E3S Web of Conferences 610, 02002 (2025) https://doi.org/10.1051/e3sconf/202561002002
RI²C 2024

Pasting profiles and gel properties of rice flour blended with native, cross-linked, and acetylated tapioca starch

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Abstract. The pasting properties of rice starch can be improved by blending it with native or modified starch. This research investigated the pasting profiles and gel properties of rice flour (RF) blended at different concentrations with tapioca starch (TS), low- and high- degrees of crosslinked starch (LCL and HCL), and low- and high- degrees of substitution of acetylated starch (LAC and HAC). The results showed that substituting RF with both native and modified starches tended to decrease the pasting temperature of the flour blends. The increase in HCL in flour blends resulted in a higher pasting temperature, final viscosity, and setback. At the same time, adding LAC and HAC did not affect the pasting temperature, but a significantly decreased final viscosity was observed. RF-HCL10 and RF-HAC10 exhibited significantly higher swelling power than RF alone. Blending RF with HCL at 5, and 10% by weight could improve the freeze-thaw stability of the gels made from each blend. The information obtained herein is useful for the prediction of product properties that are rich in starch.

1 Introduction

Starches are widely used in many food applications. However, their applications are sometimes limited due to their low resistance to shear and susceptibility to thermal decomposition [1]. Native starch is generally not suitable for food products that require chilling and freezing due to their high retrogradation during storage at low temperatures, and syneresis during thawing [2]. Blending native starch with starches from other sources (e.g., corn, tapioca, potato) or modifying them leads to an improvement in texture, rheological properties, and characteristics of the final products [3, 4]. Rice flour (RF) is gaining popularity worldwide due to its use in many food products and is considered a gluten-free alternative for patients with celiac disease [5]. Blending rice flour with other native or modified starches can help improve its pasting and gelling properties or result in the desired characteristics of the final products.

Tapioca starch (TS) has a high viscosity, a low gelatinization temperature, and rapid swelling of starch granules [6]. TS can increase the adhesiveness and water-holding capacity of the blended starch gel and provide an elastic texture to the cooked noodles [7]. In addition, modified starches can compensate for native starch or flour properties in terms of viscosity, retrogradation during cooling and storage, and syneresis, and can act as a thickening agent [4]. Crosslinking reinforces the hydrogen bonds in starch granules with covalent interconnection that interacts with bridges between the molecules, resulting in a lowered breakdown and improved viscosity and textural properties of the mixed flour [1].

Acetylated starch (AC) with a low degree of substitution is approved for food applications by the US FDA (US Food and Drug Administration). AC can act as sticky, thickening, stabilizing, film-developing, and binding agents for several food applications, such as instant fried noodles, baked food, pudding, sauces, pie fillings, and frozen food [4]. Blending AC with native starch can improve stability and resistance to retrogradation, viscosity, solubility, swelling power, starch gel texture, and decrease the initial gelatinization temperature of the blend [8]. Acetylation leads to decreased syneresis because of the increased water-holding capacity of the gels stored at low temperatures by the acetyl groups in the starch molecule [8]. The addition of acetylated potato starch resulted in shorter rehydration time and a better appearance, with a smoother and shinier surface of the cooked noodle [9]. Instant noodles can be consumed after cooking or soaking in boiling water for 3-5 min [10]. Noodles prepared from wheat flour partly mixed with esterified tapioca starch can be cooked by boiling for only 3 min [6]. The addition of AC to the flour blend can reduce the

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energy required for starch gelatinization and provide a short reheating time for frozen noodles [11].

The pasting profile of modified starches from various plant sources can indicate their potential for food application, such as property improvement of food products, including ready-to-eat, easily heated or frozen food, or food products with longer shelf life [12]. Chewiness, slipperiness, and rapid rehydration are the required qualities for pre-cooked rice noodles [13]. Chemical modification by acetylation leads to a lower gelatinization temperature, whereas cross-linked starch (CL) improves the freeze-thaw stability of native starch [12]. There are some reports on the properties of rice flour and other starches. All pasting viscosity showed an increase in RF mixed with 4-12% of AC, but pasting temperature decreased when the concentration of AC was up to 8% [14]. TS mixed with CL for soup product at increasing cross-linking level (phosphorus content 0.01–0.033%) provided limited swollen granules and resistance to shear force [15]. Adding CL at 10% by weight contributed to the creation of stable structures of rice starch paste at 12% concentration [16]. However, this research focused the pasting profiles and gel properties of the rice flour blended with TS and two types of modified starches, crosslinked and acetylated starch. The physicochemical properties and freeze-thaw stability of the gels stored at low temperatures were also compared. The information obtained will be useful for developing food products, such as instant or frozen products, with consistent quality.

