## 2. Part II: Mass Transfer Behavior during Osmotic Treatment and Mathematical Models Development

### 2.1 Mass Transfer Behavior during Osmotic Treatment

#### 2.1.1 For Persimmon Disk

##### 2.1.1.1 Change of Moisture and Solid Content for Persimmon Disk

It can be seen in Figures 11-12 that the moisture content of osmosed persimmon disk decreased with increasing immersion time during osmotic treatment, whereas the solid content increased. An initial high rate, followed by a progressively declining rate in the later stages, was observed. A similar trend has been reported by several authors (Torreggiani, 1993; Pointing *et al.*, 1966; Palou *et al.*, 1994). The initial rate observed when the sample is placed into the osmotic solution there may be attributed to a high concentration difference between the solution and the fruit. This provides the driving force for the mass transfer of water and solid from the fruit. After this initial mass transfer, the concentration of solutes in the sample increase, decreasing the concentration difference between osmotic solution and the fruit. This decreasing concentration gradient, in turn, weakens the driving force for the transfer of water out of the sample, thereby decreasing the rate at which water is removed. It was found that after 6 h of contact, the moisture content had fallen to values between 0.42 and 1.02 kg/kg, whereas the solid content had increased to values between 1.004 and 1.007 kg/kg in the case of the disk.

##### 2.1.1.2 Variation of Weight Reduction (*WR*), Water Loss (*WL*) and Solid Gain (*SG*) for Persimmon Disk

As mentioned earlier, when a fruit is immersed in concentrated sugar or salt solutions, osmotic dehydration occurs as a consequence of mass transfer. A significant amount of water flows out from the fruit to the solution, and the solute from the solution gets transferred into the fruit. Three quantities may represent adequately the osmotic process: the weight reduction, indicating the net weight loss from the fruit; the water loss, indicating the water that diffuses from the fruit to the solution; and solid gain which represents the amount of solids diffusing from the solution to the fruit, less the solids in the fruit that are lost to the solution. The transient variation in *WR*, *WL* and *SG* for different solution concentrations are shown in Figures 13-15. An initial high rate, followed by declining rate in the later stages was observed. The results showed that the proportion of water removed was always greater than the solid uptake, which is in agreement with the results of other workers (Lazarides *et al.*, 1995; Lenart, 1992). Very little solid was taken up by the sample which implies that the weight reduction is simply dependent on water loss. After immersion for 6 h, *WR* and *WL* attained values greater than 0.45 kg/kg for all treatment conditions. During the same period, the net *SG* was very small, ranging between 0.0008 and 0.0017 kg/kg. *WR*, *WL* and *SG* are the important mass transfer parameters which can used to understand the mass transfer behavior during osmotic process.

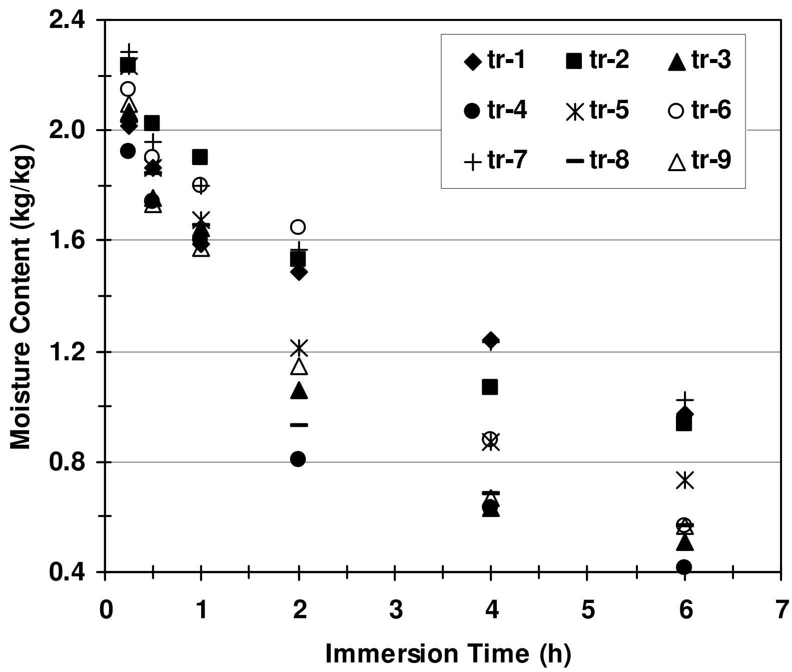



Figure 11 Change in moisture content with time during osmotic treatment of persimmon disks.

