Influence of Hydroxy Phosphorylated of Wheat Starch on Chinese Fresh White Noodles

Huili Yan Henan University of Technology, Zhengzhou, China Email: yanhuili2000@163.com

Qiyu Lu and Cuicui Li Henan University of Technology, Zhengzhou, China Email: qiyulu7120@163.com, woshilicui886@sina.com

Abstract—The effect of hydroxyl phosphorylated of wheat starch on Chinese fresh white noodles was studied by recombining phosphorylated wheat starch with other flour components to prepare noodles. Though the morphology and crystalline pattern of phosphorylated wheat starches did not change significantly, the substitution of hydroxyls would weaken the binding between starch and water molecular and lead to a shift of water molecules from immobilized to less immobilized fraction in fresh noodles. The average particle size of phosphorylated starches increased with the degree of substitution increase, and the gluten network of the reconstituted flour noodles was similar to that of the original flour noodles when the size of phosphorylated starch was close to that of native starch. There was a significant correlation between starch swelling power, pasting properties and noodle texture. When hydroxyl groups were replaced by phosphate groups, the swelling power and RVA parameters of starch decreased, which further led to the reduction of noodle hardness, springiness, resilience, cohesiveness, and chewiness. The results indicated that hydroxyl phosphorylated of wheat starch had an important effect on water distribution and texture characteristics of fresh noodles.

Index Terms—hydroxyl groups, phosphorylated wheat starch, moisture distribution, noodle texture

I. INTRODUCTION

Starch is the major component of flour, comprising about of 70% - 80% of flour, and it has a crucial impact on the processing performance of wheat flour and noodle [1]-[3]. Among all the quality starch-related physicochemical properties, gelatinization and swelling properties have been found to be highly correlated with the eating qualities of noodles [4]-[6]. Hydroxyls are the most abundant groups in starch, which are important to maintain the helical structure in crystalline part of starch, and further affecting the gelatinization and swelling properties of starch [7]-[9]. Therefore, there should be some relationship between hydroxyl groups and noodle quality. However, there is no direct method to study the effect of hydroxyl groups on noodle quality at present.

Although lack of direct way to study hydroxyls, the hydroxyl groups on starch chains can be replaced by commonly used chemical modification, such as esterification and etherification, to achieve the result of "masking" hydroxyl groups. Till now, most studies are focus on the influence of modified starches such as corn, potato and cassava on noodle quality, expecting to develop better noodle quality improvers. A few papers involve modified wheat starches, in which the modified starches were used as fat replacer in the production of yogurt and bread [10], [11]. There is little information about how the changes of starch structure, especially hydroxyl groups, affect noodle quality, only the research of Zhang et al. covered [12].

In this study, hydroxyl groups were replaced by sodium trimetaphosphate (STMP), and the other structure of wheat starch was ensured to remain unchanged maximally. The changes in the quality of wheat starch and noodles were studied after hydroxyls were replaced by phosphate groups. Although not directly proved the effect of hydroxyls, the results would go a step further towards revealing the mechanism of hydroxyl groups on noodles.

II. MATERIALS AND METHODS

A. Fractionation of Flour

The wheat flour used in this study was a commercial high-grade flour (Jinyuan cereals and oils Co., Henan, China). Starch, gluten, and water solubles were isolated by the handwashing method described by Zhang et al^[13] with slight modifications. Flour (150 g, 14% wet basis) was mixed with 80 ml of distilled water for 8 min using a mixer (Nanchang Daidayin Machinery Equipment Co., Jiangxi, China). The dough was placed in a beaker containing 200 ml of distilled water for 20 min and gently kneaded with one hand, then the liquid phase was decanted. Washing and kneading steps were repeated with a series of amounts of water (2 \times 150 ml, 4 \times 100 ml, 4 \times 75 ml, and 6 \times 50 ml). After each wash step, the liquid phase was drained through a 100-mesh screen and collected. Small pieces of dough or gluten on the screen were added back to the dough mass. The filtrate was centrifuged at $3,300 \times g$ for 10 min to obtain water solubles and starch.

Manuscript received June 1, 2019; revised October 15, 2019.

Gluten mass and starch were lyophilized, and water solubles was freeze dried after rotary evaporation at 35 °C. Starch was ground in a mortar, and gluten mass together with water solubles were powdered by high-speed universal mill (Beijing Ever Bright Medical Treatment Instrument Co., Beijing, China), and all the components were passed through a 100-mesh sieve, respectively.