2 Material and methods

2.1 Raw materials and chemicals

Broken rice grains consisting of amylose content at 25.79 % (by weight) were obtained from Aura Food Co., Ltd. (Nakhonratchasima, Thailand). Tapioca starch (TS) was bought from Sanguanwongse Industries Co., Ltd. (Nakhonratchasima, Thailand). Both crosslinked and acetylated starches were tapioca-based modified starches obtained from Siam Modified Starch Co., Ltd. (Pathumthani, Thailand). The crosslinked starch, KREATION®RT (LCL), has a lower degree of crosslinking than KREATION®MB (HCL), while the acetylated starch, KREATION®NE (LAC), presents a lower degree of substitution than KREATION®592 (HAC). The moisture content of each ingredient was determined according to AOAC methods [17]. Amylose content was measured using Juliano's iodo-colorimetric method, as described by Juliano [18]. The amylose standard (from potato) was purchased from Sigma-AldrichTM (Saint Louis, USA). All other chemicals used for analysis in this study were analytical grade.

2.2 Preparation of rice flour (RF)

The RF was prepared from the broken rice grains described by Sangpring et al. [5]. Broken rice grains were soaked in water for 4 h and then wet milled using an electric stone-milling machine (Nakhonratchasima, Thailand). The RF cake was dried in a tray dryer (ED 400 Binder, USA) at 45 °C until around 10-12% moisture content (wb). The dried RF cake was ground by a blender (7009S Waring, Japan) and sieved through a 0.150 mm sieve. The RF was packed in polyethylene bags and stored in a desiccator at room temperature until further analysis.

2.3 Pasting properties

The RF was blended at 5 and 10% by weight with native (TS), low and high cross-linked (LCL, HCL), or low and high acetylated (LAC, HAC) starches. The samples were named RF-TS5, RF-TS10, RF-LCL5, RF-LCL10, RF-HCL5, RF-LCL10, RF-LAC5, RF-LAC10, RF-HAC5, and RF-HAC10, respectively. The pasting profiles of each RF blend were determined using a Rapid Visco Analyzer (Newport Scientific, Model RVA-4, Australia). The rice flour blends were prepared at 12% (wb) and put in the canister. The RVA was run using a Thermocline for Windows software (Version 1.2) with the following conditions: the temperature was maintained at 50 °C for 2 min, then raised to 95 °C in 3 min, and held at 95 °C for 3 min, after that the gel was cooled to 50 °C within 3 min, and maintained at 50 °C for 2 min. Each sample was rotated at 160 rpm with a paddle throughout the measurement. RVA parameters were recorded, including pasting temperature, peak viscosity, breakdown, final viscosity, and setback viscosity from the trough. All tests were carried out in three replications.

2.4 Gel properties

The gel texture properties of each RF blend were measured following by Sari et al. [19] with some modifications. The gelatinized gel obtained each RVA measurement was moved into a plastic cup (2 cm diameter, 3.5 cm height) and stored at 4 °C for 24 h. Then, the gels were kept at room temperature for 10 min and a section of the gels was crossed before observing their appearance. Gel texture was analyzed using a texture analyzer (Stable Micro Systems, United Kingdom) equipped with P/36R (36 mm probe). Texture profile analysis was performed by double compression with a test speed, trigger force, and strain of 1 mm/s, 50 N, and 70%, respectively. Textural parameters were reported as hardness, adhesiveness, cohesiveness, and springiness. Hardness was defined as the maximum force that raptured the gel for the first compression. At least five measurements were carried out, and each texture parameter was expressed as an average value.

2.5 Swelling power and solubility

The swelling power and solubility of each sample were determined according to Hormdok et al. [20]. Each sample (0.5 g, dry weight) was mixed with 15 mL distilled water in centrifugal tubes. The suspensions were heated at 95°C for 30 min. The gelatinized samples were cooled at room temperature and then centrifuged (Tomy Mx-30, Japan) at 3,500 rpm for 15 min. The separated supernatant was dried at 100 °C to a constant weight. Swelling power defined as the ratio of the weight of the swollen starch granules to the initial dry sample weight. Solubility was expressed as the percentage of dried solid weight that dissolves in water by the dry sample weight. The measurements were carried out in triplicates.

