CHAPTER 5 GENERALIZED MICROSTRUCTURAL CHANGE AND STRUCTURE-QUALITY INDICATORS OF A FOOD PRODUCT UNDERGOING DIFFERENT DRYING METHODS AND CONDITIONS

This chapter presents two generalized indicators that can be used to monitor the microstructural changes of carrot cubes undergoing three representative drying methods, i.e., hot air drying, vacuum drying and low-pressure superheated steam drying, at different conditions. Moreover, these indicators can be used as a generalized structure-quality indicator to correlate the microstructural changes to some physical characteristics changes as well.

5.1 Drying Kinetics

The drying curves of carrot cubes undergoing HAD, VD and LPSSD in terms of the dimensionless moisture content (X/X_0) are shown in Figures 5.1a, 5.1b and 5.1c, respectively. Carrots having an initial moisture content in the range of 8.4-11 kg/kg (d.b.) were dried to a final moisture content of around 0.1 kg/kg (d.b.). As expected, higher drying temperatures led to higher drying rates due to increased driving force for heat transfer, which is also related to the rate of mass transfer. Moisture diffusivity is also higher at a higher drying temperature.

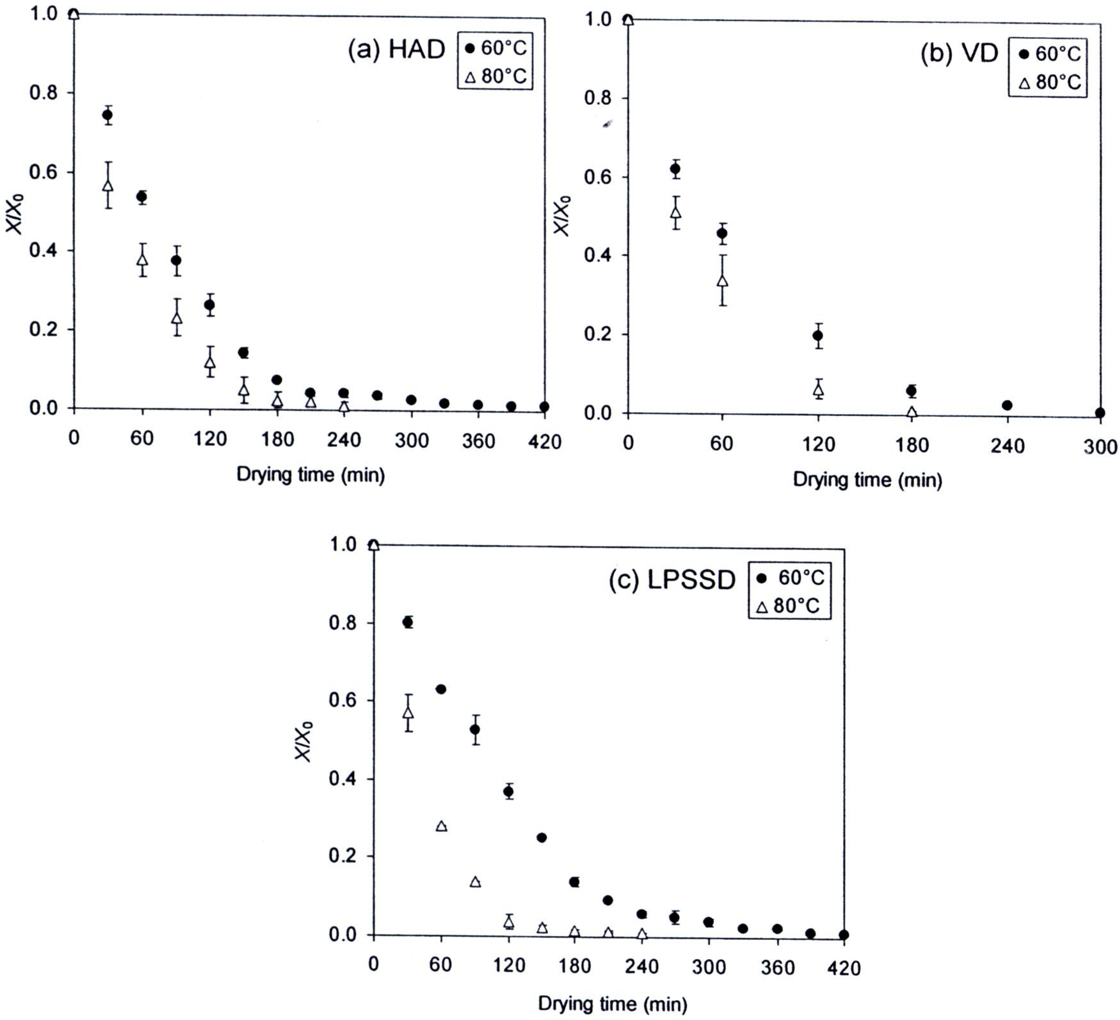

Figure 5.1 Drying curves of carrot cubes undergoing (a) HAD; (b) VD; (c) LPSSD

5.2 Generalized Microstructural Change Indicators

5.2.1 Relationships between $\Delta FD/FD_0$ and X/X_0

Figure 5.2 shows the relationships between $\Delta FD/FD_0$ and X/X_0 of carrot cubes undergoing HAD, VD and LPSSD. Regardless of the drying methods and temperature the results showed that $\Delta FD/FD_0$ increased with decreasing moisture content, indicating that the irregularity of cell walls and intercellular spaces increased due to the loss of