Moisture was determined by AACC International Approved Method 44-16.01. The dry weight ratio of starch and G-S component (gluten and water solubles) in the raw flour was 0.8074:0.1926.

B. Substitution of Starch Hydroxyl Groups by Phosphate Groups

The phosphorylated wheat starch was prepared by reference to the method described by Trksak et al. [14] with some modification. Wheat starch (250 g, dry basis), water (375 ml), STMP (50 g, 20% based on dry starch), sodium sulfate (Na2SO4, 12.5 g, 5% based on dry starch) were combined, and the mixture was adjusted to pH 11 by adding 3% sodium hydroxide. The slurry was stirred continuously at 35°C for 1 h. Then the slurry was adjusted to pH 6.5 by adding a blend of 3:1 distilled water/hydrochloric acid, and the starch was collected by centrifugation 4 times (no free phosphorus was detected). The starch was dried by lyophilization, ground in a mortar, and passed through a 100-mesh sieve. The reaction was repeated, but the STMP level was reduced from 20% to 15%, 10%, 5%, and 0, respectively. The phosphorus content in phosphorylated wheat starch was determined according to the method approved by the National Standard of China GB 5009.87-2016. The results were summarized in Table I below.

Sample ²	STMP	Na_2SO_4	Phosphorus ³
	(%)	(%)	(mg/100g)
WS	-	-	63.82±2.69 ^b
WS-0	0	5	53.85 ±4.13 ^a
WS-5	5	5	82.19±3.55°
WS-10	10	5	158.38±8.82 ^d
WS-15	15	5	185.56±3.46 ^e
WS-20	20	5	301.56±2.23 ^f

TABLE I. CONTENT OF PHOSPHORUS IN STARCH SAMPLES 1

¹ The amounts of STMP and Na₂SO₄ added are based on dry starch basis. ² WS represents Native wheat starch; WS-0, WS-5, WS-10, WS-15,

and WS-20 represent starches reacted with different amount of STMP, respectively.

³ Means within the same column followed by the same letter are not statistically different (P < 0.05).

C. Reconstitution of Flours

Starch samples with different STMP level and G-S component were blended at the ratio of 0.8074:0.1926 on dry basis, respectively, and the reconstituted flours were rehydrated to~14% moisture as described by Guo *et al.* [15].

D. Raw Noodle-making

The original flour or recombinant flours (100 g, dry basis) and a certain volume of distilled water (the final moisture content of all noodle samples was 34.22%) were mixed in a JHMZ 200 mixer (Beijing Dongfujiuheng

Instrument Technology Co., Beijing, China) for 5 min, and the dough obtained was allowed to rest in sealed containers at room temperature for 20 min. Then the dough was sheeted and cut into noodles following the procedure described by Lu *et al.* [16]. The raw noodles were placed in a zip-lock bag and stored at 4° C for later use.

E. Determination of Moisture Distribution

Moisture distribution of fresh noodles was determined by Low-field Nuclear Magnetic Resonance (Suzhou Niumai Analytical instrument Co., Jiangsu, China). Transverse relaxation times (T2) were measured using the Carr-Purcell-MeiboomGill (CPMG) sequence with the following parameters: Spectral Width (SW), 333.333 kHz; echo time (TE), 0.100 ms; waiting time (TW), 1500 ms; scanning number (NS), 32; echo count (NECH), 1500. The relaxation measurements were performed at the optimal operating temperature of 35 °C, and each sample was triplicated.

F. Microstructure of Gluten Network of Fresh Noodles

The microstructure of gluten network of fresh noodles was observed with a FluoView FV300 confocal laser scanning microscopy (CLSM, Olympus, Tokyo, Japan). The noodles were cut into 10 μ m slices, and then dyed with 0.05% (w/v) fluorescein isothiocyanate (FITC, Sigma) solution. After staining for 20 min, the sliced noodles were washed until no more free dye was released, and viewd by CLSM.

G. Texture Analysis of Cooked Noodles

Noodles (21 strips, 10 cm in length) were cooked for 2.5 min in 500 ml of boiling distilled water. The cooked noodles were placed in 500 mL of distilled water (20 $^{\circ}$ C) for 10 sec, drained for 30 sec, and analyzed by texture profile analysis (TPA) using the TA.XT.plus texture analyser (Lotun Science Co., Taipei, China). The testing procedure was performed according to the method described by Zhang *et al.* [13].