2.6 Freeze-thaw stability

The determination of freeze-thaw stability was adapted according to Yang et al. [21]. The starch suspension (6%, w/v) was boiled in a water bath (Memmert WB7, Germany) at 95 °C for 30 min with constant stirring to prevent granule sedimentation. After cooling, 15 g of each gel was placed in a centrifuge tube, frozen at −18°C in a Chest Freezer (SANYO SF-C997, Thailand) for 24 h, and thawed at room temperature for 3 h. To measure the freeze-thaw stability, each gel was frozen, thawed, and refrozen for seven freeze-thaw cycles. Syneresis of the starch gels was determined by centrifuging the gel after thawing for 5, and 7 cycles at 1,000x g for 15 min. The water leached out of the starch gel was carefully separated after centrifuging using a syringe [22] and calculated as g of the released water by the initial gel weight (g/100 g gel). The thawed gels were dried by a freeze dryer (Alpha 1-4 LSCplus, Germany) at 0.1 mbar, -50 °C for 24 h. Surface of cross-section gels were carried out using a stereo microscope (Meiji EMZ-5, Japan). This technique uses the transmitted light through the sample.

2.7 Statistical analysis

The experiments were carried out in triplicates except for the texture analysis, and the mean values ± standard deviations were reported. Duncan's multi-range test was used for determination significant differences between the data ($p < 0.05$).

3 Results and discussion

3.1 Pasting properties

The pasting profiles of RF, TS, CL, AC, and RF blended with 5, and 10% of TS and both modified starches are shown in Fig 2. RF exhibited the highest pasting temperature (84.45±0.48 °C), while the pasting temperature of TS (74.35±0.05 °C) was significantly lower ($p < 0.05$), as presented in Fig. 2 (A). The pasting temperatures of RF blends with TS at 10% by weight significantly decreased to 79.35±0.05 °C. Peak viscosity and trough of the RF blends in the profile were significantly increased in RF-TS5 and RF-TS10, while breakdown and setback were not significantly affected by the blending of TS up to 10% by weight. The final viscosity of RF-TS increased significantly with the blending of TS at 10% by weight.

Pasting temperatures of both LCL (71.32±0.46 °C) and HCL (72.48±0.59 °C) were lower than pasting temperatures of RF and TS, causing the reduction of pasting temperatures for RF blends at both concentrations (Fig 2 (B)). The cross-linked starches with the low degree of crosslinking (LCL) showed a higher peak viscosity (387.97±3.39 RVU) than that of the RF (222.81±3.84 RVU), while the higher degree of crosslinking (HCL) resulted in a much higher peak viscosity at 441.36±5.19 RVU. However, the peak viscosity of RF was significantly increased ($p < 0.05$) when HCL was added up to 10% by weight. The increases of the trough were observed in RF-LCL10 (194.31±4.40 RVU), the blending of RF with LCL at 10%, and HCL at 5%, and 10% by weight significantly increased the trough from 182.22±4.00 RVU to 194.31±4.40 RVU, 192.89±2.74 RVU, and 218.84±4.72 RVU, respectively. Only the breakdown of RF-HCL5 was lower than that of RF, while the other samples did not show any difference in the breakdown. Breakdown is caused by the disruption of the gelatinized starch structure at high temperatures [7]. In addition, only the blending with HCL at 5% and 10% could increase the final viscosity and setback of the blend of RF-HCL5 and RF-HCL10. High final viscosity would relate to a high resistance to the shear of the blend [7]. The breakdown of the RF blends decreased with increasing concentrations of LCL and HCL, while RF-HCL10 had the lowest breakdown (29.47±0.55 RVU). Therefore, blending RF with HCL tended to reduce the breakdown and increase the setback of the flour blend, which is preferable for rice noodle preparation. Crosslinking with different reagents or modification methods significantly altered the pasting attributes of starches [1]. Generally, cross-linked starches are resistant to high temperature and shear, resulting in lower breakdown in addition to stabilized granular structure and restricted swelling [23].

