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Effect of disulphide bonds and sulphhydryl concentrations on properties of wheat flour

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Abstract: Disulphide bonds and sulphhydryl concentrations were evaluated to determine the effects on rheological, thermodynamic, pasting, and dynamic rheological characteristics of mixed flours. Gluten samples, first treated with sodium sulphite of different concentrations, were added into flour at a 4% level, which had a significant impact on free sulphhydryl, disulphide bonds, and the ratio of the two indices. There was no relevance between the ratio and other parameters except for free sulphhydryl. The mixed flour doughs had reduced water absorption, dough development time, dough stability time as well as degree of weakening ($P < 0.05$). Disulphide bonds were associated negatively with the rate of starch gelatinisation (C3–C2), peak, and setback and these characteristics were correlated strongly with dough development time, dough stability time, and progressive protein weakening (C2–C1). The stability of starch gelatinisation and cooking stability of mixed flours did not remain significantly different. The larger the concentration of sodium sulphite, the higher the peak, breakdown, final viscosity, and setback values, but there were no significant differences between samples. For all samples, storage modulus and loss modulus increased with increasing scanning frequency. For mixed doughs, the trend lines of moduli decreased with increasing levels of reduction in added gluten. There was no substantial effect on thermal properties of flours.

Keywords: thermomechanics; thermodynamics; pasting; dynamic rheological characteristics

Worldwide, wheat (*Triticum* spp.) is an important source of carbohydrates in the human nutrition, and it is also an elementary food ingredient because of its unique flour properties (Uthayakumaran & Wrigley 2010). Because wheat gluten protein (WGP) can provide a network structure to embed starch granules and other components and hold the gas produced during fermentation, wheat flour is able to form a cohesive, elastic, malleable dough (Arendt et al. 2002; Gallagher et al. 2003). There is a positive relationship between WGP including gliadin and glutenin and dough properties (Kuktaite et al. 2004; Jakubauskiene & Juodeikiene 2005).

Recently, there has been increasing interest in the partial substitution of wheat flour with flours from other raw materials, such as pea (Kasprzak & Rzedzicki 2010), soybean (Traynham et al. 2007; Sabanis & Tzia 2010), quinoa, and buckwheat (Alvarezjubete et al. 2010), to alter flour properties and the nutritional and textural qualities of flour products. Most studies have focused on the optimisation of wheat varieties with the best flour properties (Barak et al. 2013). Moreover, the role of functional groups in protein chains is equally important, but it has been poorly studied. The structure of WGP is affected by the concentrations of free sulphhydryl (SH) groups and disulphide (SS) bonds. At the same time, SH and SS bonds in WGP have an influence on dough structure and processing quality (Chen & Schofield 1996; Wieser et al. 2007; Tomić et al. 2013). The network of WGP

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is formed through interchain and intrachain SS bonds within monomeric gliadin fractions and between glutenin polymers, which are formed from SH oxidation and SH-SS exchange during mixing (Rhazi et al. 2003; Delcour et al. 2012; Johansson et al. 2013).

In this study, WGP suspensions were treated using different concentrations of sodium sulphite (Na_2SO_3). The reduced WGP was added into flour to study the effect of SH and SS bonds on thermomechanical, thermodynamic, pasting, and dynamic rheological characteristics of doughs compared to the properties of wheat flour as a benchmark. This approach would be helpful in understanding the function of SS bonds in flour.

MATERIAL AND METHODS

Material. Na_2SO_3 was provided by ChangNuo Biology (Jinan, China). Special grade No. 1 wheat flour was provided by Zhengzhou Jinyuan Flour Manufacturing (Zhengzhou, China). The flour was obtained from a commercial admixture of hard, red winter wheat planted in Henan Province, China, in 2015. WGP was purchased from Henan Deda Chemical Co. Ltd. (Zhengzhou, China).

Proximate Analysis. Moisture, total starch, crude protein as well as ash content were determined using AACC44-15.02, 76-13.01, 46-13.01, and 08-01.01 (AACC International 2010, Approved Methods of Analysis). Crude fat was determined according to Offia-Olua (2014). Results of determination are shown in Table 1. These parameters met the requirements of the experimental design.