moisture. Nevertheless, toward the end of drying, at lower moisture contents ($X/X_0 \leq$ 0.1), $\Delta FD/FD_0$ kept increasing continuously, whereas the moisture content did not change much. This is probably due to the continued collapse of the sample microstructure at extended drying when the moisture content remained almost unchanged (Mayor and Sereno, 2004; Rahman, 2001).

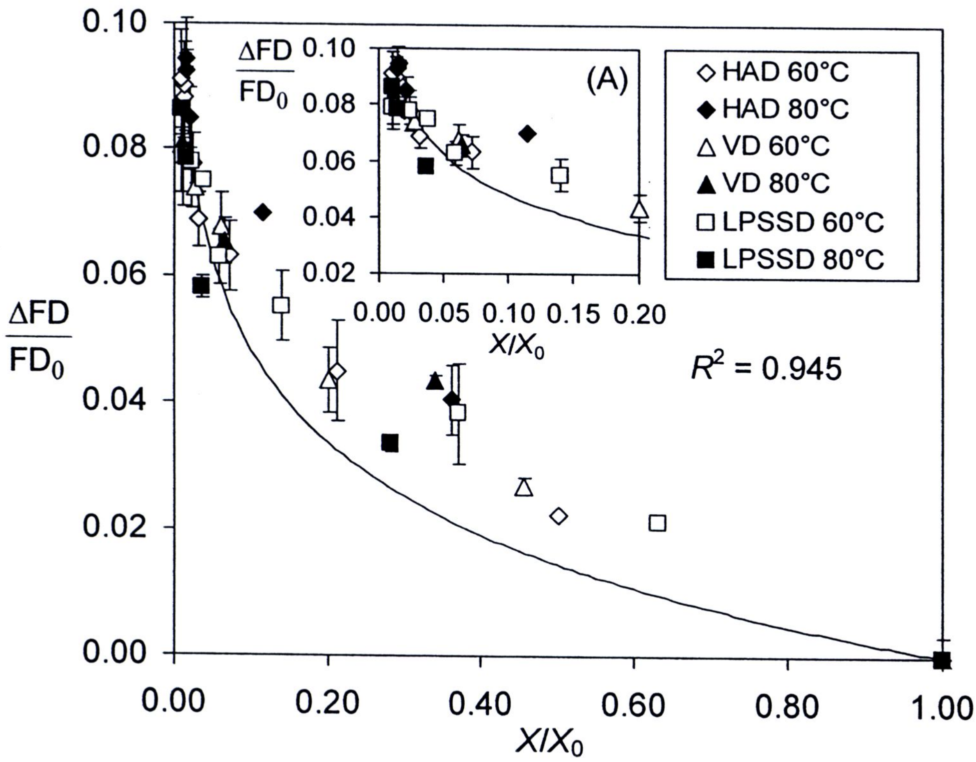

Figure 5.2 Relationships between $\Delta FD/FD_0$ and X/X_0 of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. Insert (A) represents the results over $0.01 \leq X/X_0 \leq 0.2$.

It is interesting to note that the evolution pattern of $\Delta FD/FD_0$ with X/X_0 is almost independent of the drying methods and conditions. $\Delta FD/FD_0$ therefore represents an adequate relationship between the changes of moisture content and microstructure of a sample undergoing any selected drying processes at any tested conditions.

Quantitative information on the microstructural changes of a sample undergoing a particular drying process at a particular condition should be the same as that of a sample undergoing other drying processes at other conditions if the results are considered at the same $\Delta FD/FD_0$. The following empirical correlation is proposed to represent the relationship between $\Delta FD/FD_0$ and X/X_0 of carrot cubes undergoing HAD, VD and LPSSD:

$$(\Delta FD/FD_0) = a\ln(X/X_0) \tag{5.1}$$

where a is an empirical constant obtained by fitting the equation to the experimental results; the value of this constant is shown in Table 5.1. A good correlation was found with the R^2 of around 0.945, indicating that the loss of moisture during drying significantly affected the destruction of the cell walls and intercellular spaces.

