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Research Article

Water-starch interactions of red and white cocoyam (*Xanthosoma sagittifolium*)†

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List of abbreviations:

LF- Low Field

NMR – Nuclear Magnetic Resonance

CIE - Commission Internationale de l'Eclairage

UV – Ultra violet

RVA – Rapid Visco Analyser

$T_{22}$ – Slower transverse relaxing component

$T_{21}$ – Faster transverse relaxing component

$A_{22}$ – Freely moving water population

$A_{21}$ – Restricted water population

Keywords: Cocoyam; LF-NMR relaxometry; Water-starch interactions
Abstract

This study investigated the water-starch characteristics of two cocoyam varieties, red (*mankanikọọ*) and white (*mankanifufuo*), alongside their relevant physicochemical and pasting properties. Differences between the varieties in their starch content, as well as amylose/amylopectin ratios were identified. Low-Field Nuclear Magnetic Resonance (LF-NMR) transverse relaxation time analysis of flour and starch suspensions of the two cocoyam varieties indicated changes in their gelatinization and retrogradation during heating and cooling. One to two water populations were identified for both varieties and were highly dependent on the temperature and concentration rather than the variety, however the red variety showed higher retrogradation tendency. An increase in relaxation times at 75–80 °C was observed for flours and starches corresponding well to the amylograph pasting temperatures revealed using the Rapid Visco Analyzer.
1. Introduction

Starch granules, which are polysaccharide units of plant carbohydrates, swell upon heating in excess water, and form a viscous paste on reaching the gelatinization temperature. When cooled, the starch granules can form a gel, with characteristics dependent on the botanical source, heating conditions and water-starch ratios.\(^{[1]}\) The gelatinization characteristics of starch granules determines to a large extent, the potential use of starchy crops in the food processing industry.\(^{[2]}\)

Water distribution analysis, as obtained from proton nuclear magnetic resonance (NMR) relaxometry, gives a valuable insight into water-starch interactions, which can be further complemented with pasting profiles from amylographs to give in-depth understanding of gelatinisation behaviour of root crops.\(^{[3]}\) Such studies have been carried out for potato starch and tapioca towards their enhanced utilisation; Chatakanonda et al.\(^{[4]}\) investigated the effect of irrigation on the functionality of cassava starch by proton NMR relaxation study, Chatakanonda et al.\(^{[5]}\) studied the water mobility and distribution of cassava and potato starches by solid state and proton NMR relaxometry while Mortensen et al.\(^{[3]}\) studied cooking effects on water distribution in potato.

Cocoyam (Xanthosoma sagittifolium) is a root crop widely cultivated in tropical and subtropical countries with annual production level of 10 million metric tonnes.\(^{[6,7]}\) Cocoyam is acclaimed for its use as an emergency crop during lean seasons of other staples and it is of great importance to the food chain of West and Central Africa.\(^{[6-9]}\) Ghana is the fourth largest world producer of cocoyam,\(^{[10]}\) having two commercial varieties, the red and white.\(^{[7,11]}\) Cocoyam
Cormels are usually eaten boiled, roasted and as mash (after boiling or roasting). The potential industrial food application of its flours and starches have also been proposed.[7,12]

Lawal[13,14] studied the physicochemical and retrogradative properties of modified cocoyam starches and their microstructure, Sefa-Dedeh and Agyir-Sackey[15] investigated the starch microstructure, pasting profiles and properties of raphides of two landraces in Ghana. In another study Lu et al.[16] studied the influence of seasonality on the physicochemical properties of cocoyam starches of two Taiwan cultivars and Falade & Okafor,[17,18] investigated the hydration and pasting properties of the flours and starches of two newly developed varieties in Nigeria. However, research on cocoyam has neglected the molecular processing properties and in particular, the dynamics of their water-starch interactions which limits its optimal exploitation in the food industry.[6,7]

Thus, this study investigated the dynamics of water-starch interactions of flours and starches of red and white varieties of cocoyam during heating and cooling by Low Field NMR relaxometry, combined with characterisation of their pasting and relevant physicochemical properties.

