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K.R.N. Moelants, R.P. Jolie, T.A.J. Verrijssen, S. Van Buggenhout, A. M. Van Loey, M.E. Hendrickx

Laboratory of Food Technology and Leuven Food Science and Nutrition Research Centre (LForCe)

Department of Microbial and Molecular Systems (M2S)

KU Leuven

Kasteelpark Arenberg 22, Box 2457, 3001 Leuven, Belgium

Marc.Hendrickx@biw.kuleuven.be

R. Cardinaels and P. Moldenaers

Soft Matter, Rheology and Technology

Department of Chemical Engineering

KU Leuven

Willem de Croylaan 46, B-3001 Leuven, Belgium

Paula.Moldenaers@cit.kuleuven.be

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Rheology of concentrated tomato-derived suspensions: Effects of particle characteristics

Katlijn R.N. Moelants^a, Ruth Cardinaels^b, Ruben P. Jolie^a, Tina A.J. Verrijssen^a, Sandy Van Buggenhout^a, Ann M. Van Loey^a, Paula Moldenaers^b and Marc E. Hendrickx^{a,1}

^a *Laboratory of Food Technology and Leuven Food Science and Nutrition Research Centre (LFoRCe), Department of Microbial and Molecular Systems (M2S), KU Leuven, Kasteelpark Arenberg 22, PB 2457, 3001 Leuven, Belgium*

^b *Soft Matter, Rheology and Technology, Department of Chemical Engineering, KU Leuven, Willem de Croylaan 46, PB 2423, 3001 Leuven, Belgium*

¹ **Corresponding author**

Tel: +32 16 321572

Fax: +32 16 321960

E-mail: Marc.Hendrickx@biw.kuleuven.be

Abstract

In the present work, the effect of particle properties on the rheological behaviour of tomato-derived suspensions was investigated systematically. Hereto, a range of relatively monodisperse suspensions, containing either cell fragments or single cells with varying average particle size (~148, 267, 303 and 393 μm) and pulp content (from 25 to 60 wt.%), was prepared by the reconstitution of tomato tissue-based particles in water. The effect of the presence of a serum phase on the rheological properties of tomato-derived suspensions was investigated by the comparison of the rheology of reconstituted tomato purées in water with those in serum. All the tomato-derived suspensions were non-Newtonian liquids exhibiting a yield stress. The flow behaviour could be described well by the Herschel-Bulkley model. The undisrupted network structure of all suspensions could be classified as a weak gel with a rather low critical strain. Particle concentration, size and morphology (surface/shape) turned out to be key structural properties controlling the rheological parameters of these tomato-derived suspensions. Increase in yield stress and storage modulus with particle concentration could be fitted to a power law model. The ratio of static yield stress to dynamic yield stress turned out to be larger for particles with a more irregular, less intact surface, showing the enhanced tendency of the latter particles to build up structure in rest conditions. A unique linear relation was found between the static yield stress and the maximal elastic stress in oscillatory tests, independent of the particle properties. Finally, replacing the serum phase by water led to a substantial decrease in network strength, especially in quiescent conditions.

Keywords

rheology, tomato suspensions, reconstitution, particle characteristics, serum phase

Introduction

Tomato-derived products (e.g., ketchup, tomato concentrate, sauce or juice) are very popular, frequently consumed products. These products are assumed to be health-promoting due to their high antioxidant content. For example, the frequent intake of lycopene, a carotenoid responsible for the red colour of tomato, turned out to diminish the prostate cancer risk (Bramley, 2000; Giovannucci et al., 2002).

Generally, tomato-derived products can be considered as suspensions consisting of plant-tissue-based particles in a continuous serum phase with (among others) pectin, sugars and organic acids solubilised in it (Rao, 1987; Anthon et al., 2008). Their rheological properties are known to be determined by both the particle properties of the dispersed phase and the properties of the serum phase (especially of the solubilised pectin) (Tanglertpaibul & Rao, 1987b). Moelants et al. (2012b) showed that the rheology of concentrated carrot and tomato suspensions was dominated by the particle properties of the dispersed phase rather than by the serum viscosity. The characteristics of the particle phase that affect the rheology of the suspensions include the concentration, size distribution, shape, surface properties, deformability and interparticle forces (Gallegos et al., 2004; Genovese et al., 2007; Fischer et al., 2009). Several studies showed that the flow behaviour of plant-based food suspensions is strongly influenced by the amount of suspended particles. By increasing the particle concentration, the yield stress was increased and viscoelastic properties were enhanced (Rani & Bains, 1987; Tanglertpaibul & Rao, 1987b; Yoo & Rao, 1994; Den Ouden & Van Vliet, 2002; Day et al., 2010b; Moelants et al., 2012a). Besides particle concentration, particle size can also affect the rheological properties of suspensions, although this effect is less clear as compared to that of particle concentration. Whereas Schijvens et al. (1998) noticed the lowest value of the yield stress for apple sauce composed of small particles, Qiu and Rao (1988) and Cantu-Lozano et al. (2000) observed an increase in yield stress or viscosity as particle size was reduced. The latter observation was confirmed by Yoo and Rao (1994) in tomato purée. Since smaller particles have, for the same volume fraction, a larger surface area as compared to larger particles, the interaction forces can increase at reduced particle size (Yoo & Rao, 1994). However, when large particles form aggregates, they can occupy more space in the sample than aggregates of small particles, due to less efficient particle packing. This leads to a larger volume effectively taken in by these large particles which can also cause an increase in flow resistance (Quemada, 1998). In addition to size, the particles in plant-

based food suspensions can vary in shape and are known to be deformable. Day et al. (2010a) and Moelants et al. (2012a) demonstrated that the flow behaviour and viscoelastic properties of carrot-derived suspensions were different for clustered or separated cells, intact or broken at the location of the cell wall depending on the pretreatment of the vegetables. Besides this, less deformable particles resulted in a higher yield stress for apple sauce (Schijvens et al., 1998). Because of the world-wide consumption of tomato-derived liquid products and the high expectations of product quality, it is important to be able to tailor the rheological properties of these products. The effect of paste concentration (Tanglertpaibul & Rao, 1987b) and the influence of particle size (Tanglertpaibul & Rao, 1987a; Yoo & Rao, 1994; Den Ouden & Van Vliet, 1997; Valencia et al., 2003) on the rheology of tomato concentrates have been previously reported in literature. However, the relations reported between rheological and structural properties can not be generalised to other processing conditions. Hence, the use of well-characterised samples is required to derive structure-function relations. Therefore, in this study the reconstitution principle is used to prepare aqueous tomato-derived suspensions with various concentrations of either cell fragments or single cells derived from tomato tissue and with a well-characterised size, distinguishing this study from most rheological studies on plant-based suspensions available in literature. High-pressure homogenisation (HPH) (at different pressure levels) in combination with wet sieving was used as a tool to prepare particles with different sizes. The influence of the serum properties on the rheological characteristics of the food suspensions was excluded by reconstituting the particles in water rather than serum. Most studies dealing with plant-based food suspensions are limited to one type of rheological measurement. In the present work, full rheological characterisations of the tomato-derived suspensions, both in steady shear and oscillation, can be presented. This way, relations between particle characteristics and rheological parameters of concentrated tomato-derived suspensions will be elucidated. The effect of the presence of the serum phase on the rheological properties of tomato-derived suspensions was investigated by the comparison of the rheology of reconstituted tomato purées in water with those containing serum.