Preparation of WGP and blended flours. WGP was prepared according to Li et al. (2018) and Na_2SO_3 retention analysis was done by an ion chromatography method according to Qi et al. (2017). Modified WGP (4%) was added into special grade No. 1 flour and mixed well in valve bags. The mixed flours were brought to 14% moisture by rehydration in a temperature and humidity chamber. The special grade No. 1 flour was a control group called sample 1. The mixed flours were denoted by samples 2–8 according to the concentrations of Na_2SO_3 added into WGP (0, 0.1, 0.3, 0.5, 0.7, 1.0, and 1.5 mg g^{-1} pro).

Determination of concentrations of SS bonds and SH groups. Determination of SS bonds and SH content was carried out adopting the Ellman's reagent method of Beveridge (1974) and Luo et al. (2016).

Mixolab characteristics of flours. Because Mixolab can measure the properties of protein and starch simultaneously in a single test, it has been chosen to investigate dough properties during processing conditions for many types of rheological techniques (Rosell et al. 2007; Huang et al. 2010; Schmiele et al. 2016). The rheological behaviour of flours was determined by a Mixolab apparatus (Chopin Technologies, Villeneuve La Garenne, France) that used the standard Chopin+ protocol. The added water amount should meet the torque of 1.1 ± 0.07 Nm. Total time was 45 min. The settings were as follows: dough mixing stage maintained for 8 min at 30 °C, the temperature was increased to 90 °C at 4 °C min^{-1} and then held for 7 min at 90 °C, followed by decreasing the temperature to 50 °C at 4 °C min^{-1} and subsequently held for 5 min at 50 °C.

Starch pasting characteristics. A Rapid Visco Analyser (RVA-4; WeiXun Instruments, Beijing, China) was used to determine the pasting properties of flours, referring to the AACC approved method 76-21 (AACC International 2000, Approved Methods of Analysis).

Thermodynamic properties. The thermodynamic properties of flours were measured using a Q20 Differential Scanning Calorimeter (TA Instruments, New Castle, DE, USA). The calorimeter was calibrated with an indium standard. An aliquot of 3.0 mg sample was weighed exactly into an aluminium pan, and 6 mL deionised water was added with a micropipette. The pan was sealed hermetically and equilibrated at 25 °C for 2 h before heating during a determined program (30–120 °C, 10 °C min^{-1}) with a 40 mL min^{-1} nitrogen flow rate. The initial gelatinisation temperature (T_o), termination gelatinisation temperature (T_c), denaturation peak temperatures (T_p), gelatinisation temperature range (R), and endothermic enthalpies

Table 1. Basic compositions of wheat gluten protein (WGP) and flour (n = ; mean ± SD)

	Moisture	Fat	Protein (dry basis)	Ash	Starch
			(%)		
WGP	11.5 ± 1.05	0.95 ± 0.006	77.68 ± 2.15	1.48 ± 0.53	8.71 ± 0.51
Flour	13.5 ± 0.9	0.78 ± 0.002	9.67 ± 0.46	0.55 ± 0	72.21 ± 1.72

SD – standard deviation

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(ΔH) were determined using the TA Universal Analysis Software (TA Instruments, New Castle, DE, USA).

Dynamic rheological measurements. The rheological behaviour of samples was studied according to the modified procedure of Li et al. (2012). A Mixolab was used to obtain the amount of water added to the mixed flours. Dough was prepared by mixing flour and distilled water. A DHR-1 model rheometer (TA Instruments, New Castle, DE, USA) was used to evaluate dynamic rheological properties. The test was performed at 25 °C with a 0.1–100 rad s^{-1} frequency, deformation of 0.02%, parallel plate diameter of 25 mm, and a 1.05 mm gap width. The linear viscoelastic zone was determined by a stress sweep at 1 Hz frequency. The recorded parameters were storage modulus (G') and loss modulus (G'').