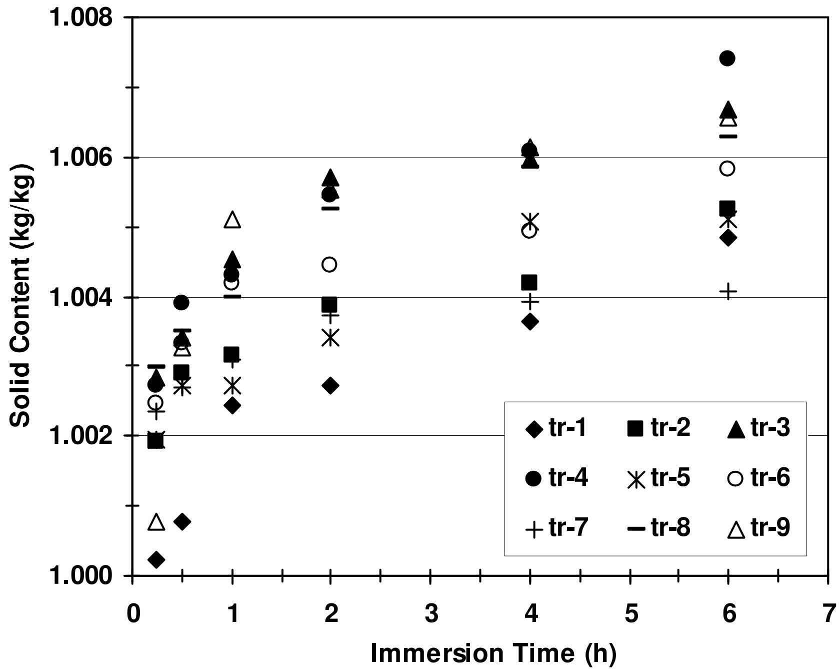



Figure 12 Change in solid content with time during osmotic treatment of persimmon disks.

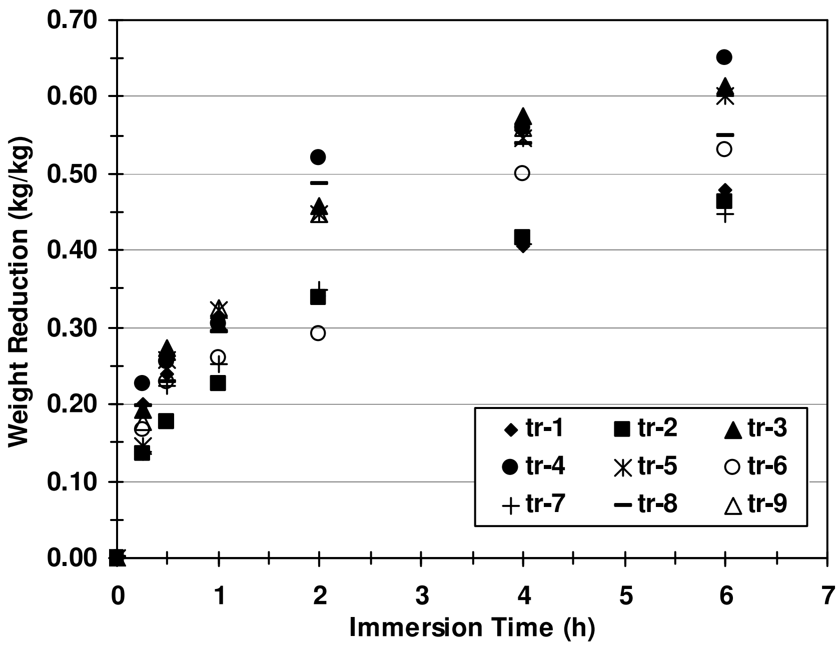



Figure 13 Variation of weight reduction with time for persimmon disks.