2. Materials and Methods

2.1. Source of Raw Materials

The two varieties of *Xanthosoma sagittifolium*, red (*mankanikɔɔ*) and white (*mankanifufuo*) were obtained from Birim North District of the Eastern region of Ghana. The roots were harvested after 12 months of planting and processed into flours and starches on the fourth and eighth day after harvest, respectively, as described in section 2.2 below.

2.2. Preparation of flours and starches

*Flour preparation*
Roots (white and red varieties treated separately) were peeled, manually sliced (average thickness of 0.5 mm) using stainless steel knives, and washed and soaked in potable tap water for an hour before drying at 60°C for 10 h in a hot-air oven dryer. The dried samples were allowed to cool and were milled to obtain flours which would pass through a 425 µm laboratory test sieve (ISO 3310-1:2000, BS 410-1:2000, UK). The flours were packaged in high density zip-lock bags until further use.

**Starch preparation**

Roots (white and red) were manually peeled with stainless steel knives, washed with potable tap water and mashed with a hammer mill. The mash was mixed with potable tap water in the ratio 1:2. The obtained slurry was washed with potable tap water and sieved through a double-layered cheese (muslin) cloth to remove cell debris. The filtrate was kept overnight in plastic containers for starch sedimentation. The supernatant was discarded and the sediment (starch) was washed 3-5 times with potable tap water to remove any traces of dirt. The washed starch was transferred unto drying trays and solar dried for 48 h. The dried starch was then milled into fine powder using a Philips home blender (HR 2027, China). The obtained starch powders were packaged into high density zip-lock bags until further use.

2.3. Physicochemical tests

**Physical dimensions of roots**

The physical dimensions (length – inner and outer measures) and weights of 100 roots used in the flour and starch preparation (section 1.2.2) were determined as described by Falade & Okafor.[18]

**CIE (Commission International d’Eclairage) L*a*b* Colour determination**
The L* a* b* colour measures were determined with a calibrated Konica Minolta chromametre CR-310 and a Konica Minolta CM-600d chromametre with the CM-S100w SpectraMagic™ NX colour data software (Konica Minolta Sensing Inc., Osaka, Japan). The colour of the root skin, the peeled roots, flours, and starches, were analysed. The determinations were obtained from five different points of the samples and the means and standard deviations were calculated. The chroma (or saturation), C*, measures the vividness of the colour and was calculated from the L*, a*, and b* cartesian coordinates using the equation,

\[ C^* = \sqrt{a^{*2} + b^{*2}} \]  

(Eq. 1)

The C* value ranges from 0 – 60; 0 being very dull and 60 being vivid.[19]

\[ pH \]

The pH was determined on 10% (w/v) solutions of the flour- and starch-water suspensions as described by Falade & Okafor. [18] Determinations for each treatment were done in triplicate.

\[ Moisture Determination and drying of flours and starches \]

The moisture content of the roots was determined by the gravimetric method[20] on 2 g of sample dried at 105 °C for 24 h. Oven drying at 60 °C for 10 h was used for the production of flours to prevent fermentation while the starches were solar dried for 28 h at a temperature range of 25 °C – 55 °C, to simulate domestic industrial protocols for production of starches and flours.

\[ Percent (%) starch content \]

The total starch content of the flours and starch powders was determined by the anthrone method as described by Hedge and Hofreiter[21] using a starch conversion factor of 0.9.[22]

\[ Determination of amylose and amylopectin ratios \]

The amylose content was determined by the colourimetric method of Juliano.[23] The absorbance of the blue colour developed was read at 590 nm using a UV spectrophotometer (UV-
1600PC, VWR international, USA). The protocol was repeated for varying concentrations (0-100 mg in 100 mL of water) of a standard amylose solution (Sigma-Aldrich, Pcode 10010106982, USA) to develop a standard curve. Iodine reagent (1 mL) was diluted to 50 mL with distilled water and used as a blank. In calculating the percent (%) amylose, it was estimated that the absorbance corresponded to 2.5 mL of the test solution. The amylopectin was determined as the difference between the total starch content and the amylose content.