H. Preliminary Study on the Influence Mechanism of Hydroxyl Phosphorylated on Noodle Quality

1) Microscopic visualization of starch granules

The starch samples were coated with gold powder, and

then observed with scanning electron microscopy (SEM, FEI, Oregon, USA) at 3.0 kV. The magnification was set at $3000 \times$.

2) Crystalline pattern analysis

The crystal structure of starch samples was measured by D8 Advance X-ray diffractometer (Bruker, Baden-Württemberg, Germany). The X-ray diffraction (XRD) analysis was performed at 40 kV and 40 mA with Cu-K radiation. The samples were scanned from 5 ° to 35 ° (20) with a scanning speed of 3°/min and sampling interval of 0.02 °.

3) FTIR spectroscopy

The dry samples were crushed with patassium bromide and pressed into pellets. Spectral scanning was done with WQF-520 FTIR machine (Beijing Beifen-Ruili Analytical Instrument (Group) Co., Beijing, China) in the range between 4000 and 400 cm⁻¹.

4) Particle size analysis of starch granules

The particle size distribution of starch granules was determined by BT-9300S laser particle size analyser (Dandong Better Instrument Co., Liaoning, China), and the starch suspension was prepared by mixing dry starch with distilled water.

5) Swelling power and solubility measurement

The swelling power and solubility of starch samples were measured according to the method described by Chen *et al.* [17].

6) Pasting properties of starches and its relationship with swelling power and noodle texture

The pasting properties of starch samples were determined in duplicate using a rapid viscosity analyser (RVA, Perten, Hägersten, Sweden) according to AACCI Approved Method 76-21.01. Pearson correlation analysis was conducted to analyze the relationship between starch swelling power, pasting properties and noodle texture.

I. Statistical Analyses

Analysis of variance (ANOVA) and Pearson correlation analysis were performed using SPSS Statistics17.0 (IBM, NewYork, USA). Significance of differences was defined at P < 0.05, and significance of correlations was defined at P < 0.05 or P < 0.01. The Graphs were drawn by OriginPro 9.0.0 (OriginLab, Massachusetts, USA).

III. RESULTS AND DISCUSSION

A. Substitution Degree

Although the reaction product of wheat starch with STMP was a mixture of monoester and diester, the main product at higher pH was diester, i.e. cross-linked starch [14]. Considering the existence of monoester, it was difficult to calculate the exact degree of substitution, so the content of phosphorus in starch samples were determined to reflect the degree of esterification (cross-linking) of wheat starch. The content of phosphorus in native wheat starch and esterified starch was listed in Table I. When the dosage of STMP was 0,

the content of phosphorus in WS-0 decreased compared with the original starch, which indicated that the original phosphorus in starch partially dissolved into the solvent under the blank treatment, resulting in the decrease of phosphorus in WS-0. With the increase of STMP, the content of phosphorus in starches increased significantly, demonstrating that hydroxyl groups on starch were gradually replaced by phosphate groups, and the degree of esterification increased.

B. Effect of Hydroxyl Substitution on Moisture Distribution of Fresh Noodles

The distribution of water in fresh noodles changed after hydroxyl groups were replaced by phosphate groups, as shown in Table II. The spin-spin or transverse relaxation time constant of protons, T₂, reflects the relative molecular mobility of water in the system compared with free water. When water is bound tightly to macromolecules (e.g., protein matrix), it is highly immobilized and shows reduced T₂, whereas free water is readily mobile and has relatively long T₂ [18]. P represented the peak area ratio that was proportional to amount of water in the sample. As listed in Table II, esterification had little effect on T_{23} and P_{23} (*P* >0.05), indicating that there was no significant change in free water content in fresh noodles. T₂₁ of NWS-5, NWS-10, NWS-15, and NWS-20 was almost all larger than that of NWS and NWS-0 while T₂₂ was the opposite, indicating that the tightly bound water became mobile, and this part of the water was mainly closely bound to starch or protein matrix. At the same time, the content of water in T₂₁ state decreased compared to that of NWS and NWS-0. A decrease of water in T₂₁ state resulted in an increase of water in T₂₂ state, indicating a shift of water molecules from immobilized to less immobilized fraction. As the protein matrix kept consistently in all recombinant samples, the change of water state in this study was mainly due to the substitution of hydroxyl groups, which led to the binding between starch and water became weaker.