Statistical analysis. All data were analysed by SPSS software 17.0, SPSS Inc., Chicago, USA) and described with the mean ± standard deviation (SD). Duncan's test was used to compare the differences. Significance was defined at $P < 0.05$. Correlation analyses between assays were carried out by Pearson correlation tests at a probability level of $P < 0.01$. All tests were performed at least in triplicate.

RESULTS AND DISCUSSION

Determination of the concentrations of SS and SH. The concentration of free SH groups is a key indicator of SS bonds that are important in protein polymerisation revealed by Wang et al. (2012). Concentrations of free SH, total SH, and SS bonds in sample 1 were lower than in the other groups (Table 2). The free SH concentrations of mixed flours increased significantly (from 1.62 μmol g^{-1} to 3.23 μmol g^{-1}) and SS decreased from 13.93 μmol g^{-1} to 12.46 μmol g^{-1}; total SH remained stable from the beginning to the end of treatment. Sample 1 had the lowest ratio of free SH/SS and sample 8 had the highest; there were significant differences between groups ($P < 0.05$). The compound Na_2SO_3 broke SS into SH in WGP at appropriate concentrations. When WGP was added to flour at a 4% level, it had a significant impact on free SH, SS, and the ratio of the two, but there was no substantial effect on total SH.

Mixolab parameters. Water absorption (WA), dough development time (DDT), dough stability time (DST), protein weakening under the dual role of mechanical force and temperature (C2), and C2 of sample 1 were lower than in the other groups (Table 3), which indicated that the added gluten had a marked effect on dough characteristics. It is already known there are many nonpolar amino acids in WGP. The added WGP can strengthen hydrophobic interaction and water absorption capacity, which leads to the increased values of WA, DDT, DST, C2, and C2–C1. For maximum torque obtained during kneading (C1) and C2, no distinct differences were observed. The mixed flour doughs showed a reduction in WA, DDT, DST, and degree of weakening because of the destructive effect of Na_2SO_3 on protein structure that resulted in a looser gluten network and diminished dough continuity.

The main derived parameters associated with the thermomechanical properties of starch told us that adding WGP contributed to a distinct reduction in C3–C2 (Table 4). The main reasons were it reduced directly the percentage of starch content in dough, and there were more starch particles embedded in WGP, which caused a reduction in the proportion of starch outside the WGP network system. Moreover, the added WGP intensified the severity of competition of starch for water. This was consistent with the conclusion of Avi et al. (2012). Starch retrogradation at a cooling stage (C5–C4) also decreased

Table 2. Concentrations of sulphhydryl (SH) and disulphide (SS) bonds in flours ($n = 3$; mean ± SD)

Sample	Free SH	Total SH	SS	Ratio of free (SH/SS)
	(μmol g^{-1})			
1	1.15 ± 0.05^{h}	25.45 ± 0.39^{b}	12.15 ± 0.18^{f}	0.10 ± 0.01^{h}
2	1.62 ± 0.05^{g}	30.00 ± 0.37^{a}	13.93 ± 0.18^{a}	0.12 ± 0.01^{g}
3	2.23 ± 0.05^{f}	30.42 ± 0.38^{a}	13.53 ± 0.17^{b}	0.17 ± 0.01^{f}
4	2.61 ± 0.05^{e}	30.63 ± 0.38^{a}	13.26 ± 0.18^{b}	0.20 ± 0.01^{e}
5	2.76 ± 0.05^{d}	30.31 ± 0.38^{a}	12.95 ± 0.17^{c}	0.21 ± 0.01^{d}
6	2.89 ± 0.05^{c}	30.28 ± 0.38^{a}	12.80 ± 0.18^{cd}	0.23 ± 0.01^{c}
7	3.12 ± 0.05^{b}	30.24 ± 0.37^{a}	12.55 ± 0.18^{de}	0.25 ± 0.00^{b}
8	3.23 ± 0.05^{a}	30.27 ± 0.38^{a}	12.46 ± 0.18^{e}	0.26 ± 0.00^{a}