Materials and methods

Preparation of tomato-derived suspensions

To investigate the effect of particle characteristics on the rheological properties of tomato-derived suspensions, suspensions with well-controlled particle characteristics were prepared. Tomatoes of a processing variety (*Solanum lycopersicum* cv. Patrona) were obtained from a wholesaler in Spain, washed, cut into slices of 0.5-1 cm and vacuum-packed in a plastic bag. These bags were heated in a temperature-controlled water bath at 95 °C for 8 min (= hot break, HB) (to inactivate enzymes), cooled and stored at 4 °C prior to processing. Treated tomato slices were mixed during 1 minute using a kitchen blender (Waring blender 7010G, Torrington, CT, USA). The obtained purée was sieved (pore size 1.0 mm) to remove skin and seeds after which the sample was homogenised at 20 MPa or 100 MPa (Panda 2K, Gea Niro Soavi, Mechelen, Belgium). The resulting samples are the original purées denoted as T_20 and T_100. From these purées, fractions of particles with different particle size were prepared by the use of wet sieving with sieves having pore sizes of 80, 125, 250, 500 and 1000 µm (Retsch, Aartselaar, Belgium). For the purée homogenised at 20 MPa, the pulp retained on the sieves with pore sizes of 125 and 250 µm was collected whereas for the purée homogenised at 100 MPa, the pulp retained on the sieves with pore sizes of 80 and 125 µm was retained. Pulp was drained over a filter to remove the excess water until constant weight was reached. Subsequently, the pulp was reconstituted with deionised water in different pulp percentages (pulp%) (ranging from 25 to 60 wt.%) resulting in reconstituted tomato-derived suspensions. The pulp% was defined as:

$$\text{pulp\% (\%)} = \frac{\text{mass of pulp}}{\text{mass of pulp and water}} \times 100 \quad (1)$$

Fig. 1 gives a schematic overview of the reconstitution process. By using water instead of serum, possible interference of the pH and the presence of ions and dissolved polymers on the rheology was eliminated. After processing, samples were stored at 4 °C until further analysis. Sample coding for the reconstituted suspensions and the original tomato purée is summarised in Table 1. Besides particle characteristics, also the presence of the serum phase can affect the rheology of tomato-derived suspensions. Therefore, three suspensions with similar particle characteristics were prepared and rheologically characterised: an original tomato purée, a reconstituted tomato-derived suspension comprising the same particles as present in the original purée with a continuous water phase and a tomato-derived suspension obtained by reconstituting the same particles as present in the original purée in tomato serum. These purées are denoted as T_20', RP(20)_35%w and RP(20)_35%s, respectively. Tomatoes (*Solanum lycopersicum* cv. Prunella) were heat-treated, separated from skin and seeds and blended as described above. The thus

obtained purée was homogenised at 20 MPa and one part was rheologically and structurally characterised (denoted as T20'). An other part of the homogenised original purée was centrifuged (30 min at $12400 \times g$ and 20°C) and vacuum-filtrated (MN 615, pore size of $8\ \mu\text{m}$) as described by Caradec and Nelson (1985) to separate the pulp from the serum phase. To obtain the particle phase, the remaining part of the original tomato purée was sieved, and the pulp, retained on the sieves with pore sizes of 40, 80, 125, 250, 500 and $1000\ \mu\text{m}$, was reconstituted with water or serum to obtain reconstituted tomato purées with a pulp% of 35 wt.% (similar as the original tomato purée). Both reconstituted purées (denoted as RP(20)_35%w and RP(20)_35%s) were rheologically and structurally characterised.

Structural characterisation of the particles

Particle size distribution

The particle size distribution (PSD) of the suspensions was measured using laser diffraction (Malvern Instrument Ltd., Worcestershire, UK), whereby particles between 0.05 and $880\ \mu\text{m}$ can be detected. Approximately 6 g of sample (50 wt.% pulp) was poured in a stirred tank filled with deionised water. The diluted sample was pumped into the measuring cell. The volumetric PSDs were calculated from the intensity profile of the scattered light with the Mie theory using the instrument's software. Parameters $D[v,0.1]$, $D[v,0.5]$ and $D[v,0.9]$ (μm) indicate the particle diameter at which 10, 50 and 90 vol% of the particles have a smaller diameter, respectively. For each sample, also the volume-based ($D[4,3]$) and the area-based ($D[3,2]$) diameter (μm) were determined according to the equations:

$$D[4,3] = \frac{\sum_i n_i d_i^4}{\sum_i n_i d_i^3} \quad (2)$$

$$D[3,2] = \frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2} \quad (3)$$

where n_i is the number of particles of diameter d_i (μm). All analyses were carried out in duplicate.

The relative width of the PSD, referred to as the spread, was calculated as:

$$spread = \frac{(D[v,0.9] - D[v,0.1])}{D[3,2]} \quad (4)$$

Phase volume

Suspensions (20 g) were centrifuged (J2-HS, Beckman, Namen, Belgium) at $12900 \times g$ for 30 min at 20 °C. The phase volume (ϕ) of the particles in each suspension was determined as:

$$\phi(\%) = \frac{M_p}{M_t} \times 100\% \quad (5)$$

with M_p the mass of the precipitate (g) and M_t the total mass of the tomato-derived suspension before centrifugation (g), assuming that the density of the tomato-derived particles was almost equal to that of water. All analyses were conducted in duplicate.

Bright field microscopy

The microstructure of the suspensions was visually analysed using an Olympus BX-41 light microscope equipped with an Olympus XC-50 digital camera (Olympus, Optical Co. Ltd., Tokyo, Japan). The fractions were diluted tenfold with a toluidin blue solution to stain the cell walls. After 20 min, two droplets of the stained sample were placed on a glass slide (not covered) and studied using an objective of 10× or 40× magnification.

Rheological characterisation of the suspensions

The rheological properties of the suspensions were measured with a stress-controlled rheometer (MCR 501, Anton Paar, Graz, Austria) at 25 °C. As geometry, a six-bladed vane with a diameter of 11 mm and a height of 16 mm was used to avoid wall slip. Approximately 50 mL of sample was loaded into a cup with 28.92 mm diameter. As it is known that a shear rate distribution occurs by the use of a vane geometry, all the shear rates indicated are apparent shear rates. Because of the relatively short duration of each measurement (i.e. 20-30 min), evaporation was considered negligible and no significant sedimentation was noticeable. To avoid the effect of loading history on the structure, samples were presheared for 1 min at a shear rate ($\dot{\gamma}$) of 100 s^{-1} followed by 2 min of rest ($\dot{\gamma} = 0 \text{ s}^{-1}$) before all measurements.

The rheological characteristics of the suspensions were studied by the execution of steady-shear tests (for the estimation of viscosity and yield stress) and small amplitude oscillatory tests (to

study the viscoelastic behaviour). The shear rate ramp, stress ramp, amplitude and frequency sweep were performed as described by Moelants et al. (2012a).

All measurements were performed in duplicate. For each measurement, a fresh sample was loaded into the cup.

Statistical analysis

Particle size analyses and rheological measurements were all carried out in duplicate.