Starch acetylation led to a much lower pasting temperature, as shown by LAC and HAC (Fig. 2 (C)). The higher acetylation degree yields a lower pasting temperature for the acetylated starch. The increased content of the AC, especially resulted in a much lower pasting temperature of the flour blend as presented by RF-HAC10 (71.30±0.52°C). HAC exhibited the highest peak viscosity compared to all other starches. However, blending with LAC and HAC up to 10% did not significantly affect the peak viscosity of the RF blend. The highest breakdown was exhibited by blending HAC at 10% by weight. High breakdown indicates to low resistance to a shear force of starch granules, which is considered a low cooking intolerance [24]. The blending with HAC at 5% and 10% by weight significantly reduced the final viscosity of the RF blend, while the blending of LAC and HAC at both concentrations significantly reduced the setback of all mixtures. AC has a different role depending on the degree of substitution, [3]. Normally, physicochemical characteristics of modified starch by acetylation were as low gelatinization temperature, high solubility, stability at low temperatures, and resistance to retrogradation [12, 25]. Therefore, AC was suitable for products that require short cooking time, or storage at low temperatures.

Pasting properties generally correlate with the quality of rice starch or flour used, a raw material for producing rice noodles [24]. RVA parameters were related to cooking and eating quality and could be used as a prediction to evaluate the quality of products [26].

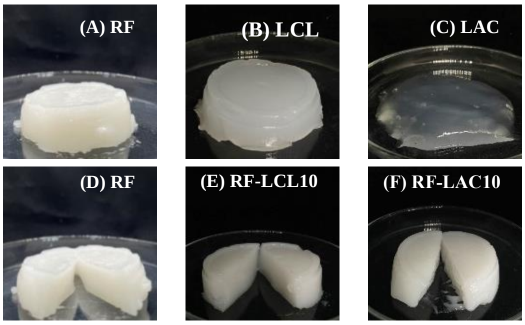

Fig. 1. Appearances of the rice flour, RF (A); cross-linked starch with low degree of crosslinking, LCL (B); and acetylated starch with low degree of substitution, LAC (C); and cross section of RF, and RF blended with LCL, and LAC at 10% by weigh (D, E, and F)

The texture of the rice noodles would be reinforced by the re-association of a three-dimensional network of amylose known as "set back" or "retrogradation" during cooling after the steaming process in rice noodle manufacturing [24]. The broken rice flour was usually mixed with flour from various rice varieties with different amylose content, which caused the inconsistent quality of the rice noodles [27]. Instead, blending with appropriate or modified starch would facilitate the production of products with more consistent quality.

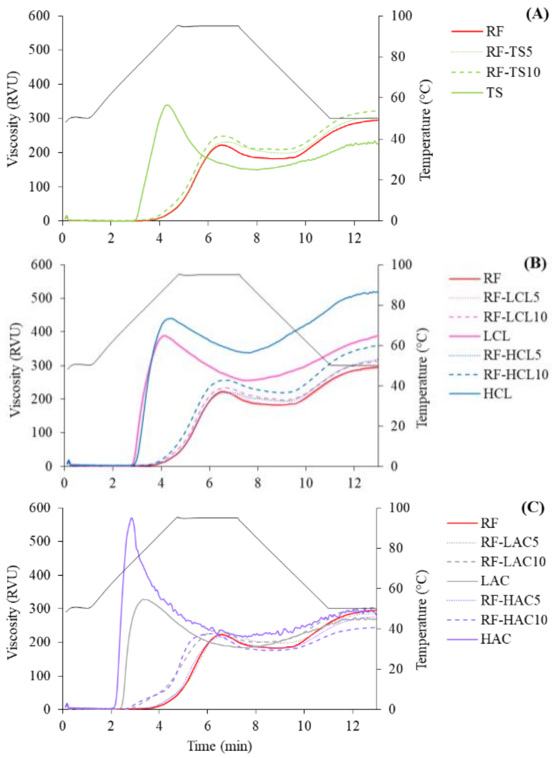

Fig. 2. Pasting profiles of rice flour (RF) and RF blended with 5%, and 10% of tapioca starch, TS (A); Crosslinked starch, CL (B); Acetylated starch, AC (C). LCL and HCL: Crosslinked starch with low and high degree of cross-linking respectively; LAC and HAC: acetylated starch with low and high degree of substitution respectively.