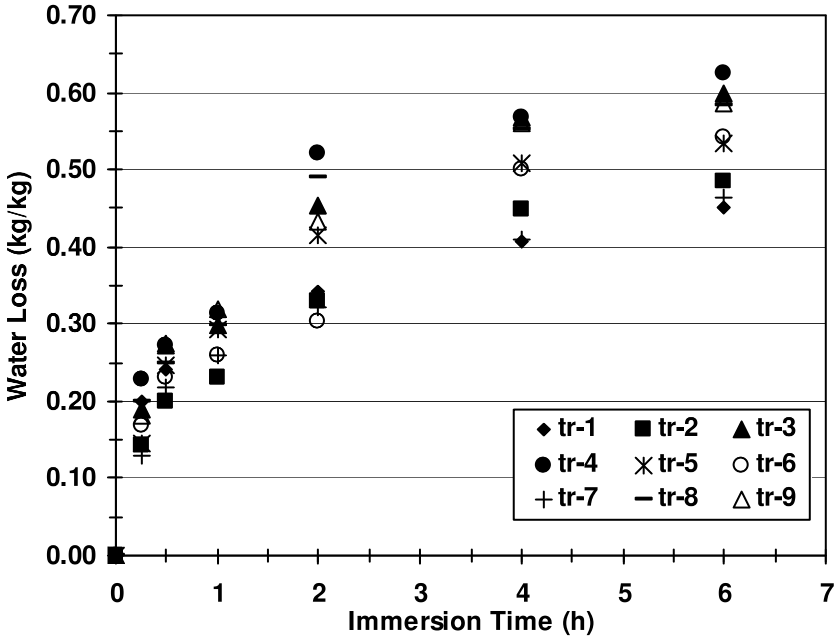



Figure 14 Variation of water loss with time for persimmon disks.

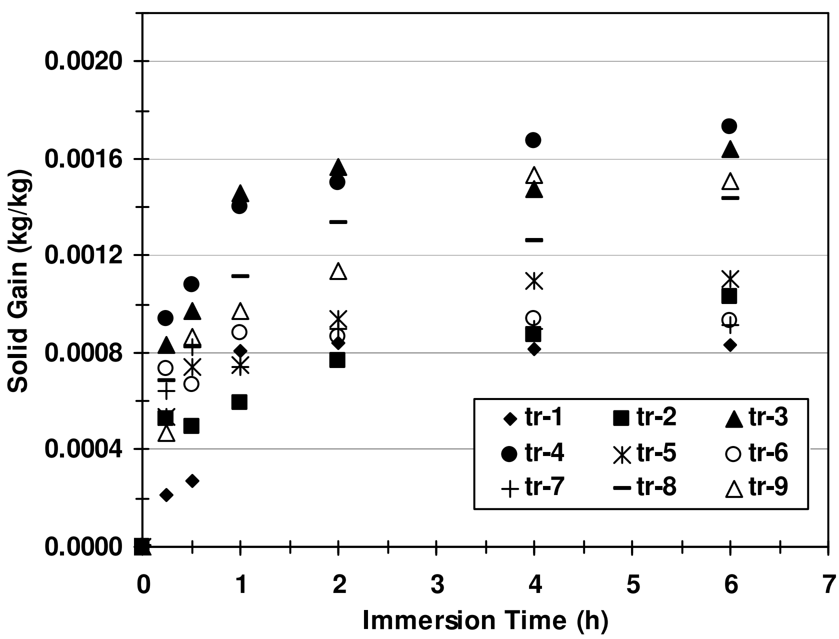



Figure 15 Variation of solid gain with time for persimmon disks.

2.1.1.3 Water and Solute Diffusion Coefficient ($D_{ew}$ and $D_{es}$) and Equilibrium Moisture and Solid Content ($m_e$ and $s_e$) for Persimmon Disk

Osmotic dehydration is a process for the partial removal of water from plant tissues by immersion in aqueous concentrated solutions. A driving force for the diffusion of water from the tissue into the solution is provided by the difference in osmotic pressure between the food and surrounding osmotic solution. The diffusion of water is accompanied by the simultaneous counter diffusion of solute from the osmotic solution into the tissue. Since the membrane responsible for osmotic transport is not perfectly selective, other solutes present in the cells can also be leached into the osmotic solution (Dixon and Jen, 1997; Lerici *et al*., 1985; Giangiacomo *et al*., 1987).