2.4. Pasting properties (Viscoamylograph tests)

The rapid visco™ analyser (RVA 4; Newport Scientific Pty. Ltd., Warriewood, NSW 2102, Australia) was employed in the determination of pasting profiles of the flours and starches. Flour/starch in water suspensions (10%, w/v) were prepared using the Newport Scientific correction formula for moisture content of samples. The pasting properties of the suspensions were determined as described by Liu et al. with slight modifications; Samples were equilibrated at 50 °C for 1 min, heated to 95°C at 5°C/min, held there for 6 min (breakdown), and then cooled to 50°C (setback) at the same rate, and finally held at 50°C for 2 min. The rotor speed was set to 960 rpm for the first 10 s and 160 rpm for the rest of the cycle. Analysis were done in duplicates and analysed using the Thermocline™ for Windows software (version 2.3).

2.5. Studies on the water-starch interactions

Nuclear Magnetic Resonance relaxometry

The water-starch characteristics of the samples were studied during heating by Low-Field (LF) NMR transverse relaxation time analysis. The analysis was performed on a 23 MHz Maran benchtop analyzer (Resonance Instruments, Witney, UK) equipped with an 18 mm temperature adjustable probe. Varying concentrations (2 – 12%, w/v) of flour or starch in water suspensions were prepared with distilled water. About 3 mL of the suspension was transferred into a small
sample tube (45x15x0.6 mm) and covered with a plastic cap. These were then inserted into longer test tubes (180x17.75x0.6 mm), which were temperature equilibrated for 35 min in a preset water bath at each of the temperatures under consideration in the range from 25 to 90°C prior to their introduction to the magnet. The study was carried with the assumption that the transverse measures are fast thus stirring ungelatinised suspensions immediately before NMR scans could prevent complete precipitation during the analysis. Measurements were also done on samples at 25°C after overnight cooling to assess the retrogradation of the formed gels. A Carr-Purcell-Meiboom-Gill (CPMG\textsuperscript{[25,26]}) pulse sequence with an interpulse spacing \( \tau \) of 150 \( \mu \text{s} \) was employed for the analysis. Eight repeated scans were used, every other echo was collected (2048 collected echoes in total) per scan and 6 s repetition time between scans. The obtained relaxation data was fitted to a discrete multi-exponential function using the LF NMR Toolbox for Matlab (The Mathworks Inc., Natric, MA, USA).\textsuperscript{[27]}

2.6. Statistical analysis

Univariate data was analysed by analysis of variance (ANOVA) at a significant level of 5% using the IBM SPSS (version 20.0) and the Statgraphics centurion (version 15.2.11, 2007) software packages.

3. Results and Discussion

3.1. Physicochemical characteristics of flours and starches

\textit{Physical dimensions of roots}

The individual roots varied in sizes within the varietal groups but did not differ (\( p > 0.05 \)) in weight between the two varieties with both varieties weighing between 122-135 g per root. This observation is in agreement with earlier reports of \textit{X. sagittifolium} roots having different sizes
within a varietal group but similar phenotypic characteristics between the unpeeled roots of the red and white varieties.\textsuperscript{[15,18]}