The flow curves of the suspensions were fitted to the Herschel-Bulkley model (Equation 6) by the use of non-linear regression procedures (statistical software package SigmaPlot, version 11, London, UK):

$$\sigma = \sigma_{0D} + K \dot{\gamma}^n \quad (6)$$

with σ = shear stress (Pa), $\dot{\gamma}$ = shear rate (s^{-1}), σ_{0D} = dynamic yield stress (Pa), K = consistency coefficient ($Pa \cdot s^n$) and n = flow index. The data points were fitted without weighing.

To evaluate the effect of particle concentration on rheological parameters such as dynamic and static yield stress and storage modulus (G'), experimental data were fitted to a power law model with two parameters by means of non-linear regression analysis. Also the frequency dependence of G' and of the loss modulus (G'') was investigated by the use of this type of power law model (SigmaPlot). To calculate the yield strain (γ_y), G' was plotted as a function of strain and fitted with an exponential function (SAS 9.3).

Results and discussion

In what follows, the structural characteristics of the reconstituted tomato-derived suspensions and the original tomato purées will first be described. Subsequently, the rheological characteristics of these suspensions (flow behaviour and viscoelastic behaviour) will be discussed and the relations between the rheological characteristics and the structural properties will be examined. Finally, the effect of the presence of a serum phase on the rheological properties of tomato-derived suspensions will be investigated by comparing the rheology of reconstituted tomato purées containing either water or serum as the continuous phase.

Effect of particle properties on the rheology of tomato-derived suspensions

Structural characterisation of the particles: Particle size

Particle size distributions (PSD) were measured both for the four separated particle fractions and for the original tomato purées homogenised at 20 or 100 MPa (T_20 and T_100). The volumetric PSD of all fractions and both original tomato purées is shown in Fig. 2. Measurements showed monomodal size distributions, both for the separated fractions and the purées. It can also be seen that the collected pulp consists of relatively large particles indicating that the particle fraction is dominated by non-Brownian particles. By comparing the curves, it can be observed that the use of a higher homogenisation pressure in the preparation of the original purées, led to smaller particle size. In addition, the width of the PSD for the reconstituted suspensions turned out to be smaller than the width of the PSD of original tomato purées, as previously observed for tomato-derived products (Lopez-Sanchez et al., 2011a; Augusto et al., 2012).

Based on the PSDs, the average particle size, expressed as $D[v,0.5]$, $D[4,3]$ or $D[3,2]$, could be obtained (Table 2). As already observed from Fig. 2, it can be seen from Table 2 that particles of RS_250 μ m(20) were the largest, whereas those of RS_80 μ m(100) turned out to be the smallest. The average particle size was also larger for particles in RS_125 μ m(20) in comparison to particles in the same fraction obtained from purée homogenised at 100 MPa. This difference in particle size can be caused by a difference in PSD between the original tomato purées. Due to the dominant contribution of large particles to the volume-based average diameters such as $D[v,0.5]$ and $D[4,3]$, their values were larger as compared to $D[3,2]$, the surface-based average diameter. The trends in particle size with sieve pore size and homogenisation pressure were however similar, independent of the average diameter used. $D[v,0.5]$ of T_100 and T_20 appeared to be almost identical to $D[v,0.5]$ of RS_125 μ m(100) and RS_250 μ m(20) respectively. However, the spread of the reconstituted suspensions was smaller than that of the purées from which they were derived. $D[v,0.9]$, the size at which 90 vol% of the particles have a smaller diameter (also given in Table 2), for each fraction was larger (~1.2-2.4 times) than expected from the pores of the sieves through which they passed (125 μ m, 250 μ m or 500 μ m). This observation may be explained by the fact that parenchyma cells, accounting for the majority of cells in vegetable suspensions, are highly deformable (Den Ouden & Van Vliet, 2002) and by the fact that tomato-

derived particles are non-spherical (cf. section “Structural characterisation of the particles: Particle type”). Hence, they can pass through pores with a smaller size than the size of the particle itself. In addition, only the second smallest dimension should be smaller than the pore size to pass through the sieve. All other dimensions can be larger, as a result of which particles can have a $D[v,0.9]$ larger than the pore size of the sieves they pass. Since particle sizes from laser diffraction are calculated assuming a spherical shape, the values in Table 2 should only be treated as indicative rather than as absolute values.

Structural characterisation of the particles: Particle type

The average diameter of a tomato tissue cell can vary between 300 and 1000 μm (Redgwell et al., 2008; Lopez-Sanchez et al., 2011b). Consequently, based on the average diameter of the fractions described above, RS_80 μm (100) and RS_125 μm (100) can be assumed to consist mainly out of small cell fragments, whereas in RS_125 μm (20) and RS_250 μm (20) rather intact cells or even clusters of cells can appear. These differences in particle type among the four particle fractions were investigated in more detail by the use of light microscopy. From the micrographs (Fig. 3A-D), it could be seen that RS_80 μm (100) and RS_125 μm (100) comprise mostly cell fragments and ruptured cells, whereas in RS_125 μm (20) and RS_250 μm (20) mainly intact cells, with a more regular surface and shape, could be found. The appearance of intact, unbroken cells indicates that cell separation along the middle lamella rather than cell breakage occurred during mechanical breakup. Thus, heat treatment of the tomato pieces (95 °C for 8 min) during the production of the tomato purée turned out to be sufficient to degrade pectin in the middle lamella to a level causing cell separation. By the use of high pressures (100 MPa) during high-pressure homogenisation (HPH) intact cell walls were torn. The particle size of the cell fragments and intact cells was increasing with the size of the sieve pores from which they were retained. Finally, cells were clearly not perfectly spherical, but more elongated in shape. Unfortunately, the micrographs could not be used to describe the structure of the suspensions because the suspensions had to be diluted for microscopic analysis, causing changes in structure (e.g., particle packing).

Structural characterisation of the particles: Particle concentration

Particle concentration was measured as the phase volume (ϕ) and the pulp percentage (pulp%). However, due to the compressible nature of particles in plant-based suspensions, the value of ϕ determined by centrifugation may differ from the exact phase volume occupied by the particles in the suspension (Lopez-Sanchez et al., 2012). In Fig. 4, the relation between ϕ and pulp% showed limited dependency on particle size or type. Because ϕ was found to be almost proportional to the pulp%, the pulp% was chosen here as parameter to express the particle concentration. Pulp% of the original purées was determined by the use of wet sieving and amounted 35 wt.%.