3.2 Gel properties

The textural properties of the gels prepared from RF blended with different concentrations of TS, and both modified starches are shown in Table 2. The higher hardness of the RF blend for the formation of gel structure was confirmed by their gel high cohesiveness and gumminess. RF-LAC10 gel showed the highest hardness of 1,577±48 g compared to the other samples. Blending with both TS and LCL at 5% and 10%, and LAC and HAC at 5% by weight did not affect the hardness of RF blend gels. Cohesiveness is related to the internal bonds that constitute the noodle structure [28]. High adhesiveness was obtained from all RF blends, especially RF-LAC10 gel, which showed the highest adhesiveness of -2,824±56 g/s, which indicated that RF blended with LAC up to 10% was highly sticky. Moreover, the higher hardness of RF gel was due to rigidity bond of the starch granule because of its low swelling power and solubility [2]. The springiness of all samples had no significant difference ($p < 0.05$), ranging from 0.92 to 0.98.

Blending with cross-linked starch was expected to yield a gel with a higher hardness, as described by the increase in the setback in Fig. 2. However, we have observed that the gel from RF blended with acetylated modified starch showed a higher gel consistency and resistance to rapture than the RF blended with cross-linked starch. Saartrat et al. [25] reported that the softer gel of acetylated canna starches demonstrated that acetyl groups introduced into the starch molecules resisted the formation of the amylose network. The observation of gels during the probe compression, it was found that RF blended with LCL and HCL was hard and brittle, while RF blended with LAC and HAC was soft and elastic. The characteristics of the gels in this study were similar to acetylated canna starch gels at different degrees of substitution which had a soft and elastic appearance and the probe surface were stuck with some gels [25]. The hardness was defined as the maximum force required to rapture the gel during the first compression in this study, which might not be related to the direct term for the hardness of food products. Hence, more detailed studies are required in the future.

The appearances of the gels after storage at -4°C for 24 h are shown in Fig. 1. The RF-LCL10 gel (Fig. 1(B)) presents a smooth surface both outside and inside after being cut by a knife, showing an improved gel texture of the RF blended with LCL at 10% by weight. A gel with a higher sticky texture was obtained from RF-LAC10, which could be observed from the gel sticking to the knife and a less smooth surface compared to RF-LCL10. The gel properties described were in line with the adhesiveness presented in Table 1. The gel properties of starch are important factors in controlling the texture of food products, especially rice starch noodles [29].

3.3 Swelling power and solubility

The swelling power and solubility of flour and starch are summarized in Table 2. Swelling power indicates the water-holding capacity of starch and is normally used to classify the differences between each starch type. Thus, higher water absorption of starch is related to granules swelling [11]. Swelling power and solubility of RF-TS5 and RF-TS10 did not differ significantly ($p < 0.05$) compared to the RF. The blending with TS at 5% and

10% by weight also did not affect to the water absorption of the blended RF.

The swelling power and solubility of RF-LCL5 and RF-LCL10 were not different ($p < 0.05$) compared with the RF. Swelling power of RF-LCL5 and RF-LCL10 tended to reduce to 11.61±0.08 g/g and 11.82±0.66 g/g, respectively. Crosslinking strengthens the bonding between the amylose and amylopectin chains, resulting in increased resistance to swelling of the starch granules [8]. However, swelling power of the CL, both LCL (10.38%) and HCL (19.00%) in our study, presented a higher swelling power than that of tapioca starch (3.48%), which were responding well to the peak viscosities explained above. The crosslinking method with a certain level of crosslinking might give the more rigid structure of starch molecule that can absorb more water before breaking down. Therefore, Blending LCL resulted in lower swelling power of RF-LCL5, which RF-HCL10 has a higher swelling power (14.20±0.20 g/g) than RF and RF blended with LCL ($p < 0.05$). As a result of The properties of swelling power and solubility of cross-linked starches differ with the source of starch, crosslinking reagent, and crosslinking method [1]. Blending 5%, and 10% by weight of LCL, and HCL into RF did not significantly affect the solubility of the samples.

Table 1. Swelling power, solubility of RF, TS, modified starches, and RF blended with different concentrations of each starch.