Diffusion coefficient is the quantitative measure of the rate at which a diffusion process occurs. It's defined as the rate of transfer of the diffusing substance across unit area of a section divided by the space gradient of the concentration of the section. Hence, $D_{ew}$ and $D_{es}$ depend on the osmotic pressure gradient, which in turn is dependent on concentration of sucrose and NaCl in the solutions. Equilibrium is achieved at the end of the osmotic process, when the net rate of mass transport is zero. The equilibrium moisture and solid contents of the fruits ($m_e$ and $s_e$) were estimated as the values of $m$ and $s$ at which d$m$/d$t$ and d$s$/d$t$ became zero. For this purpose, the two rates deduced from the plots of moisture and solid content against time, were plotted against the moisture and solid content, respectively, and extrapolated to the point where the rates vanished. The example plots of rate of change of d$m$/d$t$ and d$s$/d$t$ with average moisture and solid contents, respectively, are shown in Figures 16 and 17. Osmotic treatment resulted in some shrinkage. The reduction in thickness in the case of disk for most cases varied around 15% although it was as high as 30 % in extreme cases. A constant average dimension was assumed in the calculation of water diffusion coefficient ($D_{ew}$) and solute diffusion coefficient ($D_{es}$). The estimated values of $m_e$, $s_e$, $D_{ew}$ and $D_{es}$ are shown in Table 4. The values of $m_e$ ranged from 0.197 to 0.938 kg/kg, and those for $s_e$ between 1.0044 and 1.0074 kg/kg of initial dry matter. The $D_{ew}$ and $D_{es}$ values were in the range $1.345\times10^{-10}$ to

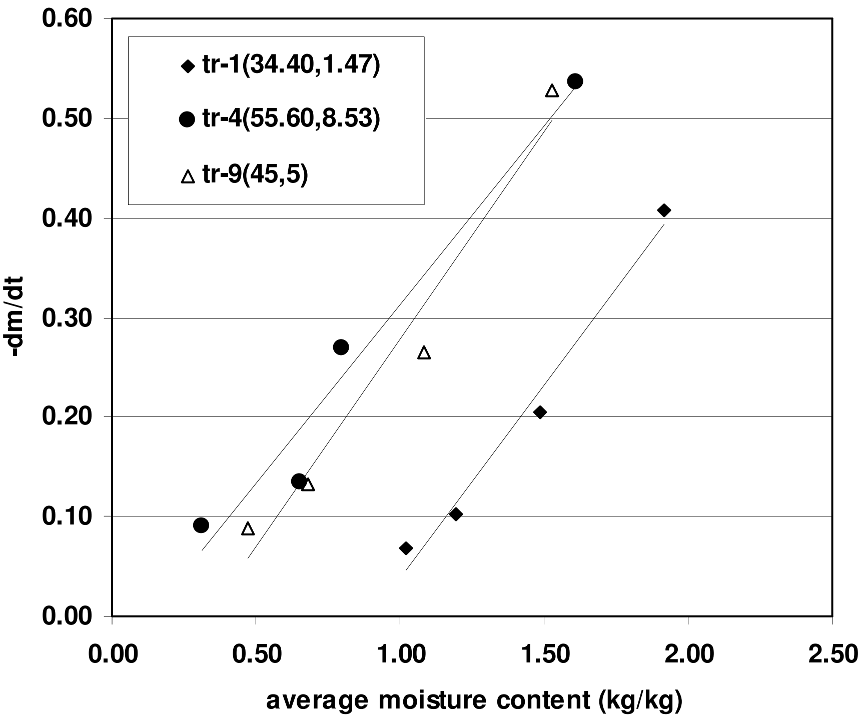



Figure 16 A Plot of rate of change of moisture (d*m*/d*t*) with average moisture content during osmotic dehydration of persimmon disks.