Characterisation of the flow behaviour: Shear thinning

All reconstituted tomato-derived suspensions and the original tomato purées listed in Table 1 showed non-Newtonian flow behaviour in combination with the occurrence of a yield stress. This non-Newtonian flow behaviour, caused by structural modifications produced while shearing (Steffe, 1996; Gallegos et al., 2004), is visualised in Fig. 5 for several representative suspensions. As the viscosity is decreasing with increasing shear rate ($\dot{\gamma}$) from 0.1 to 100 s⁻¹, it is clear from Fig. 5A that all suspensions showed shear thinning behaviour. Changing the particle concentration from 30 wt.% to 60 wt.% for RS_80 μ m(100) caused an increase in viscosity with a factor of about 100. In Fig. 5B, the appearance of a yield stress, which becomes larger at increasing particle concentration, is demonstrated for RS_80 μ m(100). Besides concentration, also the particle size appeared to have an effect on the magnitude of the yield stress. Also previous studies reported that tomato-derived products are typically non-Newtonian fluids in which the apparent viscosity is decreasing with increasing shear rate (Rao et al., 1981; Tanglerpaibul & Rao, 1987a; Barrett et al., 1998; Sanchez et al., 2003; Koocheki et al., 2009). To study the non-Newtonian flow behaviour in more detail, the flow curves (shear stress in function of shear rate) were fitted to the Herschel-Bulkley model (Equation 6), this is frequently used in literature to describe the flow behaviour of suspensions (Dekee et al., 1983; Hayes et al., 1998; Koocheki et al., 2009; Augusto et al., 2012). It takes into account the presence of a yield stress and allows for describing shear thinning or shear thickening of the fluids. For all suspensions, the data could be well described with the Herschel-Bulkley model, with $R_{adj}^2 \geq 0.986$. The flow index (n) and the consistency coefficient (K) were estimated by nonlinear regression analysis of the experimental flow curves based on Equation 6 (Table 3).

Subsequently, the influence of particle concentration and particle size on these parameters was investigated.

Values of n and K of the tomato-derived suspensions with low pulp% were comparable with those described in literature for fruit products as tomato juice (Augusto et al., 2012), açai (Tonon et al., 2009) and jaboticaba pulps (Sato & Cunha, 2009). All reconstituted tomato-derived suspensions (except RS_125 μ m(20)_25%) were showing shear thinning behaviour with $n < 1$ for all the pulp% measured in this study. While shearing, the network structure in these suspensions is broken down and shearing is facilitated. In addition, from Table 3, it can be observed that n decreased with increasing particle concentration, meaning that the suspensions' flow behaviour becomes less Newtonian at higher particle concentrations. Also most other authors, investigating the rheology of tomato-derived products, observed a decrease of n (for $n < 1$) with increasing particle concentration (Bhamidipati & Singh, 1990; Barbana & El-Omri, 2012). No unambiguous effect of particle size on the value of n was noticeable. Although in this study the effect of particle size was unclear, some other authors observed an effect of particle size on the flow index of plant-based suspensions, other than tomato-derived suspensions. Sato & Cunha (2009) for example observed the highest n ($n < 1$) for suspensions reconstituted from jaboticaba pulp with the largest particle size. Ahmed et al. (2000), on the other hand, reported a decrease of n ($n < 1$) in chilli purée retained after using a mesh screen with large pores to prepare purée with larger particle size. When comparing n of the reconstituted suspensions with n of T_100 and n of T_20, it can be seen that the flow behaviour of the original purées was less shear thinning than that of the reconstituted suspensions. The broader PSD in the original purées can be an explanation for this latter observation (Luckham & Ukeje, 1999).

In Table 3, values of the consistency coefficient (K) are shown for all tomato-derived suspensions and the original tomato purées. The value of K was increasing with increasing particle concentration. Also in several other studies on the rheology of tomato-derived suspensions, K was reported to increase with particle concentration (Rao et al., 1981; Rao & Cooley, 1983; Alviar & Reid, 1990; Bhamidipati & Singh, 1990; Yoo & Rao, 1994; Barbana & El-Omri, 2012). For the reconstituted tomato-derived suspensions investigated here, the increase in K with particle concentration could be fitted reasonably well to a power law model, as shown in Fig. 6. Previously, Alviar and Reid (1990) and Yoo and Rao (1994), among others, suggested a power law relationship between K and the total solid content or pulp content, respectively, in

tomato products. In Table 3, no unambiguous effect of particle size on the parameter K was noticeable whereas Yoo and Rao (1994) could observe a decrease of K with increasing particle size in tomato purée. K values of the original purées turned out to be smaller than those of the reconstituted suspensions with almost the same particle concentration, mainly for the samples homogenised at 100 MPa. Due to the broader PSD of the original purées, resulting in a more compact packing, the hydrodynamic contribution to the total viscosity in this purées (and the value of K) can be smaller as for the reconstituted suspensions. From Table 3, it can also be noticed that K of T_20 is larger than that of T_100. This decrease in value of K of tomato-derived suspensions homogenised at higher pressure levels was also demonstrated by Augusto et al. (2012) and can be explained by the increase in width of the PSD after HPH at higher pressure levels. In comparison to carrot-derived suspensions (Moelants et al., 2012a), K values of tomato-derived suspensions turned out to be larger, indicating that the flow curves of the carrot-derived suspensions are more dominated by the yield stress. Nevertheless, it can be seen in Fig. 5 that the yield stress contributes substantially to the flow curves of the studied suspensions.

Characterisation of the flow behaviour: Yield stress

From Fig. 5B, it could be observed that for all tomato-derived suspensions flow only occurred above a critical stress value. Hence, these suspensions possess a yield stress. The yield stress obtained from extrapolation of the flow curves to zero shear rate is the dynamic yield stress (σ_{0D}) (Cheng, 1986). It represents the yield stress of a sample from which the structure is broken down by the preceding shear flow. Since at low $\dot{\gamma}$ the datapoints of the flow curves were not always well fitted by the Herschel-Bulkley model, σ_{0D} was read from the flow curve (as the average of the shear stress measured at shear rates 0.1, 1.11 and 2.12 s⁻¹) rather than obtained as parameter from fitting the Herschel-Bulkley model. Results of σ_{0D} are shown in Fig. 7A for all reconstituted suspensions. First, the effect of particle concentration on the value of σ_{0D} was investigated. σ_{0D} increased with particle concentration and this increase could be fitted to a power law model:

$$\sigma_{0D} = a \cdot (\text{pulp}\%)^b \quad (7)$$

The results of these fits are shown in Fig. 7A and parameter estimates for a and b are summarised in Table 4A.

Besides σ_{0D} , the static yield stress (σ_{0S}), obtained as the minimum shear stress required to induce flow in the suspension, can be used as a measure of the structure of the material (Steffe, 1996;

Barnes, 1999; Moller et al., 2006; Mewis & Wagner, 2012). Contrary to σ_{0D} , σ_{0S} is a characteristic of the undisrupted sample (Cheng, 1986). The results of σ_{0S} are shown in Fig. 7B for all reconstituted suspensions and again the effects of particle properties on the value of σ_{0S} were investigated. As observed for σ_{0D} , also σ_{0S} increased with particle concentration following a power law model:

$$\sigma_{0S} = a \cdot (\text{pulp}\%)^b \quad (8)$$

The results of these fits are also shown in Fig. 7B. Parameter estimates for a and b are summarised in Table 4B.

Also in a number of other studies an increase of yield stress with increasing particle concentration was observed in plant-based suspensions (Yoo & Rao, 1994; Yoo & Rao, 1995; Bayod et al., 2007; Moelants et al., 2012a). Power law exponents obtained in the present study have similar values as those available in literature for carrot- and tomato-derived suspensions and in various colloidal dispersions (Shih et al., 1990; Yoo & Rao, 1994; Day et al., 2010a; Lopez-Sanchez & Farr, 2012; Moelants et al., 2012a). From a microstructural point of view, these values of the power law exponents can comply with strongly flocculated suspensions with a self-similar structure. In this case, the power law exponent b can be used to distinguish different types of network structure in the suspensions (Buscall et al., 1987; Bayod et al., 2007; Lopez-Sanchez & Farr, 2012). However, highly concentrated suspensions are less likely to form fractal aggregates. Nevertheless, differences in the power law exponents depending on particle type and size, suggest that these factors affect the microstructure of the suspensions. When the particle size was reduced by increasing the homogenisation pressure, which simultaneously changed the particle type from single cell to cell fragments, a decrease of the power law exponent was found. On the other hand, higher values of b were obtained for reconstituted suspensions with smaller particles made at the same homogenisation pressure, both in the case of cell fragments and single cells. Hence, particle size appears to be not the factor that determines the value of the power law exponent, but rather other particle properties dominate.