Samples	Swelling power (g/g)	Solubility (%)
RF	12.41±0.51^{efg}	13.39±0.48^{fgh}
RF-TS5	12.63±1.49^{efg}	11.91±0.94^{h}
RF-TS10	12.26±0.52^{fg}	14.68±0.45^{efg}
TS	3.48±0.45^{i}	74.70±1.89^{c}
RF-LCL5	11.61±0.08^{g}	13.77±0.21^{fgh}
RF-LCL10	11.82±0.66^{g}	13.30±0.55^{fgh}
LCL	10.38±0.03^{h}	17.97±0.87^{d}
RF-HCL5	13.01±0.09^{ef}	13.33±0.07^{fgh}
RF-HCL10	14.20±0.20^{d}	12.79±0.04^{gh}
HCL	19.00±0.35^{c}	6.05±0.84^{j}
RF-LAC5	13.02±0.43^{ef}	12.89±0.10^{gh}
RF-LAC10	13.42±0.16^{de}	15.00±0.53^{ef}
LAC	24.62±0.48^{a}	81.49±0.70^{a}
RF-HAC5	13.19±0.26^{def}	16.52±1.29^{de}
RF-HAC10	19.83±0.42^{b}	8.90±0.85^{i}
HAC	25.24±0.40^{a}	76.69±2.86^{b}

Values followed by a different superscript in each column differ significantly ($p < 0.05$).

The swelling power of RF blended with 5 % by weight of LAC, and HAC did not differ significantly compared to RF. Blending of both acetylated starches resulted in increasing swelling power of blended RF, which RF-HAC10 showed the highest swelling power of 19.83±0.42 g/g. The viscosity changes during heating in Fig. 2 (C) showed that both LAC and HAC had high swelling power. Highest swelling of the starch granules may already be reached at a lower temperature than the other samples because of their low pasting temperature. The swelling process mainly happens in the amorphous region. Introducing acetyl groups to the starch molecules helps water permeate the inner space of starch granules more easily [30]. LAC and HAC showed higher solubility (81.49±0.70% and 76.69±2.86 respectively) than RF, TS, LCL, and HCL, which LAC was highest solubility.

Therefore, RF blended with 5% and 10% of TS, LCL, HCL, LAC, and HAC did not affect their swelling power, except for RF-HCL10 and RF-HAC10, which showed a higher swelling power. Blending with HAC, both concentrations have affected on increasing the swelling power of the blended RF. Moreover, the higher swelling power might be due to the lower granule rigidity of the starch. During gelatinization, molecules of soluble and leached-out polymeric from starch granules exhibit a higher solubility [2]. Solubility is associated with the degree of rice starch dispersion at high temperatures. Lower solubility resulted in lower cooking losses for rice noodles [25].

3.4 Freeze-thaw stability

Freeze-thaw stability of starch gels was determined from syneresis, is regarded as an indicator of the ability to resist undesirable physical changes during the

Table 2. Texture properties of the gels obtained from RF, RF blended with TS, and modified starches at different concentrations

Samples	Hardness (g)	Adhesiveness (g/s)	Cohesiveness	Springiness^{ns}	Gumminess
RF	1,316±222^{bc}	-1,188±96^{a}	0.45±0.19^{b}	0.93±0.05	562±132^{c}
RF-TS5	1,420±175^{ab}	-1,564±308^{a}	0.47±0.14^{b}	0.92±0.05	649±109^{bc}
RF-TS10	1221±64^{cd}	-1,477±639^{a}	0.67±0.08^{a}	0.97±0.03	809±65^{ab}
RF-LCL5	1,238±87^{bcd}	-1,057±517^{a}	0.55±0.12^{ab}	0.95±0.04	669±118^{bc}
RF-LCL10	1,130±68^{cd}	-1,222±67^{a}	0.67±0.02^{a}	0.98±0.00	761±74^{ab}
RF-HCL5	1,104±34^{d}	-942±359^{a}	0.59±0.10^{ab}	0.97±0.01	653±128^{bc}
RF-HCL10	1,051±38^{d}	-1,289±77^{a}	0.62±0.06^{ab}	0.97±0.01	653±80^{bc}
RF-LAC5	1,232±46^{bcd}	-1,454±420^{a}	0.70±0.04^{a}	0.97±0.02	870±73^{a}
RF-LAC10	1,577±48^{a}	-2,824±56^{b}	0.57±0.03^{ab}	0.93±0.04	916±37^{a}
RF-HAC5	1,246±37^{bcd}	-1,274±52^{a}	0.69±0.00^{a}	0.98±0.00	866±30^{a}
RF-HAC10	CD	CD	CD	CD	CD