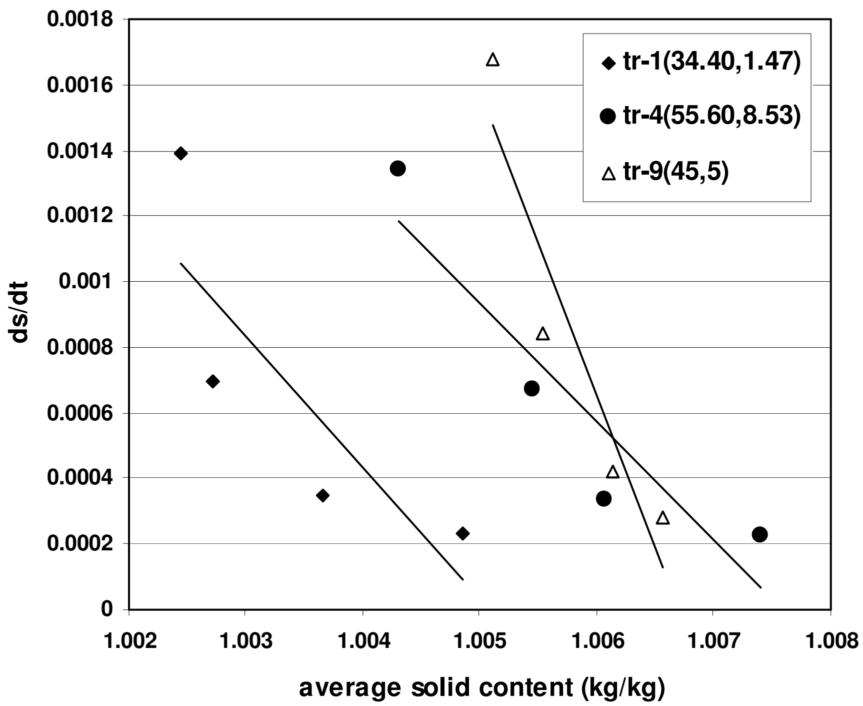
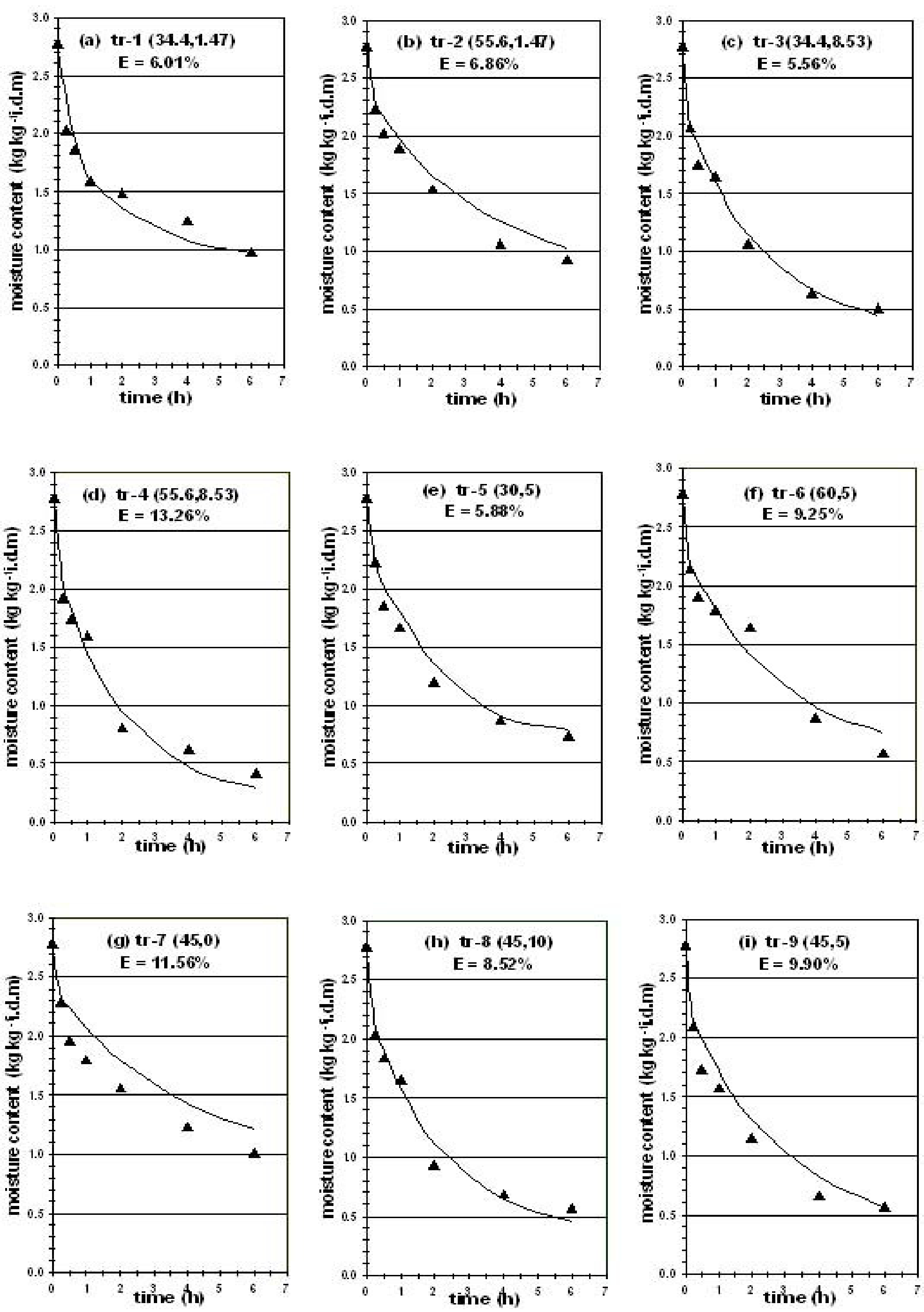