To investigate the effect of particle size on the value of the yield stress, this rheological parameter is represented for all reconstituted suspensions with a constant pulp% of 35 wt.% and for the original purées (also 35 wt.% pulp) in Fig. 8. Effects of particle size on σ_{0D} and σ_{0S} of the reconstituted suspensions were similar. In addition, the trends observed in Fig. 8 are present for all investigated pulp contents. From this figure, it is clear that particle size is not the dominant

factor that controls the yield stress. At constant pulp%, for fractions made at the same homogenisation pressure, both for the cell fragments and for the single cells, the yield stresses σ_{0D} and σ_{0S} increased with increasing particle size. Based on the fact that smaller particles have a larger interaction surface at the same volume fraction or pulp content as compared to larger particles, a reverse trend was expected. However, Tanglerpaibul and Rao (1987a) also reported a reduced viscosity in tomato concentrate produced with smaller screen size. Some other studies on reconstituted plant-suspensions also observed lower values of the yield stress in suspensions with smaller particle size (Schijvens et al., 1998; Moelants et al., 2012a). On the other hand, when comparing RS_125 μ m(100) and RS_125 μ m(20), the yield stress decreased with increasing particle size. A similar effect of the intensity of homogenisation was found by Moelants et al. (2012a) for reconstituted carrot-derived suspensions. This decrease in yield stress can be explained by a increase in particle size, but also by the changes in particle type from cell fragments to single cell when reducing the homogenisation pressure. Hence, particles obtained at a lower homogenisation pressure were more regular by shape and had a rather smooth surface as compared to particles obtained after HPH at higher pressures (cf. section “Structural characterisation of the particles: Particle type”). A higher homogenisation pressure appears to result in smaller but also less spherical, more irregular particles whereby the yield stress can increase. Hand et al. (1955) and Den Ouden and Van Vliet (1997), among others, already demonstrated the possible role of particle surface and shape in influencing the rheological properties of plant-based suspensions. In conclusion, the prediction of the effect of individual particle properties on rheological parameters in food suspensions turns out to be complex: as the particle size changes, other particle properties such as the width of the PSD or the particle shape are often changing at the same time.

In Fig. 8, also the yield stresses of the original tomato purées are shown. The values of σ_{0D} of T_100 and T_20 were similar to those of RS_125 μ m(100)_35% and RS_250 μ m(20)_35%, respectively (Fig. 8A). On the basis of results from Moelants et al. (2012a) for carrot-derived suspensions, a lower value of σ_{0D} for the original purée was expected as compared to σ_{0D} of the reconstituted suspension with a similar average particle size, but smaller spread (Table 2). When comparing σ_{0S} of the original purées with those of the reconstituted suspensions, σ_{0S} of the original purées was also larger as expected from the particle size. The presence of a serum phase with solubilised pectin may be an explanation for the higher values of the yield stresses of the

original purées as compared to those of the reconstituted suspensions. The effect of the presence of a serum phase on the rheological properties of tomato-derived suspensions will be discussed in more detail in the section “Effect of the serum phase on the rheology of tomato-derived suspensions”.

Further, σ_{0S} was larger than σ_{0D} for all the reconstituted suspensions and for both original tomato purées. Hence, the shear stress that is required to initiate flow is larger than the shear stress required to maintain flow at low shear rates. This is caused by the fact that additional connections can be formed between the aggregates/flocs in the sheared suspension when keeping it in quiescent conditions for a certain time. The difference between σ_{0S} and σ_{0D} can provide a measure for the stress necessary to break these bonds in the network (Genovese et al., 2007). To investigate the relation between σ_{0S} and σ_{0D} , the first was plotted versus the latter in Fig. 9. Two straight lines through the origin with different slopes were found. Data points for reconstituted suspensions made at the same homogenisation pressure were situated on the same straight line. The ratio of σ_{0D} to σ_{0S} was approximately 0.83 and 0.55 for all reconstituted suspensions made from purée homogenised at 20 or 100 MPa, respectively. For carrot-derived suspensions containing either carrot cells or cell clusters, this ratio turned out to be 0.75, independent of the homogenisation pressure (Moelants et al., 2012a). Therefore, it can be concluded that the suspensions containing tomato cell fragments show the highest increase in strength due to structural reorganisations in quiescent conditions. The latter can be attributed to the presence of flexible and protruding parts. In addition, an open cell structure might enable more physical entanglements of polymers and additional interactions. Suspensions consisting of intact cells with a smooth particle surface and less irregular shape exhibit much less structure enhancement. Carrot clusters and fragments with an intermediate amount of dangling parts, showed an intermediate ratio of σ_{0D} to σ_{0S} (Moelants et al., 2012a). Hence, changing the particle type can clearly be used as a tool to tailor the amount of structural strengthening after cessation of flow in plant-based food suspensions. The ratio σ_{0D}/σ_{0S} of the original tomato purées was smaller than that of the reconstituted suspensions, meaning even more structure is build up in quiescent conditions in the original purées. The presence of a serum phase and the broader particle size distribution can be responsible for this observation.

In conclusion, the rheological parameters characterizing the flow behavior of tomato-derived suspensions such as the yield stress, flow index and consistency coefficient are highly dependent on the particle concentration. Other particle properties such as size and surface characteristics turn out to mainly affect the yield stress. Next to particle size, particle shape and surface roughness clearly play a role.

Characterisation of the viscoelastic behaviour

Small-amplitude oscillatory tests were performed to gain insight in the network structure of the plant-based suspensions. To start, the linear viscoelastic region was determined from strain sweep experiments. At constant angular frequency and low strains, the storage modulus (G') and the loss modulus (G'') were strain independent, meaning a zone of linear viscoelasticity was present. At low strain, G' turned out to be larger than G'' , indicating that the suspensions behave elastically. Increasing the strain caused a decrease in both G' and G'' whereby the zone of linear viscoelasticity ended and the structure in the sample started to break down. From this oscillatory measurement the critical strain (γ_y) (95%) was calculated by fitting the measured values of G' as function of strain to Equation 9. The γ_y was determined as shown in Equation 10 (Lopez-Sanchez & Farr, 2012).

$$G' = G'_0 \exp(-A\gamma^B) \quad (9)$$

$$\gamma_y = \left[\frac{\ln(\frac{1}{0.95})}{A} \right]^{1/B} \quad (10)$$

where A and B are constants.