Table 5.1 Empirical constants in Equations (5.1)-(5.6)

Equation	Variable of the relationship		a	b	c	R^2
(5.1)	$\Delta FD/FD_0$	X/X_0	-0.021	-	-	0.945
(5.2)	$\overline{\Delta D}/\overline{D_0}$	X/X_0	-0.138	-	-	0.958
(5.3)	$\Delta FD/FD_0$	% Shrinkage	0.006	0.031	-0.006	0.942
(5.5)	$\overline{\Delta D}/\overline{D_0}$	% Shrinkage	0.007	0.052	-0.007	0.851
(5.4)	$\Delta FD/FD_0$	Hardness	0.072	-0.177	-	0.948
(5.6)	$\overline{\Delta D}/\overline{D_0}$	Hardness	0.491	-1.210	-	0.917

5.2.2 Relationships between $\overline{\Delta D}/\overline{D_0}$ and X/X_0

The evolutions of $\overline{\Delta D}/\overline{D_0}$ during HAD, VD and LPSSD as a function of X/X_0 are shown in Figure 5.3. Again, it is seen that the evolutions of $\overline{\Delta D}/\overline{D_0}$ during the three drying methods are quite similar. $\overline{\Delta D}/\overline{D_0}$ increased with decreasing moisture content, indicating that the moisture removal also led to a decrease in the sample cellular dimension.

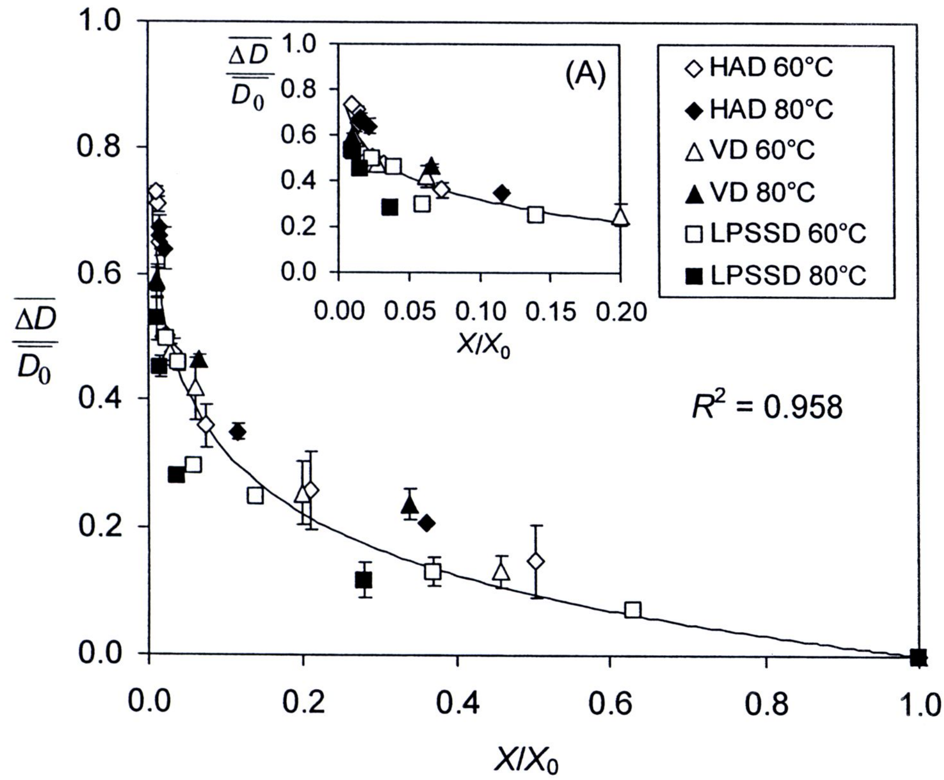

Figure 5.3 Relationships between $\overline{\Delta D}/\overline{D_0}$ and X/X_0 of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. Insert (A) represents the results over $0.01 \le X/X_0 \le 0.2$.

However, $\overline{\Delta D} / \overline{D_0}$ changed less rapidly with X/X_0 compared with $\Delta FD/FD_0$, representing the fact that the cellular dimension was less affected by the change of the moisture content than the sample microstructural irregularity, especially during an early period of drying. This is probably because during the early period of drying the content of bound water, which is held mostly within the cell volume, is not much affected (Park et al., 2006). The cell volume thus decreased less significantly compared with the changes of the microstructural irregularity. Later, however, moisture started to migrate from the cells, leading to moisture-gradient induced stresses and loss of turgor pressure. The cell walls were pulled down, leading the cells to wrinkle and hence collapsed structure. At this later stage of drying the irregularity of the cell walls and intercellular spaces increased, leading to an increase in the fractal dimension; at the same time the cellular dimension decreased as shown in Figure 5.4.