Figure 17 A Plot of rate of change of solid content (d*s*/d*t*) with average solid content during osmotic dehydration of persimmon disks.

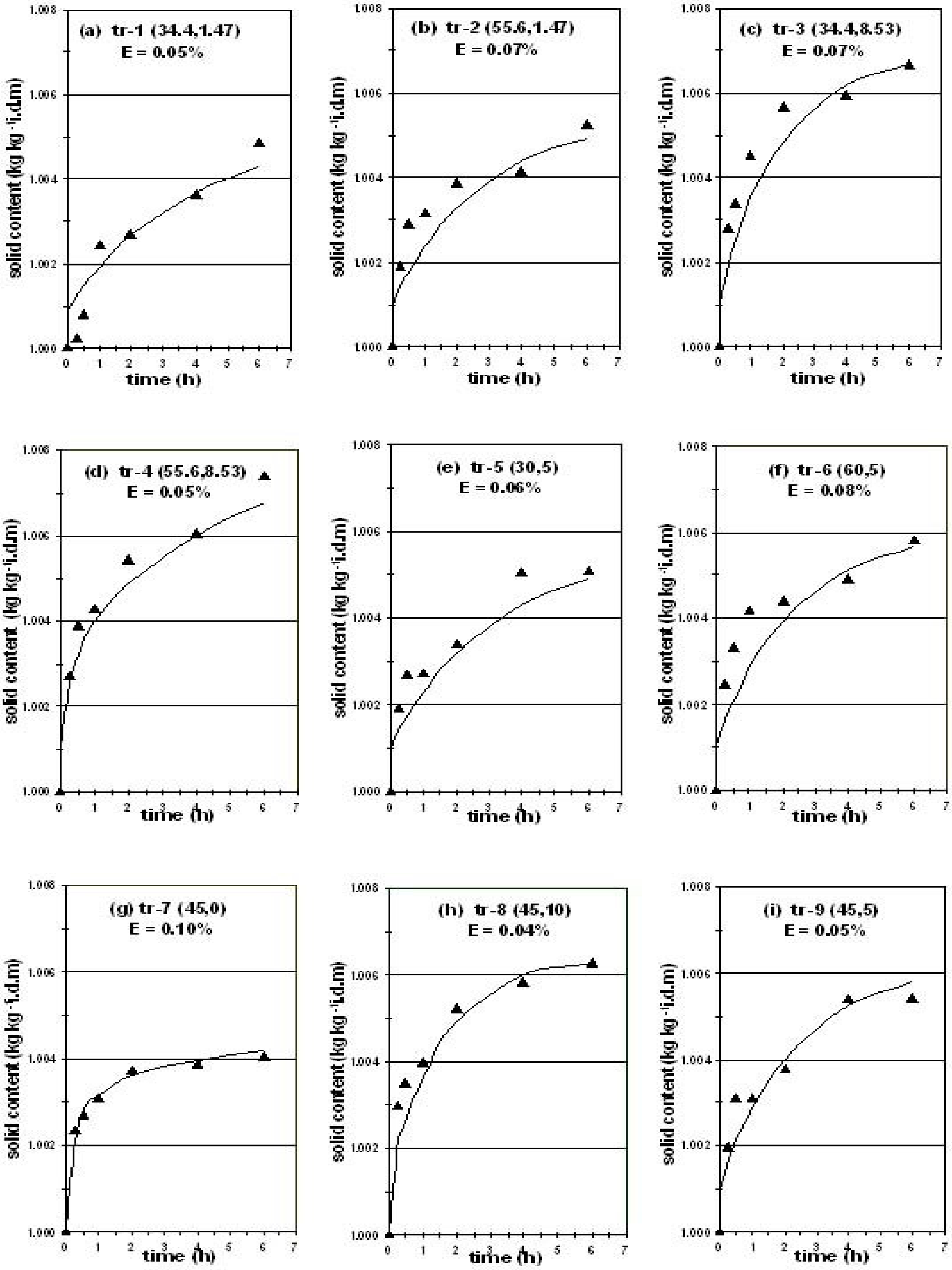
$2.061 \times 10^{-10}$ $m^2$ /s and $1.267 \times 10^{-10}$to $4.302 \times 10^{-10}$ $m^2$/s, respectively. Difference osmotic solution concentration can cause the diffusion property in difference value. It was found that $D_{ew}$ and $D_{es}$ value can be considerably increase by using high concentrations of sucrose and NaCl. It is clearly seen that at the highest concentration level of sucrose and NaCl in treatment 4, $D_{ew}$ and $D_{es}$ shown the highest value while at the lowest concentration in treatment 1 shown the lowest value as well. High values of $R^2$ (0.896-0.992) were found in the estimation of $D_{ew}$ and $D_{es}$ values. The $E$ values reported in the figures indicate the adequacy of the model for describing the osmotic treatment of persimmon under the given experimental conditions. Figures 18(a)-(i) compare the experimental moisture