\textit{Colour determination}

CIE L*\textsuperscript{a}b* colour determination indicated that the starches had relatively higher L*\textsuperscript{-} values, lower a*\textsuperscript{-} values, and lower b*\textsuperscript{-} values compared to the flours, signifying a lighter appearance, less redness, and lighter yellow colour, respectively (Table 1). The trend was the same for both varieties, although the flours of the white variety had higher L*\textsuperscript{-}, but lower a*\textsuperscript{-} and b*\textsuperscript{-} values compared to the flours of the red variety. However, there were no differences (p>0.05) among the colour nuances of the starches with regards to their variety. The chroma was also higher in the flours (C* values of 12.29 and 14.37) than the starches (C* value of 8.20 and 8.02) for the red and white varieties, respectively. The stronger colour nuances of the flours compared to the starches could be attributed to the presence of other pigmented constituents (e.g., proteins is 6.24\% and high levels of phosphorous, potassium, calcium and magnesium identified (data not shown)), which are reduced through the starch extraction process.\textsuperscript{[12]}

\textit{Chemical composition and pH}

The moisture content of the starches were higher than that of the flours (Table 1) and within recommended levels for long storability of flours and starches.\textsuperscript{[24]} This might be partially explained by the different drying methods used for their preparation. The pH, which is an important indicator of the rate of starch conversion to dextrin,\textsuperscript{[17]} was in the low acid region for all samples (pH 5.11 to 6.14) and within recommended safety levels for long shelflife of edible flours and starches.\textsuperscript{[28]} The two varieties had relatively high starch contents, ranging between 44\% and 58.7\% for the white and red varieties, respectively (Table 1) in agreement with and other high starch crops.\textsuperscript{[16]}
The extracted starches also had relatively high purities for the white and red varieties, respectively. The findings suggest the potential for industrial exploitation of cocoyam starches.

Amylose content has significant influence on functionality of starchy root crops. Higher amylose starches have higher tendencies towards retrogradation and breakdown than those with lower amylose fractions. The amylose content was slightly higher in the red variety (37.65%) than in the white (36.73%). The obtained amylose fractions were, however, higher than those reported in literature for other *Xanthosoma* varieties, but similar to work done by Falade & Okafor on a Nigerian variety (with 33.77% amylose content), and a South American variety (with 35.34% amylose content) as reported by Pérez et al. It is noteworthy that the amylose content of the starch fractions are highly influenced by the analytical method employed and are dependent on the environmental factors and planting period in addition to the botanical differences between the root species.

3.2. Pasting properties of flours and starches

The pasting properties of the flours and starches as determined using the RVA are presented in Table 1. The pasting characteristics of the starches differed significantly from the flours. Higher peak viscosities and breakdown and lower peak time and pasting temperatures were observed for the starches than their corresponding flours. The red cocoyam variety, had slightly higher peak viscosities than the white variety. The peak viscosity indicates the highest swelling potential of the starch granules before disintegration, and reflects the viscous load likely to be encountered during cooking. Starches with low peak viscosities are preferred in products that require less thickening during cooking such as in infant (complementary) gruels, while high peak viscosities are desired in thickeners, gels and other products in which high viscous loads are preferred.
Flours and starches of the white variety generally had lower breakdown viscosities than the red variety (Table 1). Breakdown viscosity is the reduction in starch viscosity with reference to the peak viscosity and largely measures the strength of cohesive bonds of the starch granules. High breakdown viscosities indicate weaker associations of starch granules and vice-versa. Starch granules with low breakdown viscosities can thus withstand much heat and stir stress and are preferred in production of baked products and gruels.

The setback determines the retrogradative tendencies of the starch granules. Relatively lower setback values were obtained for the flours of the white variety compared to the red, indicating a greater potential of the use of the white flour in the flour industry for products requiring slower staling rates. The starch final viscosity also determines its retrogradative tendencies, and this was slightly higher in samples of the red variety for both the flours and starches (Table 1).

The peak time of pastes is a measure of how fast a starch is heated and therefore has economic (energy and time) implications on industrial use. It is influenced by the ability of the starch granules to imbibe water and swell in the presence of heat. The peak time of the starches were slightly lower than their corresponding flours, which may arise from the different components of the flours, as opposed to its extracted starch. The trend was the same for the pasting temperature, which measures the paste-forming tendencies of the flours and starches when heated. The higher the pasting temperature, the higher the potential for the starch to absorb water, swell and form a paste. Thus, the high pasting temperatures observed indicated that both flours and starches of both varieties could be utilised as gelling and thickening agents.