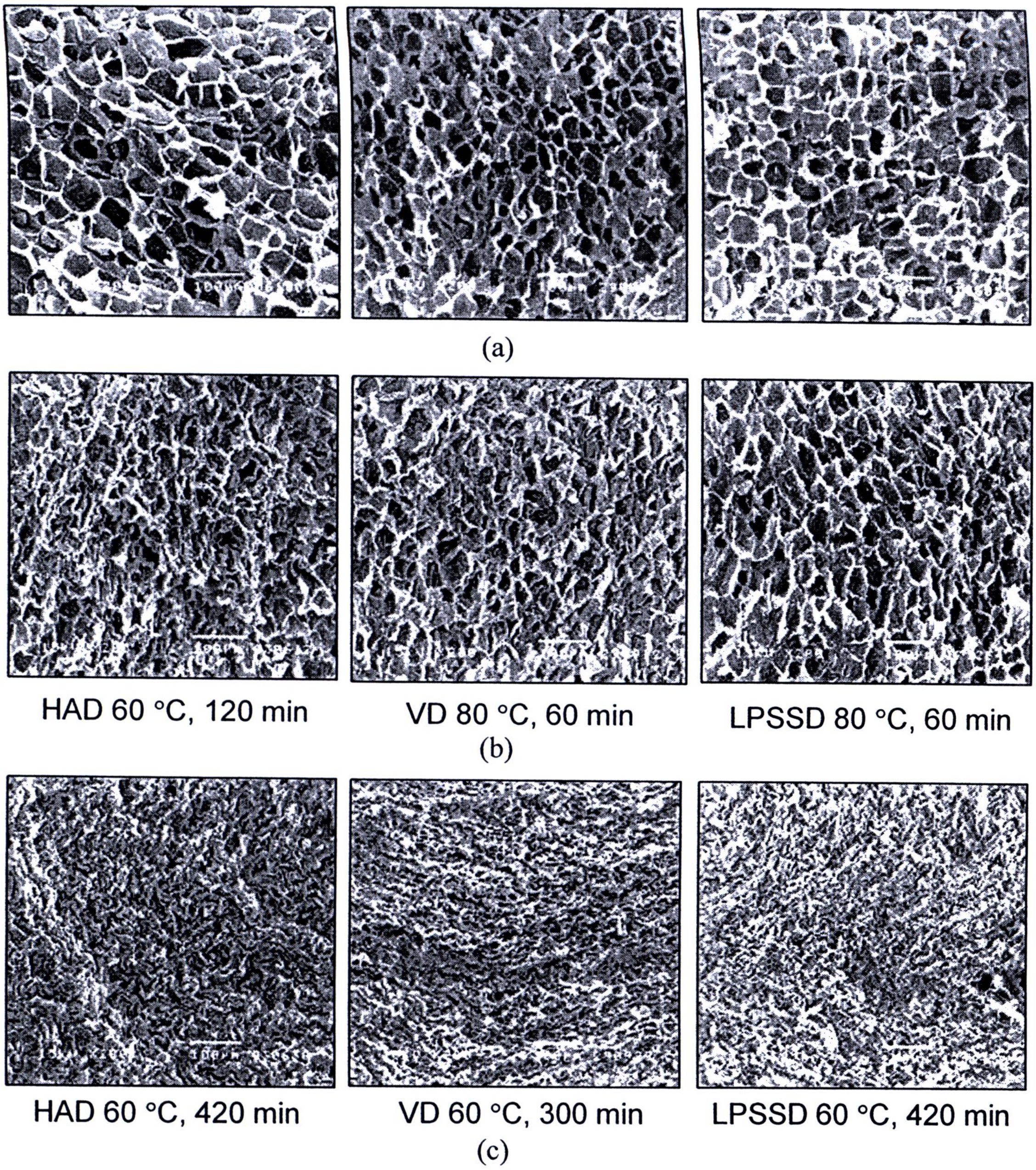

Figure 5.4 Microstructure of carrot cubes undergoing HAD, VD and LPSSD at (a) $X/X_0 = 1.00$ (fresh carrot); (b) $X/X_0 \approx 0.27$; (c) $X/X_0 \approx 0.01$

A relationship between $\overline{\Delta D}/\overline{D_0}$ and X/X_0 for carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C also takes the same form as that between $\Delta FD/FD_0$ and X/X_0:

$$(\overline{\Delta D}/\overline{D_0}) = a\ln(X/X_0) \tag{5.2}$$

where a is an empirical constant listed also in Table 5.1

When considering the three drying methods altogether it is seen from Figures 5.2 and 5.3 as well as Table 5.1 that either $\Delta FD/FD_0$ or $\overline{\Delta D}/\overline{D_0}$ seems to be an adequate generalized microstructural change indicator and correlates well with the loss of moisture during drying. Similar R^2 values of Equation (5.1) and Equation (5.2) may help confirm the aforementioned argument. It may thus be possible to say that either indicator could be used to quantitatively monitor the microstructural changes of carrot cubes undergoing HAD, VD and LPSSD.