Values followed by a different superscript in each column differ significantly ($p < 0.05$).
ns: not significantly different at $p < 0.05$.
CD: could not measure for TPA because the sample did not set into gel

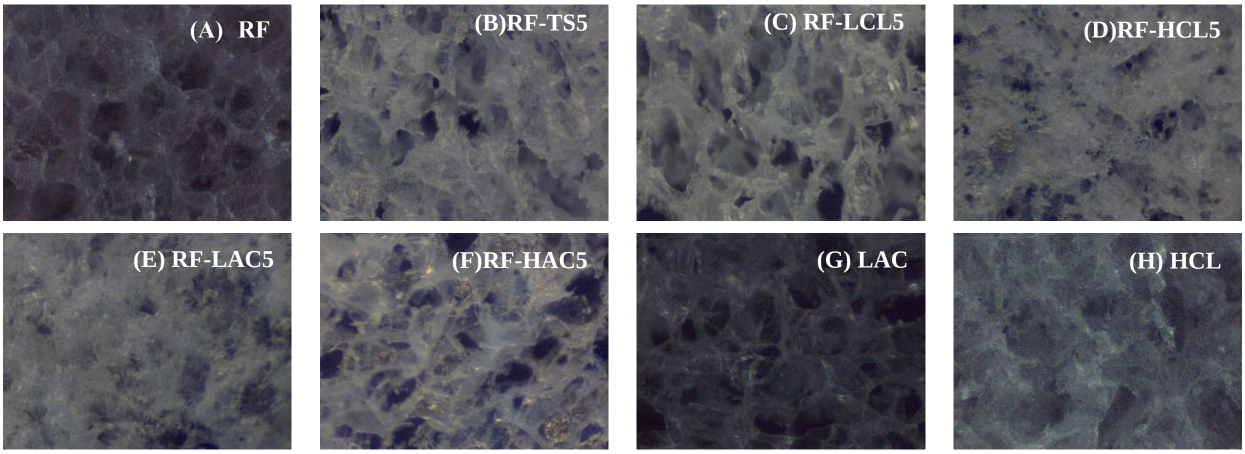

Fig. 3. Stereo micrographs of a cross-section of the gels from rice flour, RF (A); RF blended with TS, LCL, HCL, LAC, and HAC at 5% by weight (B, C, D, E, and F); LAC, and HCL (G and H) after seven freeze-thaw cycles (storage at −18 °C).

freezing and thawing. The syneresis of RF, TS, CL, AC, and RF blended with TS and each modified starch is presented in Table 3. Overall, most RF blend gels' syneresis increased with increasing freeze-thaw cycles. The syneresis was increased during storage due to retrogradation or re-association of the starch molecules between leached-out amylose and amylopectin chains [8, 30]. Crosslinking was reported to result in an ordered structure of the starch pastes with a higher degree of retrogradation. The paste became more stable at low temperatures [8]. RF blended with LCL at both concentrations indicates the highest syneresis at five cycles. HLC showed very low syneresis, while LAC and HAC did not, indicating their potential for improving freeze-thaw stability [1]. The syneresis of RF-TS10, RF-HCL5, RF-HCL10, and RF-HAC10 gel at five cycles was significantly reduced from RF gel (22.52±0.71 g/ 100 g gel) to 17.25±2.46, 18.44±2.07, 14.44±0.06, and 17.53±0.38 g/ 100 g gel, respectively. The bond strength between starch molecules is reduced by the introduction of acetyl upon acetylation, resulting in an increased swelling power and solubility of the starch granule, decreased starch coagulation, and improved stability of starch for freezing and thawing [31]. The syneresis of all RF blend gel at seven cycles was higher than RF gel, except for RF-HCL5, RF-HCL10, and RF-LAC5. More importantly, all the syneresis of RF-HCL5 and RF-HCL10 gels was significantly ($p < 0.05$) lower than that of RF gel at seven freeze-thaw cycles, indicating that crosslinked starch with a high degree of crosslinking could effectively improve the freeze-thaw stability of RF gels to reduce their syneresis. In addition, the syneresis at seven freeze-thaw cycles of the gels using acetyl starch at seven, both LAC and HAC, was about twice times those at five cycles. This might be because of the limited re-association of starch molecules after many freeze-thaw cycles [8].