Means in the same column marked with different letters show significant differences at $P < 0.05$

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Table 3. Changes in the thermomechanical properties of protein in flours (n = 3; mean ± SD)

Sample	WA	DDT	DST	C1	C2	C2–C1
	(%)	(min)		(Nm)		
1	56.8 ± 0.1^{e}	1.6 ± 0.14^{e}	5.60 ± 0.03^{e}	1.11 ± 0.02^{a}	0.42 ± 0.01^{d}	–0.69 ± 0.01^{d}
2	61.6 ± 0^{a}	5.51 ± 0.33^{a}	8.50 ± 0.25^{a}	1.08 ± 0.03^{a}	0.48 ± 0^{a}	–0.60 ± 0.03^{a}
3	61.5 ± 0^{a}	5.02 ± 0.13^{ab}	8.47 ± 0.11^{a}	1.08 ± 0^{a}	0.47 ± 0^{ab}	–0.61 ± 0^{ab}
4	61.3 ± 0^{b}	4.78 ± 0.21^{abc}	8.20 ± 0.25^{ab}	1.10 ± 0.02^{a}	0.46 ± 0^{abc}	–0.64 ± 0.02^{bc}
5	61.1 ± 0.14^{c}	4.51 ± 0.47^{bcd}	8.02 ± 0.04^{b}	1.09 ± 0.02^{a}	0.46 ± 0.02^{abc}	–0.64 ± 0^{abc}
6	61.1 ± 0^{c}	4.30 ± 0.75^{bcd}	7.45 ± 0.03^{c}	1.08 ± 0.01^{a}	0.44 ± 0.01^{cd}	–0.64 ± 0^{abc}
7	61.0 ± 0^{c}	4.05 ± 0^{cd}	7.42 ± 0.14^{c}	1.12 ± 0.01^{a}	0.47 ± 0.01^{ab}	–0.65 ± 0^{c}
8	60.7 ± 0.1^{d}	3.82 ± 0.21^{d}	6.49 ± 0.04^{d}	1.11 ± 0^{a}	0.45 ± 0^{bc}	–0.66 ± 0^{cd}

Means in the same column marked with different letters show significant differences at $P < 0.05$; WA – water absorption; DDT – dough development time; DST – dough stability time; C1 – maximum torque obtained during kneading; C2 – protein weakening under the dual role of mechanical force and temperature

significantly because of the inhibition of complex substances that were formed from WGP and starch during heating to the aging of amylose. There were no significant differences in stability of starch gelatinisation (C3–C4) and cooking stability (C4/C3), but there was a rise in the rate of starch gelatinisation (β) and rate of enzyme degradation (γ). There were no obvious changes in the above parameters of composite flours, which proved that 4% of treated WGP was not enough to affect the thermomechanical properties of starch.

Starch pasting properties. From Table 5, the peak viscosity, final viscosity, and maximum setback values for sample 1 were 2 214 mPa s, 2 330 mPa s and 1 042 mPa s, respectively. There were no large differences in breakdown, peak time, and pasting temperature. Adding WGP had an effect on the pasting properties, and the change in the range of the peak was basically equal to trough viscosity. In addition, the aging of starch was also delayed. The viscosity values were related mainly to starch concentration. Adding WGP might reduce starch content and intensify the competition for water between starch granules and WGP. Another reason for the high viscosity values may be the formation of a gluten-starch complex. As a result, the free starch granules decreased and viscosity values declined, which was consistent with the opinion of Olkku & Rha (1978). In our study, it was observed that the larger the concentration of Na_2SO_3 added to WGP, the higher were the peak viscosity, breakdown, final viscosity as well as setback values, although there were no significant differences between samples. Moreover, the pasting temperature changed little.