5.3 Generalized Structure-Quality Indicators

5.3.1 Relationships between $\Delta FD/FD_0$ and Physical Characteristic Changes

The relationships between $\Delta FD/FD_0$ and volumetric shrinkage of carrots undergoing HAD, VD and LPSSD are shown in Figure 5.5. It can be observed that $\Delta FD/FD_0$ increased with the shrinkage; in particular, when the shrinkage reached around 80% $\Delta FD/FD_0$ increase quite abruptly. This may probably be due to a rigid crust that was formed at low moisture contents; this retarded apparent dimensional change of the samples, but not the microstructure. This indicated that the cellular structure continued to be more irregular, whereas the external physical characteristic change (volumetric shrinkage) was inhibited (Sansiribhan et al., 2010). Similar trend existed in all drying cases.

A relationship between $\Delta FD/FD_0$ and volumetric shrinkage could be fitted to the following empirical correlation:

$$(\Delta FD/FD_0) = a\exp[b(\%\ \text{Shrinkage})] + c \quad (5.3)$$

where a, b and c are empirical constants listed in Table 5.1. The high R^2 values imply that $\Delta FD/FD_0$ is capable of being a generalized structure-quality indicator of carrot cubes undergoing all three tested drying processes. For example, at $\Delta FD/FD_0$ of around 0.04 the percentage of shrinkage was around 65-70 in all cases.

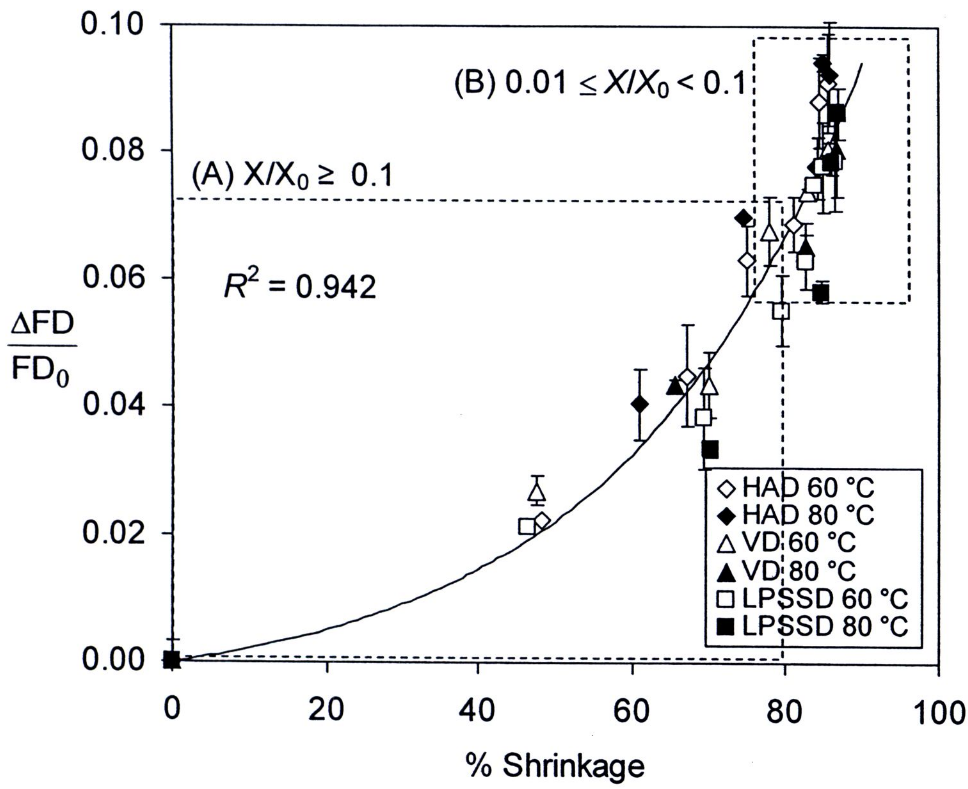

Figure 5.5 Relationships between $\Delta FD/FD_0$ and shrinkage of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. (A) and (B) represent the results over $X/X_0 \geq 0.1$ and $0.01 \leq X/X_0 < 0.1$, respectively.

The hardness of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C is shown in Figure 5.6. The results showed that the hardness in all cases increased continuously with decreasing moisture content. This is probably due to pectin depolymerization in cell walls that occurred after heat treatment (Chong et al., 2008). The particularly higher values of hardness at lower moisture contents were observed when the sample surface layers were rigid and crusted as mentioned earlier. In addition, the samples might have undergone transformation from rubbery to leathery state; the samples were then tougher to deform (Rahman and Al-Farsi, 2005).