Sample ²	T ₂₁ /ms	T ₂₂ /ms	T ₂₃ /ms	P ₂₁ /%	P ₂₂ /%	P ₂₃ /%
NWS	0.13±0.02 ^{bc}	5.34±0 ^a	100.22±22.58 ^a	18.08 ± 1.57^{abc}	81.02±1.44 ^{abc}	0.90±0.20ª
NWS-0	0.13±0.02 ^{bc}	4.86±0.19 ^b	$110.51 \pm\!\! 15.50^a$	18.62±0.43 ^{ab}	80.77±0.43 ^{bc}	0.60±0.10 ^a
NWS-5	0.21 ± 0.04^{a}	4.75±0.19 ^{bc}	103.28±33.44 ^a	15.93±2.80 ^{bc}	83.33±2.76 ^{ab}	0.74±0.13 ^a
NWS-10	$0.18\pm\!0.057^{ab}$	4.43±0.18 ^{de}	100.65±14.01 ^a	16.39±1.33 ^{bc}	82.88±1.42 ^{ab}	0.73±0.19 ^a
NWS-15	0.12±0.01°	4.23±0.17 ^e	89.95 ± 16.00^{a}	20.35±2.04ª	78.84±2.01°	0.80±0.11ª
NWS-20	0.16±0.03 ^{abc}	4.54±0.18 ^{cd}	110.17±11.92 ^a	14.79±2.35°	84.39±2.22ª	0.82±0.14 ^a

 TABLE II.
 MOISTURE DISTRIBUTION OF FRESH RAW NOODLES¹

¹Means within the same column followed by the same letters are not statistically different (P < 0.05).

²NWS represents noodles made from raw flour; NWS-0, NWS-5, NWS-10, NWS-15, and NWS-20 represent noodles made from reconstituted flours containing WS-0, WS-5, WS-10, WS-15, and WS-20, respectively.

C. Gluten Network of Fresh Noodles Observed by CLSM

CLSM was used to visualize the microstructure of gluten network of fresh noodles, and the gluten network

was seen in green by dying with FITC (Fig. 1). For NWS (Fig. 1A), the starch granules were evenly embedded in gluten network, and the gluten network was continuous and dense. There was no obvious distinction between the

gluten network of NWS-0 (Fig. 1B) and NWS, implying that reconstitution of components and blank treatment of starch did not cause distinguishable changes in gluten network. The gluten network of NWS-5 (Fig. 1C) was evidently different from other samples, and there were more tiny holes in the gluten network. As more and more hydroxyl groups were replaced, the gluten network of NWS-10, NWS-15, and NWS-20 (Fig. 1D-F) gradually improved, and the gluten network of NWS-20 was similar to that of NWS and NSW-0.



50µm

Figure 1. Microstructure of gluten network of fresh noodles. (A) NWS; (B) NWS-0; (C) NWS-5; (D) NWS-10; (E) NWS-15; (F) NWS-20.



Figure 2. Texture of cooked noodles. The same letters in the figure are not statistically different (P < 0.05).

D. Effect of Hydroxyl Substitution on Cooked Noodle Texture

The TPA parameters of NWS-5 and NWS-10 were not determined because of the delamination of NWS-5 and NWS-10 during the last pressing process and the serious

breakage of the strips during cooking, which may be related to the relatively poor gluten network structure. As shown in Fig. 2, the springiness, cohesiveness and resilience of NWS-0 were not significantly different from those of NWS, indicating that blank treatment has no significant influence on springiness, cohesiveness and resilience of noodles. However, when the hydroxyl groups were substituted by phosphate groups, cohesiveness and resilience of NWS-15 and NWS-20 decreased, and springiness also showed a decreasing trend, demonstrating that the changes of cohesiveness, resilience and springiness were caused by the substitution of hydroxyl groups. Compared with NWS, hardness and chewiness of NWS-0, NWS-15 and NWS-20 decreased gradually, which may be ascribed to two reasons: one was the substitution of hydroxyl groups on starch, and the other was the inevitable damage to starch during processing, and the former was the main reason for the gradient descent of hardness and chewiness.