The values of the critical strain are presented in Table 5 and indicate the departure from the linear viscoelastic region. It can be noted that a strain of 0.1% is small enough to fall within the zone of linear viscoelasticity for all samples. Also, a decrease of γ_y as a function of particle concentration was observed (especially visible for RS_80 μ m(100) and RS_250 μ m(20)). This trend is in agreement with other observations in literature, both for hard (Shih et al., 1990) and deformable particles (Lopez-Sanchez & Farr, 2012). For suspensions containing especially cell fragments (homogenised at 100 MPa) γ_y was slightly larger than for suspensions comprising mainly intact cells (homogenised at 20 MPa). This might be caused by the larger deformability of the former particles. For one particle morphology, a limited decrease in γ_y could be observed

with increasing particle size at constant pulp%. Possibly, small particles have more contact points than larger particles, allowing more reorganisations in the network and the possibility of more polymer entanglements between particles, whereby γ_y is increasing. When comparing γ_y of the original tomato purées, γ_y of T_100 (= 0.49) was higher than γ_y of T_20 (= 0.32), supporting the fact that γ_y increases when more cell fragments are present and as particle size becomes smaller. Also Moelants et al. (2012a) and Lopez-Sanchez and Farr (2011) found a lower critical strain for smaller particles in both carrot-derived and tomato-derived suspensions. In general, values of γ_y at high particle concentrations were small, indicating that the tight packing of the deformable tomato cells in these concentrated suspensions causes yielding at very low strains, as in concentrated emulsions (Mason et al., 1996).

Beside strain sweeps, frequency sweeps at a constant strain in the linear viscoelastic region were used to characterise the network structure of the reconstituted suspensions and the original tomato purées. As magnitudes of G' were larger than those of G'' at all ω (except for a few reconstituted suspensions with low pulp% for which G'' crossed G' at high ω), suspensions exhibited solid-like behaviour. The results of the frequency sweeps were analysed using a power law model (Equations 11 and 12) where c , d , e and f are constants and ω is the angular frequency.

$$G' = c \cdot \omega^d \quad (11)$$

$$G'' = e \cdot \omega^f \quad (12)$$

Values of parameters c and e (data not shown) increased with increasing pulp% for the reconstituted suspensions. Values of the power law exponents d and f ranged between 0.01 and 0.08 for all the reconstituted suspensions and the original tomato purées (results not shown) and no unambiguous effect of particle concentration or size was noticed. Because $G' > G''$ and the values for d and f were very low (but different from zero), the rheological behaviour of these reconstituted suspensions and original tomato purées can be described as that of weak gels. Moreover, the ratio of G'/G'' at low angular frequency ($\omega = 0.1$ rad/s) was about 10, supporting this last conclusion. Also, among others, Yoo and Rao (1996) and Bayod et al. (2008) concluded that the behaviour of tomato paste corresponds to that of a weak gel. Changes in particle concentration (between 30-65 wt.%) did not cause a transition in type of gel. However, as particle concentration increased the plateau moduli were higher and the plateau extended to higher frequencies, indicating that at increasing particle concentration a more pronounced gel

character evolved. Remarkable was the lower ratio of G'/G'' of the original tomato purées in comparison to the reconstituted suspensions. Since the values of G' were larger for the original purées than for the reconstituted suspensions (cf. below), this implies that the original purées were also more viscous than the reconstituted suspensions (larger values of G''), possibly due to the absence of a serum phase in the latter. Moelants et al. (2012b) already demonstrated that the serum viscosity of tomato purées can be 6 times higher than the viscosity of water.

For the reconstituted suspensions, values of G' at low angular frequency (ω of 0.1 rad/s), used as direct measure of the structure in the samples, increased with pulp%. Consequently, the network in these suspensions is stiffer at higher particle concentration. Also Day et al. (2010b), Bayod and Tornberg (2011), Lopez-Sanchez and Farr. (2012) and Moelants et al. (2012a) reported an increase of G' with particle concentration for plant-based suspensions. By analogy with the yield stress, this increase could be fitted to a power law model (Fig. 10):

$$G' = g \cdot (\text{pulp}\%)^h \quad (13)$$

Estimates for parameters g and h are summarised in Table 6. Trends in exponents b (Table 4) and h (Equation 13) with changing particle size and type were similar, indicating that the same changes in network structure between suspensions prepared from particles with different particle size can be seen in steady shear and oscillatory tests. Recently, it was shown that modelling these suspensions as a non-affine network of folded elastic sheets leads to a power law exponent of 3 (Lopez-Sanchez & Farr, 2012), which is relatively close to the values shown in Table 6.

As for the yield stress, the effect of particle size on the value of G' was investigated at a constant pulp% of 35 wt.% in Fig. 11. Similar to the conclusions for the yield stress, the effect of particle concentration on G' is clear, but the effect of particle size is more difficult to interpret. For the reconstituted suspensions prepared from original tomato purée homogenised at the same pressure, G' increased with particle size, whereas G' decreased when the particle size was increased by reducing the homogenisation pressure. Hence, besides particle size, also particle shape, deformability and particle surface can influence the value of G' and the network structure at the same time. From Fig. 11, it can be noticed that the magnitude of G' of T_20 is higher than that of T_100. This decrease in value of G' of tomato purées after HPH at higher pressure levels was also demonstrated by Lopez-Sanchez et al. (2011b). Values for G' of the original tomato purées homogenised at a given pressure were larger than the ones of the reconstituted suspensions with a pulp% of 35 wt.% prepared from the purée homogenised at this pressure

while $D[v,0.5]$ was almost equal in both products. The presence of a serum phase in the original tomato purées can be an explanation for this observation.

Relations between yield stress and elastic modulus

As last, the relation between G' and the static yield stress is studied in more detail, because comparable trends for G' and the yield stress with particle concentration and size were found. Thereto, G' is shown as a function of σ_{0S} in Fig. 12. The ratio of σ_{0S} to G' was independent of particle size and concentration, but this ratio changed for suspensions made at a different homogenisation pressure. σ_{0S}/G' was approximately 0.11 and 0.16 for all reconstituted suspensions made from purée homogenised at 20 or 100 MPa, respectively. In a previous study of Moelants et al. (2012a) on carrot-derived suspensions, a unique relation of σ_{0S}/G' of about 0.16 for all suspensions was found, independent of the homogenisation pressure that was used. Data may indicate that σ_{0S}/G' is larger for suspensions made out of particles with a more irregular surface/shape. As σ_{0S} characterises the strength of the suspensions whereas G' indicates their stiffness, a higher ratio of σ_{0S}/G' might comply with a larger yield strain.

In order to assess the relations between oscillatory and steady shear data further, the maximal elastic stress obtained from an oscillatory strain sweep is compared with the static yield stress in Fig. 13. A linear relation was found, independent of the homogenisation pressure used. The static yield stress can thus be obtained by the performance of an oscillatory strain or stress sweep test. This relation was not shown in Moelants et al. (2012a) for carrot-derived suspensions, but it is also valid for these suspensions. Also for non-food suspensions, the maximal elastic stress has been shown to be a good estimate for the yield stress (Walls et al., 2003).

Effect of the serum phase on the rheology of tomato-derived suspensions

Results discussed above (Fig. 8 and 11) suggest that the presence of a serum phase can increase the structural strength, especially in quiescent conditions. To confirm this hypothesis, the rheological properties of reconstituted tomato purées in water (RP(20)_35%w) and serum (RP(20)_35%s) were compared. To assess the effect of the sieving and reconstitution steps, the rheological properties of the reconstituted purées are also compared to those of the original tomato purée (T_20').