Table 4. Changes in the thermomechanical properties of starch in flours (n = 3; mean ± SD)

Sample	(C3–C2)	(C3–C4)	(C5–C4)	(C4/C3)	β	γ
	(Nm)					
1	1.34 ± 0.01^{a}	0.25 ± 0.03^{ab}	0.84 ± 0.01^{a}	0.86 ± 0.01^{a}	0.50 ± 0.01^{b}	–0.05 ± 0.02^{a}
2	1.19 ± 0.02^{e}	0.32 ± 0.06^{a}	0.66 ± 0.03^{c}	0.81 ± 0.03^{b}	0.60 ± 0.01^{a}	–0.04 ± 0.02^{a}
3	1.22 ± 0.02^{de}	0.24 ± 0.03^{b}	0.68 ± 0.03^{bc}	0.86 ± 0.01^{a}	0.56 ± 0.07^{ab}	–0.02 ± 0.01^{a}
4	1.25 ± 0.02^{bcd}	0.25 ± 0.01^{ab}	0.69 ± 0.02^{bc}	0.85 ± 0^{a}	0.59 ± 0.02^{ab}	–0.03 ± 0.01^{a}
5	1.24 ± 0.03^{cd}	0.25 ± 0^{ab}	0.69 ± 0.03^{bc}	0.85 ± 0^{a}	0.54 ± 0.06^{ab}	–0.03 ± 0^{a}
6	1.27 ± 0.01^{bc}	0.25 ± 0.01^{ab}	0.70 ± 0.03^{bc}	0.85 ± 0^{a}	0.56 ± 0.03^{ab}	–0.02 ± 0.03^{a}
7	1.26 ± 0.01^{bcd}	0.24 ± 0.01^{b}	0.70 ± 0.02^{bc}	0.86 ± 0^{a}	0.55 ± 0.06^{ab}	–0.03 ± 0.01^{a}
8	1.29 ± 0.01^{b}	0.24 ± 0.04^{b}	0.73 ± 0.01^{b}	0.86 ± 0.03^{a}	0.55 ± 0.03^{ab}	–0.03 ± 0.01^{a}

Means in the same column marked with different letters show significant differences at $P < 0.05$; C2 – protein weakening under the dual role of mechanical force and temperature; C3 – maximum torque at the heating stage; C4 – minimum torque during the heating period; C5 – torque after cooling at 50 °C; β – the rate of starch gelatinisation; γ – the rate of enzyme degradation

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Table 5. Changes in the pasting properties of flours (n = 3; mean ± SD)

Sample	Peak viscosity	Breakdown	Final viscosity	Setback	Pasting temperature.
	(mPa·s)				(°C)
1	2214 ± 212^{a}	925 ± 29^{ab}	2330 ± 279^{a}	1042 ± 50^{a}	67.7 ± 0^{a}
2	1845 ± 16^{c}	878 ± 31^{b}	1874 ± 19^{b}	907 ± 24^{d}	68.0 ± 4.1^{a}
3	1920 ± 38^{bc}	912 ± 17^{ab}	1941 ± 29^{b}	933 ± 14^{cd}	68.3 ± 1.9^{a}
4	1958 ± 32^{bc}	937 ± 15^{a}	1974 ± 35^{b}	952 ± 23^{bcd}	67.5 ± 2.4^{a}
5	1960 ± 47^{bc}	929 ± 33^{a}	1995 ± 33^{b}	964 ± 19^{bc}	70.5 ± 0.5^{a}
6	1966 ± 49^{bc}	935 ± 22^{a}	1997 ± 37^{b}	966 ± 13^{bc}	67.5 ± 0.4^{a}
7	1989 ± 8^{bc}	958 ± 22^{a}	2019 ± 10^{b}	988 ± 16^{b}	66.6 ± 2.6^{a}
8	2017 ± 52^{b}	961 ± 32^{a}	2047 ± 40^{b}	991 ± 30^{b}	66.9 ± 0.8^{a}

Means in the same column marked with different letters show significant differences at P < 0.05

Thermodynamic properties. The heating process of polymers is not just a transformation of temperature and heat, it is a change from a vitreous state to a rubbery state to a viscous flow state (Borde et al. 2002). T_o, T_c, and T_p of sample 1 were the lowest among all samples, but the enthalpy was the highest (Table 6), which coincided with the results of Marshall et al. (1990) and Lionetto et al. (2010). In addition, there were not any great changes among mixed flours. By the test, the gluten-starch ratio was about 1 : 7.5, which showed the impact of starch was far greater than that of WGP. Moreover, 4% WGP only reduced the percentage of free water that was absorbed by starch, but there was no change in the starch structure. In conclusion, there was no substantial effect of adding 4% WGP that had been reduced by Na_2SO_3 on the thermal properties of flours.