3.5 Surface of starch gel

The topographical surface of the frozen gel after seven freeze-thaw cycles is shown in Fig. 3. The formation of ice crystals from slow-freezing created different regions of the starch matrix and aggregation of facets in the starch phase [2]. The gel was frozen in a chest freezer, which indicates a slow freezing rate. Slow freezing possibly produced large ice crystals; therefore, a non-homogenous structure was seen in slow freezing. RF gel and RF blended with TS, CL, and AC gel after seven freeze-thaw cycles showed that a cross-section of

Table 3. Syneresis of RF, TS, CL, AC, and RF blended with TS, and each modified starch at 5, and 7 freeze-thaw cycles expressed as g of total water released from 100 g of the gel (g/ 100 g gel).

Sample	Cycles 5	Cycles 7
RF	$22.52±0.71^{b}$	$31.62±0.15^{de}$
RF-TS5	$20.44±3.00^{bcd}$	$35.84±1.43^{ab}$
RF-TS10	$17.25±2.46^{de}$	$33.13±0.45^{cde}$
TS	$4.20±0.28^{g}$	$5.81±0.68^{i}$
RF-LCL5	$32.08±2.69^{a}$	$31.46±1.52^{e}$
RF-LCL10	$32.61±4.07^{a}$	$33.56±0.89^{cd}$
LCL	$10.12±1.03^{f}$	$18.57±0.64^{h}$
RF-HCL5	$18.44±2.07^{cd}$	$24.33±0.88^{g}$
RF-HCL10	$14.44±0.06^{e}$	$28.19±0.97^{f}$
HCL	$1.78±0.17^{gh}$	$2.36±0.46^{j}$
RF-LAC5	$21.40±0.80^{ab}$	$29.55±1.76^{f}$
RF-LAC10	$19.09±0.16^{bcd}$	$37.72±2.09^{a}$
LAC	ND	ND
RF-HAC5	$20.11±2.35^{bcd}$	$36.05±0.58^{ab}$
RF-HAC10	$17.53±0.38^{de}$	$34.81±0.04^{bc}$
HAC	ND	ND

Values followed by a different superscript in each column differ significantly ($p < 0.05$).
ND, not detected syneresis of the gels

RF gel exhibited large pores with rough surfaces (Fig. 3A). RF-HCL10 presented the lowest syneresis at seven cycles (Table 3) and the gel structure was more homogeneous than the other samples (Fig. 3D). Even though RF blended with AC exhibited higher syneresis than RF blended HCL, it obtained a smooth texture after all freeze-thaw cycles. Amylopectin chains reportedly formed and absorbed water during heating but could not retain the water during centrifugation [29], leading to syneresis. Seetapan et al. [2] reported that spongy texture in RF gels could be inhibited with TS addition.

4 Conclusions

The blending of RF with TS, CL with different degrees of crosslinking, and AC with different degrees of substitution resulted in different pasting profiles. RF-TS and RF-CL obtained higher viscosity with increased TS and CL concentrations than RF. Mixing RF with AC presented a lower final viscosity and setback than RF and the other samples. The pasting profile of blended RF can be used to predict the properties of food products. The hardness of RF blended with TS, and CL tended to increase the increased adhesiveness, cohesiveness, and springiness, but RF blended with AC showed contrasting results. The blending of TS, and CL is expected to improve the quality of the RF blend when applied to the quality development of rice noodles. The higher swelling power was obtained from RF-HCL, RF-LAC, and RF-HAC.

The topographical surface of the frozen gel after seven freeze-thaw cycles showed that RF-HCL could prevent the synthesis of the gel from the RF blend, and a homogenous structure was observed. These results showed that the RF blended with a higher ratio of TS and CL would have desirable and improved rheological properties for further product development, especially rice noodles, frozen rice noodles, or instant noodles.

Acknowledgment

The authors would like to thank Mrs. Onpapha Morin, chief executive officer, Aura Food Co., Ltd. for the support of raw materials and the Electric Stone-Milling machine, and Siam Modified Starch Co., Ltd., Pathumthani, Thailand for the support of acetylated starch.

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