Results of the dynamic and static yield stress of T_20', RP(20)_35%w and RP(20)_35%s are represented in Fig. 14. Although the average particle size and the spread of the PSD of T_20', RP(20)_35%w and RP(20)_35%s were almost the same (results not shown), σ_{0S} of RP(20)_35%s was significantly higher as compared to σ_{0S} of RP(20)_35%w. The serum phase turned out to be able to increase the resistance against flow. As serum comprises, among others, solubilised pectin and ions, the presence of a serum phase may change particle properties (like the surface charge) and also particle interactions may be altered. This way, more structure can build up in quiescent conditions in reconstituted purées with a serum phase as compared to reconstituted purées in water. σ_{0S} of T_20' was even larger than σ_{0S} of RP(20)_35%s. By using reconstitution, very small particles and cell material (with a particle size between 11-40 μm) are possibly lost during the sieving process, weakening the network strength. For G' the same effect of the presence of a serum phase was found as described for σ_{0S} (results not shown).

In contrast to σ_{0S} , the presence of a serum phase turned out to have little effect on σ_{0D} (measured after breaking down the structure in shear flow). Therefore, it can be concluded that the serum phase especially alters the structure build up at rest and that its presence is less important for the structure that remains under flow conditions.

In contrast, Lopez-Sanchez et al. (2011a) observed no changes in rheological behaviour of carrot-derived suspensions when the serum was replaced by deionised water. However, the serum viscosity of tomato-derived suspensions was shown to be higher as compared to that of carrot derived suspensions and, moreover, the ability of pectin chains to overlap and entangle turned out to be larger in tomato sera (Moelants et al., 2012b).

Conclusion

With regard to the possibility to tailor the rheology of plant-based food suspensions, the effect of structural characteristics (particle properties) on the rheological properties of tomato-derived suspensions was investigated. Rheology of these tomato-derived suspensions appeared to be complex. The particle concentration was a dominant property in controlling the rheology of the tomato-derived suspensions. Also the particle size was influencing the rheological properties. Within the same particle type (single cells or cell fragments) the strength and stiffness of the suspensions was increasing with increasing particle size. When increasing the particle size by

reducing the homogenisation pressure, the opposite trend was found. This indicates that next to particle size, also other particle properties such as the particle shape and width of the particle size distribution affect the rheology.

All suspensions showed non-Newtonian flow behaviour and the flow curves were dominated by the yield stress. Network strength and stiffness, measured as the yield stress and the storage modulus, respectively, increased with increasing particle concentration for all the tomato-derived suspensions and this increase could be fitted to a power law model. Exponents of these models demonstrate that the network structure in the suspensions was changing when particle size or type (single cells versus cell fragments) was altered. The ratios of the dynamic to static yield stress and the ratio of the static yield stress to storage modulus turned out to be only dependent on the homogenisation pressure used to prepare the reconstituted suspensions. This shows that changing the particle type by high-pressure homogenisation can be used as a tool to tailor the amount of structural strengthening after cessation of flow. All systems could be described as weak gels. Changing particle size or concentration did not significantly change the gel type. It was found that the yield stress of tomato-derived suspensions can be determined from the maximal elastic stress in an oscillatory strain sweep experiment, as the relation between these two parameters was independent of particle size and type. Most reported effects are similar to those found in earlier work on carrot-derived suspensions (Moelants et al., 2012a).

Replacing the serum phase by water led to a substantial decrease in network strength and stiffness, especially in quiescent conditions.

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Fig. 1 Schematic overview of the preparation and reconstitution of tomato-derived suspensions from tomato purée.

778 **Fig. 2** Volumetric particle size distribution of RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$), T_100
779 ($\square$), RS_125 μ m(20) ($\blacktriangle$), RS_250 μ m(20) ($\bullet$) and T_20 ($\square$).

Fig. 3 Microscopic images (10×) of 1/10 diluted fractions with different particle size stained with toluidin blue (RS_80µm(100) (A); RS_125 µm(100) (B); RS_125 µm(20) (C) and RS_250 µm(20) (D)).

787 **Fig. 4** Relation between phase volume and pulp% for the reconstituted suspensions
788 RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$), RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$).

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Fig. 5 Non-Newtonian flow behaviour for several suspensions: (A) Shear thinning behaviour and (B) appearance of a yield stress for the reconstituted suspensions RS_80 μm (100)_30% ($\diamond$), RS_80 μm (100)_60% ($\blacklozenge$), RS_125 μm (100)_30% ($\square$), RS_125 μm (20)_30% ($\triangle$) and RS_250 μm (20)_30% ($\circ$).

797 **Fig. 6** Consistency coefficient (K) ($\pm$ standard deviation) as a function of pulp% for the
798 reconstituted suspensions RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$), RS_125 μ m(20) ($\blacktriangle$) and
799 RS_250 μ m(20) ($\bullet$). Lines represent the power law model fits.

802 **Fig. 7** Average dynamic (σ_{0D}) (A) and static (σ_{0S}) (B) yield stress ($\pm$ standard deviation) as a
803 function of pulp% for the reconstituted suspensions RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$),
804 RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$). Lines represent the power law model fits ($\sigma_0 =$
805 $a \cdot (\text{pulp}\%)^b$).

808 **Fig. 8** Dynamic (■) and static (■+■) yield stress ($\pm$ standard deviation) of the reconstituted
809 tomato-derived suspensions with a pulp% of 35 wt.% and of the original tomato purées
810 homogenised at 20 MPa or 100 MPa. For the suspensions RS_80 μ m(100) and RS_250 μ m(20)
811 the values at 35 wt.% pulp were determined from the power law fits (Table 4).

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814 **Fig. 9** Relation between the dynamic yield stress (σ_{0D}) and the static yield stress (σ_{0S}) ($\pm$ standard
815 deviation) for the reconstituted suspensions RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$),
816 RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$).

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819 **Fig. 10** Storage modulus (G') (at $\omega = 0.1$ rad/s) ($\pm$ standard deviation) of reconstituted tomato-
820 derived suspensions as a function of pulp% for the reconstituted suspensions RS_80 μ m(100)
821 ($\blacklozenge$), RS_125 μ m(100) ($\blacksquare$), RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$). Lines represent the
822 power law model fits ($G' = g \cdot (\text{pulp}\%)^h$).

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Fig. 11 Storage modulus (G') (at $\omega = 0.1$ rad/s) ($\pm$ standard deviation) of the reconstituted tomato-derived suspensions with a pulp% of 35 wt.% and of the original tomato purées homogenised at 20 MPa or 100 MPa. For the suspensions RS_80 μ m(100) and RS_250 μ m(20) the values at 35 wt.% pulp were determined from the power law fits (Table 6).

831 **Fig. 12** Relation between the storage modulus (G') (at $\omega = 0.1$ rad/s) and the static yield stress
832 (σ_{0S}) ($\pm$ standard deviation) for the reconstituted suspensions RS_80 μ m(100) ($\blacklozenge$),
833 RS_125 μ m(100) ($\blacksquare$), RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$).

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836 **Fig. 13** Relation between the maximal elastic stress in oscillation and the static yield stress (σ_{0S})
837 ($\pm$ standard deviation) for the reconstituted suspensions RS_80 μ m(100) ($\blacklozenge$), RS_125 μ m(100)
838 ($\blacksquare$), RS_125 μ m(20) ($\blacktriangle$) and RS_250 μ m(20) ($\bullet$).