Dynamic rheological analysis. The addition of WGP changed the viscoelasticity of samples (Figures 1 and 2). For all the samples, G' was larger than G", which indicated the doughs exhibited solid, elastic-like behaviour (Ptaszek et al. 2009). It is apparent from the graphs that G' and G" increased with increasing frequency. The growth rate of G' and G" slowed down and fluctuated in the range of 0.1–10 rad s^{-1}, but there was a larger and more stable rate in the scope of 10–100 rad s^{-1}. This result indicated the stability of dough was low in the low frequency range and high in the high frequency range.

It was noted that the viscoelasticity of pure dough was between the values of sample 7 and sample 8. For mixed doughs, the trend lines of moduli decreased with increasing levels of reduction for added WGP. It may be that added WGP formed a larger and stronger gluten network after hydration, which increased the viscoelasticity of the dough. On the contrary, a looser structure of WGP contributed to a weaker gluten network and viscoelasticity in doughs.

Correlation coefficients between assays. There was no relationship between free SH/SS and other parameters

Table 6. Changes in the thermodynamic properties of flours (n = 3; mean ± SD)

Sample	T_o	T_c	R	T_p	ΔH
	(°C)				(J g^{-1})
1	57.49 ± 0.16^{b}	70.80 ± 0.85^{b}	13.31 ± 0.71^{a}	62.18 ± 0.23^{b}	6.49 ± 0.28^{a}
2	58.23 ± 0.13^{a}	72.83 ± 0.95^{a}	14.60 ± 1.08^{a}	62.88 ± 0.31^{a}	5.81 ± 0.45^{b}
3	58.05 ± 0.34^{a}	71.26 ± 0.98^{ab}	13.21 ± 1.02^{a}	62.61 ± 0.22^{ab}	4.86 ± 0.62^{c}
4	57.89 ± 0.19^{a}	72.23 ± 0.57^{ab}	14.34 ± 0.55^{a}	62.84 ± 0.22^{a}	5.57 ± 0.24^{bc}
5	57.87 ± 0.07^{a}	71.58 ± 1.07^{ab}	13.71 ± 1.14^{a}	62.74 ± 0.21^{a}	5.15 ± 0.21^{bc}
6	58.01 ± 0.18^{a}	72.33 ± 0.71^{ab}	14.33 ± 0.88^{a}	62.81 ± 0.13a	5.73 ± 0.27^{b}
7	58.22 ± 0.33^{a}	72.69 ± 1.17^{a}	14.46 ± 0.87^{a}	62.28 ± 0.34^{b}	5.30 ± 0.31^{bc}
8	58.07 ± 0.16^{a}	72.72 ± 0.71^{a}	14.65 ± 0.81^{a}	62.72 ± 0.18^{a}	5.32 ± 0.41^{bc}

Means in the same column marked with different letters show significant differences at $P < 0.05$; T_o – gelatinisation temperature; T_c – termination gelatinisation temperature; R –gelatinisation temperature range; T_p – denaturation peak temperatures; ΔH – endothermic enthalpies

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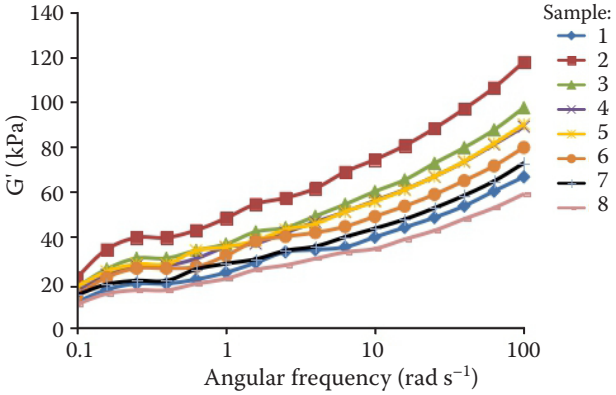