The volume fraction taken up by starch granules is large in comparison to the surrounding polymeric network, and as a consequence, the relative consistency of the granules should have large effect on the overall texture of the composite [2]. The gluten network of NWS-20 was closer to NWS than that of NWS-15 in Fig. 1, but its TPA parameters were almost all less than that of NWS-15, which further proved that the changes of TPA parameters of noodles were mainly affected by the changes of starch properties.

E. Mechanism for the Influence of Hydroxyl Phosphorylated on Noodle Quality

1) Morphology of starch

Fig. 3 was the morphology of starch granules magnified 3000 times. Wheat starch can be divided into A-type starch and B-type starch according to their morphological size. The average diameter of A-type starch is generally larger than 10 μ m, and its shape is mostly disk or lenticular. The average diameter of B-type starch is generally less than 10 μ m, and its shape is mostly spherical or irregular. As shown in Fig. 3, the esterified wheat starch had no obvious changes in morphology, particle size and granular surface compared with native starch, which indicated that hydroxyl substitution had little influence on the external structure of starch. Therefore, the change of the properties of reconstituted flour noodles should not be affected by starch morphology.



Figure 3. SEM photographs of starch samples. (A) WS; (B) WS-0; (C) WS-5; (D) WS-10; (E) WS-15; (F) WS-20.



Crystalline pattern of starch granules

2)

Figure 4. XRD patterns of starch samples. (A) WS; (B) WS-0; (C) WS-5; (D) WS-10; (E) WS-15; (F) WS-20.

The XRD pattern of native wheat starch in Fig. 4 was typical A-type crystal structure of cereal starch, which showed strong diffraction peaks at around 15° , 17° , 18° and 23° [19]. With the increase of substitution degree, the crystal structure of starch had not changed significantly, and still presented A-type crystal structure (Fig. 4). In accordance with the results reported by Koo et al. [20], the crystalline form of corn starch remained unchanged after cross-linking reaction under the action of STMP, as the cross-linking reaction mainly took place in the amorphous region of starch granules, and did not change the crystalline patterns of starches.

3) FTIR analysis of starches

The FTIR spectrum of native and esterified starches was shown in Fig. 5. The characteristics absorption peaks of starches were substantially maintained in the process of esterification. The extremely broad band at about 3300-3500 cm⁻¹ was attributed to inner- and

intro-hydroxyl groups[17], and with the degree of esterification increased, the bands at about 3300-3500 cm⁻¹ tended to be wider and wider, which illustrated that more and more hydroxyl groups were replaced by phosphate groups. The characteristic peaks belonged to P=O (at aroud 1150-1130 cm⁻¹) did not show obvious change, and the characteristic absorption attributed to P-O-C (at aroud 810 cm⁻¹) was strengthened slightly with the degree of esterification increased [21]-[23]. This was probably due to the low cross-linking degree under the given experimental conditions, and only a few starch molecules had crosslinked with STMP. The results suggested that the substitution of hydroxyl groups did not significantly affect the chemical structure of starch, and it also proved that the changes of noodle properties were mainly caused by the substitution reaction.



Figure 5. FTIR spectrum of starch samples. (A) WS; (B) WS-0; (C) WS-5; (D) WS-10; (E) WS-15; (F) WS-20.

4) Particle size distribution

Size distribution of starch samples was shown in Fig. 6. With the degree of esterification (cross-linking) increasing, the D₁₀, D₅₀ and D₉₀ of phosphorylated starches were gradually increased, respectively, which was consistent with the results of Li et al.[21]. The D_{50} values of WS-0, WS-5 and WS-10 were lower than that of the native starch, which indicated that the average size of starch was decreased due to damage during separation and esterification process. However, with the degree of esterification increased, the effect of cross-linking on the size of starch exceeded that of starch damage, making the average size of WS-15 and WS-20 larger than that of the original starch. In addition, the D_{10} of esterified starches were greater than or equal to the original starch, while the D_{90} were smaller than the native starch, and this phenomenon suggested that the cross-linking reaction seemed more inclined to occur on B type starch or relatively small A type starch.

Particle size should be an important reason for the difference of gluten network in Fig. 1. Since the weight ratio of gluten to starch was the same in all reconstituted flours, the smaller the granule size is, the more starch granular surface needed to be covered by the gluten film, which would lead to the "thinning" of the gluten network[24].

