500 N and therefore the crushing force was not measurable.

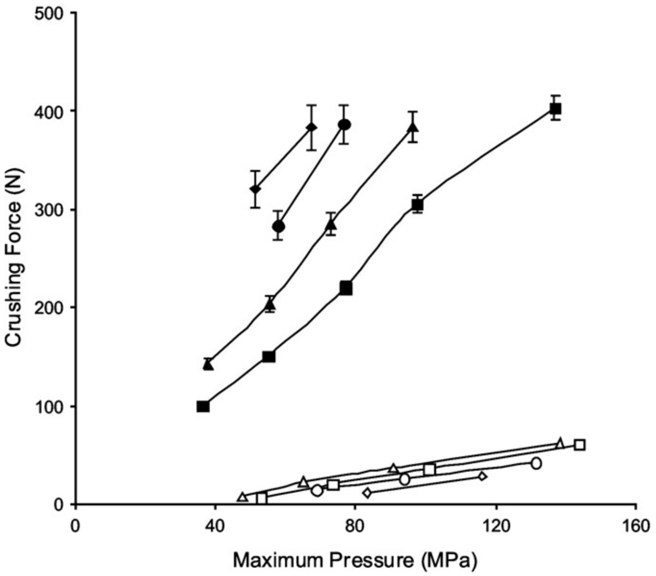

Fig. 10. Compactibility plot of tablets made from pregelatinized (open) and freeze-dried pregelatinized (closed) *Dioscorea* starches: ▲, Water yam; ♦, Chinese yam; ●, Bitter yam; ■, White yam.

The disintegration time of the starch tablets at $\rho_{\text{rel, max}}$ of 0.90 is shown in Table 7. The tablets disintegrated rapidly and the European Pharmacopoeia limit of 15 min was never exceeded except for FD Chinese and FD Bitter which did not disintegrate after 3 h. Thus, FD White and FD

Water starches disintegrated fast even though their crushing forces were very high. These starches could be useful when high crushing force and fast disintegration are of concern. On the other hand, FD Chinese and FD Bitter hydrated and formed a gel-like layer at the matrix periphery exposed to aqueous fluid and the tablets remained intact after 3 h. Thus FD Chinese and FD Bitter could find application as excipients for controlled drug delivery where slow release rates are desired. A similar application has been found for pregelatinized forms of tapioca, potato and corn starches [6,7,10,11].

Previous work on native *Dioscorea* starches showed that Bitter and Chinese were more compressible and formed compacts with acceptable crushing force [2]. Unfortunately, the PS forms of these starches were less compressible probably due to the destruction of the polygonal structure of the granules of the native starches. Native White and Water on the other hand, which were not compressible and did not form compacts, became more compressible when pregelatinized. Thus, pregelatinization improved the flowability and compressibility of the starches except for PS Chinese and PS Bitter. The FD starches showed higher compressibility even though they possessed poor flow properties. Furthermore, freeze drying appears to have improved the plasticity of the materials probably due to an increase in the amorphous property of the starches which enhances compactibility.

5. Conclusions

The results obtained indicate that pregelatinization improved the compressibility and flowability of the *Dioscorea* starches. However, the FD starches showed very low density values which may result in problems during die filling as a result of high bulk volume in tablet production. On the other hand, the high bulk and tap densities of PS coupled with their good flowability offer a unique possibility of the starches being used as fillers in capsule formulations. However, FD starches generally showed higher compactibility compared to the PS forms of the *Dioscorea* starches. While FD White and FD Water showed fast disintegration time and high compactibility, FD Chinese and FD Bitter were non-disintegrating and showed high compactibility. The high compactibility observed with the FD starches appears to be as a result of material change occurring during tableting probably due to the effect of temperature or pressure or a combination of both factors. Thus, FD White and FD Water starches could be useful when high crushing force and fast disintegration are of concern while FD Chinese and FD Bitter which were non-disintegrating, could find application as excipients for controlled drug delivery.

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