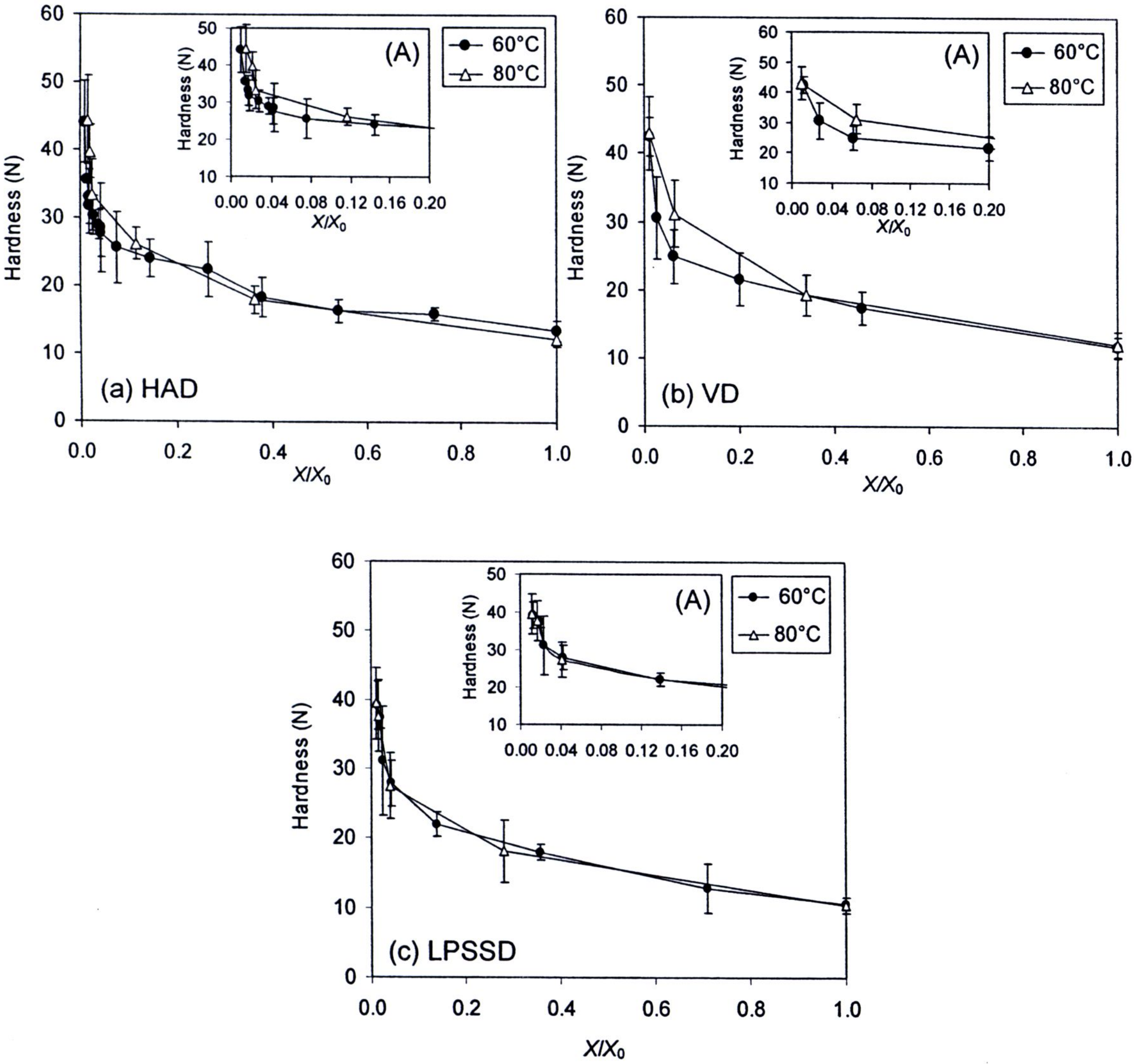

Figure 5.6 Hardness of carrot cubes undergoing (a) HAD; (b) VD; (c) LPSSD. Insert (A) represents the results over $0.01 \leq X/X_0 \leq 0.2$.

The relationships between ΔFD/FD_0 and hardness of carrot cubes are shown in Figure 5.7. It can be seen that ΔFD/FD_0 increased with an increase in the hardness, indicating that the changes in the shape of the cell walls and intercellular spaces significantly affected the hardness.