As shown in Fig. 6, WS-5 possessed the smallest particle size, and its D_{90} and D_{50} were much less than that of the original starch, so the gluten network of NWS-5 was relatively poor, and there were more small holes in the gluten network. With the increase of particle size, the gluten network of reconstituted flour noodles gradually approached the original flour noodles.



Figure 6. Particle distribution of starch samples. (A) WS; (B) WS-0; (C) WS-5; (D) WS-10; (E) WS-15; (F) WS-20.

5) Swelling power and solubility of starches



Figure 7. Swelling power and solubility of starch samples. The same letters in the figure are not statistically different (P < 0.05).

The swelling power and solubility of starch samples were shown in Fig. 7. There was no distinct difference between the solubility of WS and WS-0, and the swelling power of WS-0 was slightly above that of WS. As was known in particle size analysis, starch was inevitably damaged during drying and grinding, and this probably was an important reason for the expansion of swelling power of WS-0 [25]. After esterification, the solubility and swelling power of WS-5 decreased sharply, and with more and more hydroxyls were replaced by phosphate groups, the solubility and swelling power of WS-15 and WS-20 decreased, but the downtrend was not

significant. The result was in agreement with the findings of Chen *et al.* [17] and Koo *et al.* [20] who respectively reported the reduced swelling power and solubility of cross-linked kudzu and corn starch, and this was related to the formation of inter-molecular bridges by phosphorous residual after cross-linking reaction, which strengthened the bonding between starch chains. Therefore, the phosphorylated starches were hardly to swell and disintegrate.

6) Pasting properties of starches and its correlation with swelling power and noodle texture

sample	$PV(cP)^2$	BD $(cP)^3$	$FV (cP)^4$	SB (cP) ⁵	
WS	2530 ^a	670 ^a	3070 ^a	1237 ^a	
WS-0	2342 ^b	363 ^b	3188 ^b	1208 ^a	
WS-5	51°	6 ^c	69 ^c	23 ^b	
WS-10	24 ^c	1°	31°	8 ^b	
WS-15	18 ^c	1 ^c	23°	7 ^b	
WS-20	16 ^c	3°	17°	4 ^b	

TABLE III. RVA PASTING PROPERTIES OF STARCH SAMPLES¹

¹Means within the same column followed by the same letters are not statistically different (P < 0.05).

² PV=Peak Viscosity; ³ BD=Breakdown; ⁴ FV=Final Viscosity; ⁵SB= Setback.

The RVA parameters were listed in Table III, and the gelatinization properties of starch changed greatly. Compared with native starch, the peak viscosity and

breakdown value of the blank sample decreased, the final viscosity increased, and the setback value had no significant difference. However, when the hydroxyl groups were replaced by phosphate groups, there was a marked drop in starch viscosity. The very low pasting viscosity profiles indicated that the cross-linked starches did not gelatinize fully at the maximum temperatures (< 95 °C) in which RVA was performed. The result was consistent with the swelling power in this study. For esterified starches, the peak viscosity, final viscosity and setback value decreased with the increase of esterification degree, but the differences of gelatinization parameters among WS-5, WS-10, WS-15 and WS-20 were very small.

Swelling power and rapid viscosity analyser values of starch were closely related to noodle texture properties [4]-[6]. The relationships between starch swelling properties, pasting viscosity and boiled noodle texture were summarized in Table IV. The swelling power was very significantly correlated with peak viscosity, final viscosity and setback value (P < 0.01), and it was significantly correlated with breakdown value(P < 0.05). The springiness, cohesiveness and chewiness of noodles had a significant correlation with the swelling power(P < 0.05), and the resilience of noodles had a very significant correlation with swelling power(P < 0.01). It could be concluded that the reduction of starch swelling power caused by the substitution reaction was an important factor affecting the texture of noodles.