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Fig. 14 Dynamic (■) and static (■+■) yield stress ($\pm$ standard deviation) of a original tomato purée homogenised at 20 MPa (T_20'), a reconstituted suspension comprising the same particles as present in the original purée with a continuous water phase (RP(20)_35%w) and a suspension reconstituted in serum comprising the same particles as present in the original purée (RP(20)_35%s). Pulp content was 35 wt.%. The purée and suspensions were prepared from another tomato variety than that used in the rest of the work.

849 **Table 1** Sample coding and preparation conditions.

Sample code	Preparation conditions
Original tomato purée	
T _p	Tomato purée T homogenised at pressure p (in MPa)
Reconstituted suspensions	
RS _{x(p)} -y%	Reconstituted suspension in water made from the particle fraction retained on the sieve with pore size x after wet sieving of tomato purée homogenised at pressure p. y represents the pulp% of this suspensions.
Reconstituted tomato purée	
RP(p) _y %z	Reconstituted purée made by reconstitution of the particles obtained after wet sieving of the original purée in z (water w or serum s) with a pulp% of y.

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Table 2 Particle size of the reconstituted tomato-derived suspensions and the original purées expressed as the size of which 10, 50 or 90 vol% of the particles have a smaller diameter (D[v,0.1], D[v,0.5] and D[v,0.9]), the area-based diameter (D[3,2]) and the volume-based diameter (D[4,3]). The spread of the particle size distribution is calculated as in Equation 4.

Sample	D[v,0.1] (μm)	D[v,0.9] (μm)	D[v,0.5] (μm)	D[3,2] (μm)	D[4,3] (μm)	Spread
RS_80 μm (100)	57.3	297.1	147.7	94.1	163.8	2.5
RS_125 μm (100)	105.0	511.1	267.0	162.5	288.8	2.5
RS_125 μm (20)	154.2	484.6	303.0	194.2	310.3	1.7
RS_250 μm (20)	218.9	578.0	392.8	281.8	393.8	1.3
T_100	76.2	572.9	269.1	119.3	299.8	4.2
T_20	174.8	643.9	381.2	177.6	394.8	2.6

Table 3 Flow index (n) and consistency coefficient (K) ($\pm$ standard deviation) of the reconstituted tomato-derived suspensions and original tomato purées in function of pulp% estimated using the Herschel-Bulkley model.

Pulp% (wt.%)	RS_80µm(100)	RS_125µm(100)	RS_125µm(20)	RS_250µm(20)	T_20	T_100
	n (-)					
25		0.53 $\pm$ 0.03	1.18 $\pm$ 0.01			
30	0.68 $\pm$ 0.05 ^a	0.36 $\pm$ 0.02	0.65 $\pm$ 0.02	0.56 $\pm$ 0.06		
35		0.36 $\pm$ 0.01	0.56 $\pm$ 0.02		0.89 $\pm$ 0.07	1.00 $\pm$ 0.09
40	0.40 $\pm$ 0.01	0.35 $\pm$ 0.06	0.56 $\pm$ 0.01	0.61 $\pm$ 0.00		
45		0.36 $\pm$ 0.05	0.55 $\pm$ 0.00			
50	0.38 $\pm$ 0.02	0.45 $\pm$ 0.05	0.49 $\pm$ 0.00	0.60 $\pm$ 0.00		
55		0.39 $\pm$ 0.03	0.48 $\pm$ 0.09			
60	0.32 $\pm$ 0.03	0.31 $\pm$ 0.01	0.38 $\pm$ 0.00	0.48 $\pm$ 0.04		
	K (Pa·s ^{n})					
25		0.46 $\pm$ 0.09	0.01 $\pm$ 0.00			
30	0.26 $\pm$ 0.06	2.27 $\pm$ 0.35	0.20 $\pm$ 0.02	0.46 $\pm$ 0.12		
35		4.28 $\pm$ 0.21	0.54 $\pm$ 0.07		0.53 $\pm$ 0.194	0.31 $\pm$ 0.132
40	3.61 $\pm$ 0.28	6.47 $\pm$ 2.31	0.87 $\pm$ 0.08	0.76 $\pm$ 0.05		
45		7.44 $\pm$ 1.95	0.98 $\pm$ 0.04			
50	7.59 $\pm$ 0.74	5.43 $\pm$ 1.13	1.88 $\pm$ 0.02	1.34 $\pm$ 0.04		
55		9.78 $\pm$ 1.78	3.88 $\pm$ 0.15			
60	16.62 $\pm$ 2.80	21.88 $\pm$ 1.18	6.21 $\pm$ 0.28	3.39 $\pm$ 0.96		

^a stdev

Table 4 Parameters a and b ($\pm$ standard error) of the power law model ($\sigma_0 = a \cdot (\text{pulp}\%)^b$) fitted to the dynamic (A) and static (B) yield stress as a function of the pulp%.

A

	a			b			R_{adj}^2
RS_80 μm (100)	7.71E-07	$\pm$	3.54E-07 ^a	4.40	$\pm$	0.11	1.00
RS_125 μm (100)	8.33E-05	$\pm$	4.13E-05	3.27	$\pm$	0.12	0.99
RS_125 μm (20)	2.94E-06	$\pm$	2.00E-06	4.08	$\pm$	0.17	0.99
RS_250 μm (20)	2.47E-04	$\pm$	3.00E-04	3.07	$\pm$	0.31	0.97

^a st error

B

	a			b			R_{adj}^2
RS_80 μm (100)	2.00E-04	$\pm$	2.00E-04 ^a	3.11	$\pm$	0.25	0.98
RS_125 μm (100)	4.00E-04	$\pm$	2.00E-04	3.00	$\pm$	0.13	0.99
RS_125 μm (20)	1.01E-06	$\pm$	8.77E-07	4.39	$\pm$	0.22	0.99
RS_250 μm (20)	3.00E-04	$\pm$	3.00E-04	3.05	$\pm$	0.27	0.98

^a st error

Table 5 Critical strain (γ_y) (for $\omega = 10$ rad/s) of all reconstituted tomato-derived suspensions as measure of the limit of the zone of linear viscoelasticity.

Pulp%	γ_y (%)			
(wt.%)	RS_80μm(100)	RS_125μm(100)	RS_125μm(20)	RS_250μm(20)
25		1.21	0.41	
30	2.07	1.40	0.75	1.13
35		0.46	1.16	
40	0.75	0.49	0.45	0.30
45		0.39	0.37	
50	0.52	0.40	0.37	0.27
55		0.35	0.40	
60	0.49	0.33	0.36	0.24

Table 6 Parameters g and h ($\pm$ standard error) of the power law model ($G' = g \cdot (\text{pulp}\%)^h$) fitted to G' (at $\omega = 0.1$ rad/s) as a function of the pulp%.

	g			h			R_{adj}^2
RS_80 μm (100)	4.07E-05	$\pm$	3.30E-05 ^a	3.96	$\pm$	0.20	0.99
RS_125 μm (100)	1.45E-04	$\pm$	1.00E-04	3.74	$\pm$	0.19	0.98
RS_125 μm (20)	1.96E-05	$\pm$	1.39E-05	4.19	$\pm$	0.18	0.99
RS_250 μm (20)	1.90E-03	$\pm$	2.40E-03	3.15	$\pm$	0.31	0.97

^a st error