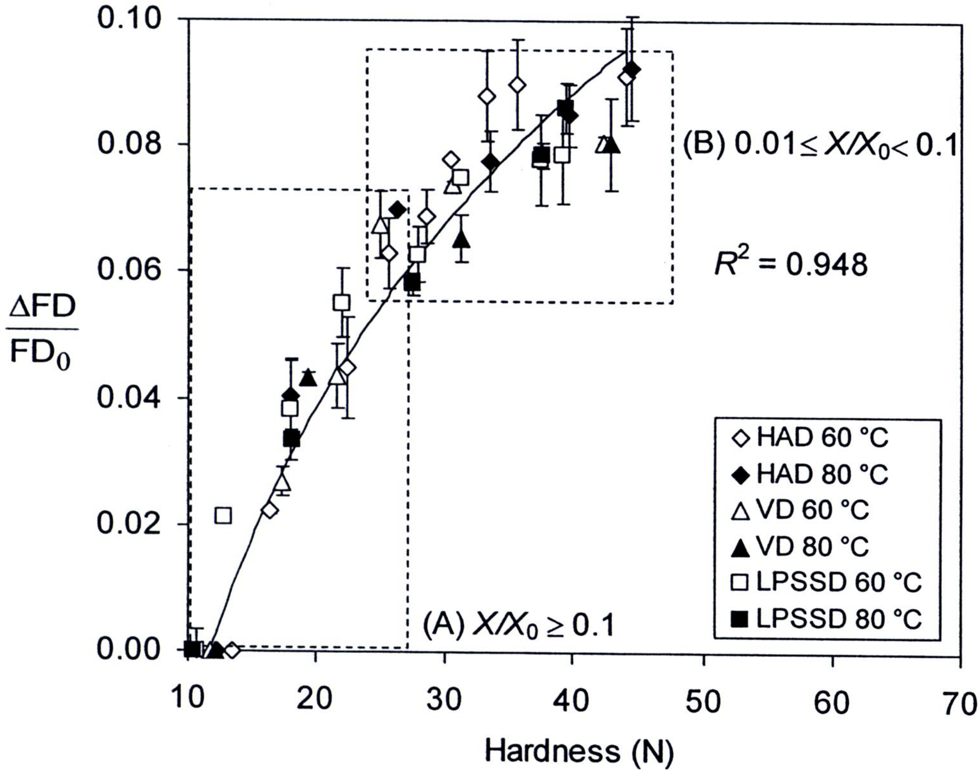

Figure 5.7 Relationships between ΔFD/FD_0 and hardness of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. (A) and (B) represent the results over $X/X_0 \geq 0.1$ and $0.01 \leq X/X_0 < 0.1$, respectively.

The relationships between ΔFD/FD_0 and hardness of carrot cubes can be fitted to the following equation:

$$(\Delta FD/FD_0) = a\ln(\text{Hardness}) + b \tag{5.4}$$

where a and b are empirical constants listed in Table 5.1. Again, the relatively high R^2 values indicate that $\Delta FD/FD_0$ is capable of serving as a generalized structure-quality indicator of carrot cubes undergoing HAD, VD and LPSSD. For example, at $\Delta FD/FD_0$ of around 0.04 the hardness of the samples was around 15-20 N in all cases.

5.3.2 Relationships between $\overline{\Delta D}/\overline{D_0}$ and Physical Characteristic Changes

The relationships between $\overline{\Delta D}/\overline{D_0}$ and the volumetric shrinkage of carrot cubes undergoing HAD, VD and LPSSD are shown in Figure 5.8. Similar trends as those of $\Delta FD/FD_0$ were noted. The relationships could again be fitted to an exponential function:

$$(\overline{\Delta D}/\overline{D_0}) = a\exp[b(\%\ \text{Shrinkage})] + c \tag{5.5}$$

where a, b and c are empirical constants listed in Table 5.1. The high R^2 values imply that $\overline{\Delta D}/\overline{D_0}$ is also capable of being a generalized structure-quality indicator of carrot cubes undergoing HAD, VD and LPSSD. However, comparison between the two microstructural change indicators revealed that $\Delta FD/FD_0$ correlated better to the volumetric shrinkage than $\overline{\Delta D}/\overline{D_0}$ when considering altogether the three drying methods. At lower percentage of shrinkage (less than around 40-50%, when $0.4 \leq X/X_0 < 1$) the change of volumetric shrinkage was not dependent on $\overline{\Delta D}/\overline{D_0}$ but it was dependent on the sample microstructural irregularity ($\Delta FD/FD_0$).