	SP^2	PV	FV	BD	SB	HA ³	SR^4	$\rm CO^5$	CH^6	RE ⁷
SP	1									
PV	0.976**	1								
FV	0.982**	0.997**	1							
BD	0.894*	0.954**	0.931**	1						
SB	0.979**	0.999**	0.999**	0.944**	1					
HA	0.905	0.945	0.923	0.970*	0.936	1				
SR	0.972*	0.962*	0.970*	0.857	0.966*	0.823	1			
СО	0.985*	0.985*	0.987*	0.907	0.987*	0.953*	0.919	1		
СН	0.971*	0.989*	0.981*	0.955*	0.986*	0.980*	0.912	0.991**	1	
RE	0.995**	0.998**	0.998**	0.925	0.999**	0.943	0.957*	0.993**	0.990*	1

TABLE IV. The Relationships between Starch Swelling power, Pasting Properties and Boiled Noodle $$\rm Texture^1$$

¹** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

²SP=Swelling power; ³HA=Hardness; ⁴SR=Springiness; ⁵CO=Cohesiveness; ⁶CH=Chewiness; ⁷RE=Resilience.

Since there was a significant correlation between RVA parameters and swelling power of starch, the texture quality of noodles will be affected by RVA parameters spontaneously, and this was conformed in Table IV. The springiness, cohesiveness and chewiness of noodles were significantly correlated with peak viscosity, final viscosity and setback value of starch (P < 0.05), and the resilience of noodles was very significantly correlated with peak viscosity, final viscosity and setback value (P < 0.01). Therefore, peak viscosity, final viscosity and

setback value were crucial to determine the texture quality of noodles to some extent, and the root of this result was cross-linking reaction, that was, the hydroxyl groups of starch were replaced by phosphate groups.

IV. CONCLUSION

The morphology and XRD patterns of wheat starches did not change significantly after hydroxyl groups were replaced by phosphate groups, but the substitution of hydroxyl groups would weaken the binding of starch to water and lead to a shift of water molecules from immobilized to less immobilized fraction in fresh noodles. The average particle size of phosphorylated starches increased with the degree of substitution increase, and the gluten network of the reconstituted flour noodles was similar to that of the original flour noodles with the increase of particle size. There was a significant correlation between starch swelling power, pasting properties and noodle texture. When hydroxyl groups were replaced by phosphate groups, the swelling power and RVA parameters of starch decreased, which further led to the reduction of noodle hardness, springiness, resilience, cohesiveness, and chewiness. The results indicated that hydroxyl phosphorylated of wheat starch had an important effect on water distribution and texture characteristics of fresh noodles.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 31772002).

REFERENCES

- K. Shevkani, N. Singh, R. Bajaj, and A. Kaur, "Wheat starch production, structure, functionality and applications-a review," *International Journal of Food Science and Technology*, vol. 52, pp. 38-58, 2017.
- [2] M. Li, S. Dhital, and Y. Wei, "Multilevel structure of wheat starch and its relationship to noodle eating qualities," *Comprehensive Reviews in Food Science and Food Safety*, vol. 16, pp. 1042-1055, July 2017.
- [3] S. Siah and K. J. Quail, "Factors affecting Asian wheat noodle colour and time-dependent discolouration - A review," *Cereal Chemistry*, vol. 95, no. 2, pp. 189-205, March/April 2018.
- [4] N. Meng, G. G. Hou, and S. Zhao, "Dough rheological properties and noodle-making performance of non-waxy and waxy whole-wheat flour blends," *Journal of Cereal Science*, vol. 75, pp. 261-268, May 2017.
- [5] A. Kaur, K. Shevkani, M. Katyal, N. Singh, A. K. Ahlawat, and A. M. Singh, "Physicochemical and rheological properties of starch and flour from different durum wheat varieties and their relationships with noodle quality," *Journal of Food Science and Technology*, vol. 53, no. 4, pp. 2127-2138, April 2016.
- [6] G. B. Crosbie, "The relationship between starch swelling properties, paste viscosity and boiled noodle quality in wheat flours," *Journal of Cereal Science*, vol. 13, no. 2, pp. 145-150, March 1991.
- [7] A. Imberty, H. Chanzy, S. Pérez, A. Bul'on, and V. Tran, "The double-helical nature of the crystalline part of A-starch," *Journal* of *Molecular Biology*, vol. 201, no. 2, pp. 365-378, May 1988.