Figure 1. Storage modulus G' changes in the frequency sweep test

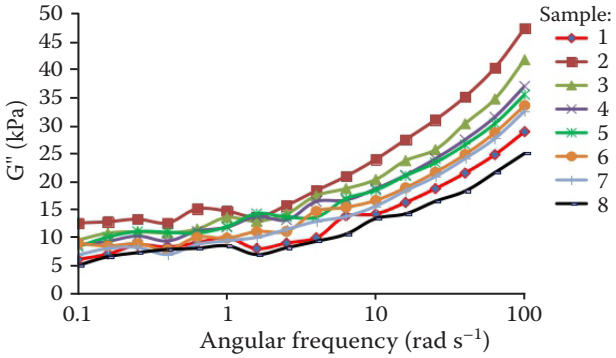

Figure 2. Loss modulus G'' changes in the frequency sweep test

except for free SH (0.993) (Table 7). However, SS was associated negatively with C3–C2 (–0.932), peak (–0.865), and setback (–0.966) and it was correlated strongly with DDT (0.868), DS (0.898), and C2–C1 (0.951).

CONCLUSION

In this study, SH and SS in mixed flours were adjusted by adding 4% WGP treated with Na_2SO_3 of different concentrations. The rheological, thermodynamic, pasting, and dynamic rheological characteristics of samples were investigated. There was a significant impact on free SH, SS, but there was not a significant impact on total SH. The mixed flour doughs showed reductions in WA, DDT, DST, and degree of weakening, but there were no large differences in stability of starch gelatinisation and cooking stability. Adding gluten contributed to a distinct reduction in C3–C2 and C5–C4. Setback, peak, breakdown, and final viscosity increased, but trend lines of moduli decreased with increasing levels of reduction for added gluten. T_o, T_c, and T_p of wheat flour were the lowest, but the enthalpy was the highest, and there was no substantial effect on thermal properties of blended flours. The correlation analysis revealed that there was no relationship between free SH/SS and other parameters, except for free SH. SS was correlated negatively with C3–C2, peak, and setback and it was correlated strongly with DDT, DST, and C2–C1. Overall, it can be assumed that the concentration of SS bonds in flours markedly influenced the thermomechanical properties of proteins and moduli, but there were no significant differences in pasting, thermomechanical properties of starch, and thermal properties. These results should help us to understand the role of SS in dough, so that special wheat flours can be developed.

Table 7. Correlation coefficients between sulphhydryl (SS) and disulphide (SH), Mixolab parameters, starch pasting properties, and thermodynamic properties

	Free SH	SS	Free SH/SS	DDT	DST	C2–C1	C3–C2	Peak	Setback	ΔH
Free SH	1									
SS	–0.186	1								
Free SH/SS	0.993**	–0.286	1							
DDT	0.32	0.868**	0.22	1						
DST	0.158	0.898**	0.05	0.946**	1					
C2–C1	0.02	0.951**	–0.076	0.934**	0.923**	1				
C3–C2	–0.073	–0.932**	0.03	–0.948**	–0.951**	–0.972**	1			
Peak	–0.292	–0.865**	–0.196	–0.991**	–0.921**	–0.946**	0.957**	1		
Setback	–0.053	–0.966**	0.048	–0.960**	–0.937**	–0.983**	0.968**	0.962**	1	
ΔH	–0.653	–0.342	–0.591	–0.642	–0.601	–0.517	0.551	0.598	0.482	1

**Correlation is significant at 0.01 level; DDT – dough development time; DST – dough stability time; ΔH – endothermic enthalpies; C1 – maximum torque obtained during kneading; C2 – protein weakening under the dual role of mechanical force and temperature; C3 – maximum torque at the heating stage

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