3.3. Water-starch interactions by Nuclear Magnetic Resonance (NMR) Relaxometry
Discrete exponential fitting of Low field NMR transverse relaxation data indicated the presence of 1-2 water populations in the flour/starch – water suspensions, dependent on the temperature and concentration of the flours and starches, respectively. A comparison of the mono-exponential fit of the data was performed to obtain an overview of the main critical points in the heating process, and to compare the effects of the increasing concentrations on the water-starch interaction (Figure 1). There was a decrease in overall relaxation rates with increasing concentration for all samples. The observation indicates stronger interactions of water with the starch granules in the suspensions as the flour or starch concentration increased.

(Insert Figure 1)

Only minor changes were observed in the mono-exponential behaviour during heating up to 75-80°C, where all samples experienced a rapid increase in relaxation times. The distinct change in relaxation measures indicate the onset of gelatinisation at this temperature range. The finding is in good agreement with the observed pasting temperature obtained from the RVA analysis. However, on the whole, the changes in relaxation rates due to heating were much more subtle in the flours than in the starches. This may be explained by the lower starch concentration and the presence of other components in the flours. All samples showed a decrease in the mono-exponential relaxation times after overnight cooling, indicating the formation of a more compact network and increased interaction between the water and starch/flour after retrogradation. To understand these water-starch relations in the suspensions in more detail, it was necessary to take a closer look at the dynamics of the water distribution, as affected by the heating and retrogradation processes.

Starch suspension with equal or lower concentrations than 6%, and flour suspensions with concentrations equal to or lower than 4% generally showed mono-exponential behaviour
throughout the heating and retrogradation processes. However a small second water population with a short relaxation time below 30 ms was observed at approximately 35-45°C, and again at 75-80°C (data not shown). This appearing and disappearing of populations indicated that the interaction between the protons in the starch and the water at these low concentrations was limited, and that a fast proton exchange occurred between these proton populations during the heating process.\textsuperscript{[2]}

However, at higher concentrations a bi-exponential proton distribution was observed (concentrations equal or above 6% and 8% for the flours and starches, respectively), with a faster transverse relaxing component, $T_21$, having relaxation times below 300 ms (Figure 2), and a slower relaxing component $T_22$ with relaxation times between 200 and 1400 ms (Figure 3).

(Insert Figures 2 and 3)

The information is key for processor selection of starch/flour suspension concentrations depending on end use. Protons with relaxation times at or below 10 ms, were observed at 25-45°C for some samples. These protons are commonly assigned to CH protons of the starch in crystalline or rigid amorphous structures.\textsuperscript{[35]} This population however, did not remain stable and was not observed further throughout the rest of the heating process. Thus, the fast relaxing component $T_21$ can be generally attributed to water molecules interacting with the starch molecules, while the slower relaxation component $T_22$ would represent the more freely moving bulk water in the suspensions. In the starches the clear decrease of the bulk water population $A_22$ (Figure 4) with temperatures up to 75°C was in good agreement with increasing dissolution of the starches, and thus, enhanced interaction between the water and the starch molecules leading to increased starch swelling and amylose leaching at elevated temperatures.\textsuperscript{[35]}

(Insert Figure 4)
At 75°C, up to 90% of the water in the starch samples was restricted and interacting with the starch molecules (as identified by a large relative population A21). The simultaneous decrease in the less restricted population A22 was furthermore coupled with a decrease in the shorter relaxation time T21 at temperatures up to 75°C in the starches. This indicated an overall increase in restriction of the water protons as they interacted more with the starch. This trend was more evident as the concentration of the starch suspensions increased. However, a similar decrease in A22, and corresponding increase in A21, was not observed in the flours until at temperatures between 60°C and 65°C, indicating that the starch granules of the flours were swelling to a much lower degree than the starches (only up to 50% of the water was restrained), at higher temperatures. It is worth mentioning that the flour production process is a harsher process than that of the starch production, leading to higher probability of granule disintegration in the flours. This is likely to impact the swelling ability of the starch in the flours on a microscopic scale.