- [8] V. Varatharajan, R. Hoover, Q. Liu, and K. Seetharaman, "The impact of heat-moisture treatment on the molecular structure and physicochemical properties of normal and waxy potato starches," *Carbohydrate Polymers*, vol. 81, no. 2, pp. 466-475, June 2010.
- [9] R. D. Hancock and B. J. Tarbet, "The other double helix—the fascinating chemistry of starch," *Journal of Chemical Education*, vol. 77, no. 8, pp. 988-992, August 2000.
- [10] M. Radi, M. Niakousari, and S Amiri, "Physicochemical, textural and sensory properties of low-fat yogurt produced by using modified wheat starch as a fat replacer," *Journal of Applied Sciences*, vol. 9, no. 11, pp. 2194-2197, June 2009.
- [11] R. Balic, T. Miljkovic, B. Ozsisli, and S. Simsek, "Utilization of modified wheat and tapioca starches as fat replacements in bread formulation," *Journal of Food Processing and Preservation*, vol. 41, no. 1, pp. e12888, February 2017.
- [12] K. Zhang and Q. Lu, "Physicochemical properties of oxidized wheat starch and its effect on the quality of fresh noodles," *Food Science*, vol. 38, no. 15, pp. 26-30, 2017.
- [13] S. B. Zhang, Q. Y. Lu, H. Yang, and D. D. Meng, "Effects of protein content, glutenin-to-gliadin ratio, amylose content, and starch damage on textural properties of chinese fresh white noodles," *Cereal Chemistry*, vol. 88, no. 3, pp. 296-301, March 2011.
- [14] R. M. Trksak, "Crosslinking reactions," U.S. Patent 8481717B2, July 9, 2013.
- [15] Q. Guo, Z. He, X. Xia, Y. Qu, and Y. Zhang, "Effects of wheat starch granule size distribution on qualities of chinese steamed bread and raw white noodles," *Cereal Chemistry*, vol. 91, no. 6, pp. 623-630, November 2014.
- [16] Q. Lu, S. Guo, and S. Zhang, "Effects of flour free lipids on textural and cooking qualities of Chinese noodles," *Food Research International*, vol. 42, no. 2, pp. 226-230, March 2009.
- [17] B. Chen, L. Dang, Z. Xiao, W. Fang, M. Hou, T. Liu, and Z. Wang, "Physicochemical properties and micro-structural characteristics in starch from kudzu root as affected by cross-linking," *Food Chemistry*, vol. 219, pp. 93-101, March 2017.
- [18] L. Xiong, B. Zhang, M. Niu, and S. Zhao, "Protein polymerization and water mobility in whole-wheat dough influenced by bran particle size distribution," *LWT - Food Science and Technology*, vol. 82, pp. 396-403, September 2017.
- [19] R. Bajaj, N. Singh, A. Kaur, and N. Inouchi, "Structural, morphological, functional and digestibility properties of starches from cereals, tubers and legumes: A comparative study," *Journal* of Food Science and Technology, vol. 55, no. 9, pp. 3799-3808, September 2018.
- [20] S. H. Koo, K. Y. Lee, and H. G. Lee, "Effect of cross-linking on the physicochemical and physiological properties of corn starch," *Food Hydrocolloids*, vol. 24, no. 6-7, pp. 619-625, August-October 2010.
- [21] B. Z. Li, L. J. Wang, L. Dong, Y. L. Chiu, Z. J. Zhang, J. Shi, X. D. Chen, and Z. H. Mao, "Physical properties and loading capacity of starch-based microparticles crosslinked with trisodium trimetaphosphate," *Journal of Food Engineering*, vol. 92, no.3, pp. 255-260, June 2009.
- [22] D. M. Suflet, G. C. Chitanu, and V. I. Popa, "Phosphorylation of polysaccharides: New results on synthesis and characterisation of phosphorylated cellulose," *Reactive and Functional Polymers*, vol. 66, no. 11, pp. 1240-1249, November 2006.
- [23] F. Gao, D. Li, C. Bi, Z. Mao, and B. Adhikari, "Preparation and characterization of starch crosslinked with sodium trimetaphosphate and hydrolyzed by enzymes," *Carbohydrate Polymers*, vol. 103, pp. 310-318, March 2014.
- [24] Y. C. Huang, and H. M. Lai, "Noodle quality affected by different cereal starches," *Journal of Food Engineering*, vol. 97, no. 2, pp. 135-143, March 2010.
- [25] G. N. Barrera, M. C. Bustos, L. Iturriaga, S. K. Flores, A. E. Le ón, and P. D. Ribotta, "Effect of damaged starch on the rheological properties of wheat starch suspensions," *Journal of Food Engineering*, vol. 116, no. 1, pp. 233-239, May 2013.