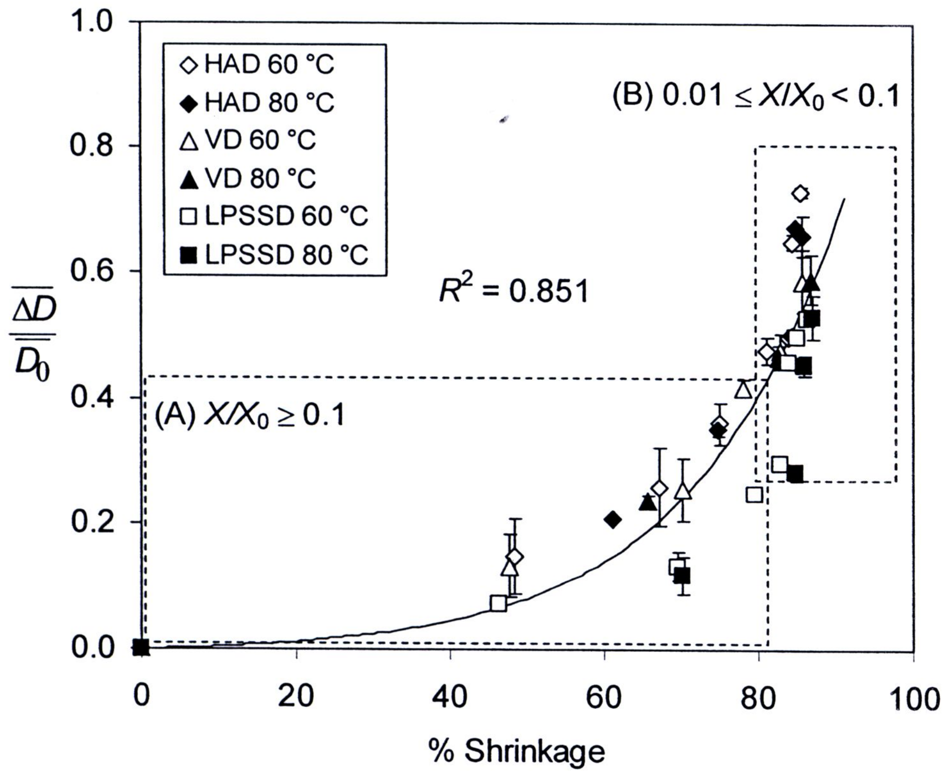

Figure 5.8 Relationships between $\overline{\Delta D}/\overline{D_0}$ and shrinkage of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. (A) and (B) represent the results over $X/X_0 \geq 0.1$ and $0.01 \leq X/X_0 < 0.1$, respectively.

The relationships between $\overline{\Delta D}/\overline{D_0}$ and the hardness of carrot cubes undergoing the three drying processes are shown in Figure 5.9. The evolution trends of $\overline{\Delta D}/\overline{D_0}$ during HAD, VD and LPSSD are similar to those of $\Delta FD/FD_0$ and can be correlated via the natural logarithm correlation as:

$$(\overline{\Delta D}/\overline{D_0}) = a\ln(\text{Hardness}) + b \tag{5.6}$$

where a and b are empirical constants listed also in Table 5.1. The hardness correlated well with $\overline{\Delta D}/\overline{D_0}$.

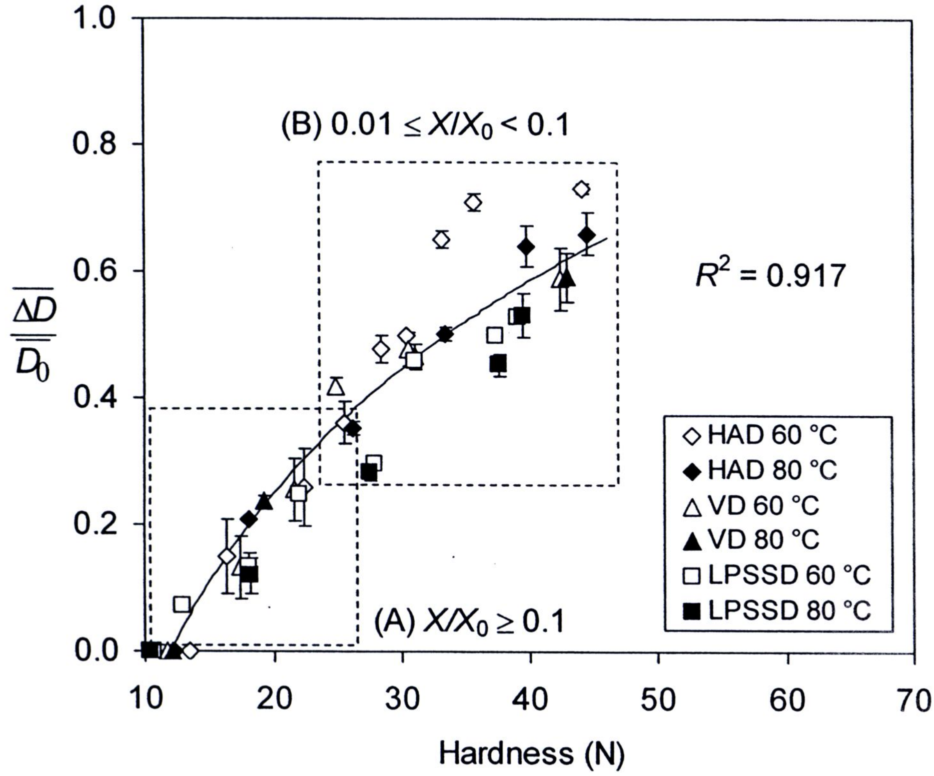

Figure 5.9 Relationships between $\overline{\Delta D}/\overline{D_0}$ and hardness of carrot cubes undergoing HAD, VD and LPSSD at 60 and 80 °C. (A) and (B) represent the results over $X/X_0 \geq 0.1$ and $0.01 \leq X/X_0 < 0.1$, respectively.

Comparison between the two microstructural change indicators revealed that $\Delta FD/FD_0$ correlated as well to the hardness values as $\overline{\Delta D}/\overline{D_0}$. This may probably imply that hardness depends both on the changes of the shape and irregularity as well as the size of the cellular structure.