The discussed change in water distribution at temperatures below 60-65°C was only associated with minor changes in the observed relaxation times in the flours. Small peaks in T22 were observed around 60-75°C in the red flours and starches. These are believed to relate to the gelatinization of amylopectin crystal residues, which commonly occur in the range from 60-70°C, dependent on the type of starch studied. However, similar peaks were not obvious in the white starches and flours, possibly due to their relatively lower amylopectin content compared to the red cocoyam products (Table 1).

An increase in T22 was observed during gelatinization, simultaneous to the expelling of water from the gel network to the less restricted population A22. This behaviour was observed between 75 and 80°C in the starch suspensions, and in the red cocoyam flour suspensions. However, no gelatinization was indicated by the relaxation times in the white cocoyam flour,
although it was observed through changes in the water distribution (increase in A22 at 75°C for all concentrations). These gelatinization temperatures are in good agreement with the pasting temperatures observed with the RVA analysis, as well as the changes observed in the mono-exponential relaxation times.

During gelatinization, up to 90% of the water was expelled from the gel matrix. Due to the dominance of the less restricted water population after gelatinisation, the changes caused due to retrogradation during overnight cooling were thus best described by a small general decrease in the T22 relaxation parameter. Only at 10% concentration was a small but significant difference observed in the amount of retained water for A21 between the red and white starches, with the white starch retaining slightly more water than the red starch at this concentration. However, the shorter relaxation times observed after retrogradation with increasing concentration indicated that the concentration had a greater influence on the strength of the water-starch interaction than the type of cocoyam root used for the flour and/or starch production.

4. Conclusions

NMR relaxometry identified 1 - 2 water populations in both read and white varieties of cocoyam, and these were highly dependent on the temperature and concentration of the starch/flour suspensions. Both flours and startche showed a sudden increase in relaxation times between 75 – 80°C in agreement with the observed pasting temperatures from the RVA analysis. The white variety however, showed lower tendencies to retrogradation relative to the red. Moreover, the relaxation time that measures the water-starch interactions further indicated changes in gelatinization and retrogradation properties during heating and cooling processes, which were more pronounced in the starch samples than in the flours. Concentration of flour/ starch
suspensions had higher effect on behaviour of water-starch interactions during heating and cooling than varietal difference for the studied varieties of *Xanthosoma sagittifolium*.

5. Novelty statement

The present manuscript documents for the first time, the dynamics of the water-starch interactions of cocoyam (*Xanthosoma sagittifolium*) flour and native starch suspensions during cooking at the molecular level. There are no known publications on this and the information provides deeper insight into the processing behaviour of two commercial varieties of cocoyam for enhanced food application.

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Conflict of Interest

The authors declare no conflict of interest.
6. References


[10] FAO, Statistical yearbook. Food and Agriculture Organization of the United Nations,
Rome, Italy 2013.


2010, 90, 1886.


Figure Legend

**Figure 1:**
Mono-exponential transverse relaxation times of different concentrations of flour/starch-water suspensions during heating and cooling of red and white varieties of cocoyam. Changes in the relaxing components are depicted as a function of heating and or cooling temperatures.

**Figure 2:**
Fast relaxing component $T_{21}$ with relaxation times below 300 ms observed in the bi-exponential proton distribution of transverse relaxation times at concentrations equal to or above 6% and 8% for the cocoyam flours and starches, respectively. The component represents the water molecules interacting with the starch molecules and are depicted as a function of temperature during heating and cooling.

**Figure 3:**
Slow relaxing component $T_{22}$ with relaxation times between 200 and 1400 ms observed in the bi-exponential proton distribution of transverse relaxation times at concentrations equal to or above 6% and 8% for the cocoyam flours and starches, respectively. The component represents the bulk water in the suspensions and are depicted as a function of temperature during heating and cooling.
Figure 4:
Apparent water population of the slower relaxing component (A₂₂) of the cocoyam flour/starch-water suspensions. Changes are depicted as a function of temperature during heating and cooling.
Table 1: Physicochemical and pasting properties of starches (S) and flours (X) of the red (R) and white (W) varieties of cocoyam (Xanthosoma sagittifolium)

### Physicochemical properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moisture (%)</th>
<th>% Starch (as purity for starches)</th>
<th>Amylose (%)</th>
<th>Amylopectin (%)</th>
<th>pH</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>Chroma (C*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XR</td>
<td>5.46±0.08a</td>
<td>58.65±1.17a</td>
<td>-</td>
<td>-</td>
<td>6.13±0.04a</td>
<td>84.40±0.33a</td>
<td>-1.75±0.02a</td>
<td>12.16±0.14a</td>
<td>12.29±0.14a</td>
</tr>
<tr>
<td>XW</td>
<td>6.50±0.10b</td>
<td>44.06±0.11b</td>
<td>-</td>
<td>-</td>
<td>6.14±0.01a</td>
<td>85.84±0.35a</td>
<td>-2.77±0.09b</td>
<td>14.10±0.16b</td>
<td>14.37±0.15b</td>
</tr>
<tr>
<td>SR</td>
<td>12.06±0.13c</td>
<td>96.00±0.15c</td>
<td>37.65±0.00c</td>
<td>58.35±0.15c</td>
<td>5.86±0.07b</td>
<td>95.34±1.02c</td>
<td>-4.24±0.14c</td>
<td>7.02±0.38c</td>
<td>8.21±0.27c</td>
</tr>
<tr>
<td>SW</td>
<td>11.71±0.08d</td>
<td>89.12±0.03d</td>
<td>36.73±0.02b</td>
<td>52.38±0.02b</td>
<td>5.04±0.12c</td>
<td>95.46±0.25c</td>
<td>-4.34±0.06c</td>
<td>6.75±0.20c</td>
<td>8.03±0.15c</td>
</tr>
</tbody>
</table>

### Pasting Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Peak viscosity (cP)</th>
<th>Trough viscosity (cP)</th>
<th>Breakdown (cP)</th>
<th>Final Viscosity (cP)</th>
<th>Peak Time (min)</th>
<th>Pasting Temp (°C)</th>
<th>Setback (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XR</td>
<td>2671.50±7.14a</td>
<td>1995.50±13.43a</td>
<td>676.00±14.14a</td>
<td>3356.00±16.97a</td>
<td>9.82±0.15a</td>
<td>80.13±1.10b</td>
<td>1360.50±3.54a</td>
</tr>
<tr>
<td>XW</td>
<td>2436.50±7.78b</td>
<td>1970.50±21.92b</td>
<td>466.00±14.14b</td>
<td>3277.50±3.54b</td>
<td>9.95±0.10b</td>
<td>80.43±0.11b</td>
<td>1307.00±25.46b</td>
</tr>
<tr>
<td>SR</td>
<td>3399.00±0.00c</td>
<td>1478.00±5.66c</td>
<td>1921.00±5.66c</td>
<td>2753.50±13.44c</td>
<td>7.99±0.03b</td>
<td>77.70±0.07b</td>
<td>1275.50±7.78b</td>
</tr>
<tr>
<td>SW</td>
<td>3327.00±11.31d</td>
<td>1444.00±7.07d</td>
<td>1863.50±0.71d</td>
<td>2675.50±13.45d</td>
<td>8.04±0.03b</td>
<td>77.68±0.11b</td>
<td>1212.00±1.41d</td>
</tr>
</tbody>
</table>

a) Results are stated as means ± standard deviations.

b) Results with different superscripts within a column are significantly different at $p = 0.05$

c) cP: centipoise
Figure 1

Figure 2
Figure 3

Figure 4