contents with the predicted values which show $E$ values between 5.56% and 11.56%. Figures 19(a)-(i) likewise, compares the experimental values of average solid content with predicted values which give $E$ values between 0.04% and 0.10%.

Table 4 Values of $m_e$, $s_e$, $D_{ew}$ and $D_{es}$ for variation treatments by persimmon disks.

| **Treatment** | $m_e$ **(kg /kg)** | $s_e$ **(kg /kg)** | $D_{ew}$**x10$^{10}$ (m$^2$ /s)** | $R^2$ | $D_{es}$**x10$^{10}$ (m$^2$ /s)** | $R^2$ |
|---|---|---|---|---|---|---|
| 1 | 0.919 | 1.0053 | 1.345 | 0.896 | 1.267 | 0.999 |
| 2 | 0.780 | 1.0054 | 1.480 | 0.992 | 1.767 | 0.954 |
| 3 | 0.304 | 1.0070 | 1.858 | 0.972 | 2.098 | 0.999 |
| 4 | 0.197 | 1.0074 | 2.061 | 0.928 | 4.302 | 0.925 |
| 5 | 0.585 | 1.0056 | 1.404 | 0.989 | 1.522 | 0.999 |
| 6 | 0.528 | 1.0061 | 1.519 | 0.949 | 1.776 | 0.948 |
| 7 | 0.938 | 1.0044 | 1.375 | 0.978 | 1.284 | 0.969 |
| 8 | 0.333 | 1.0064 | 1.980 | 0.913 | 2.708 | 0.973 |
| 9 | 0.337 | 1.0062 | 1.601 | 0.964 | 1.815 | 0.971 |




<u>Figure 18 (a)-(i)</u> A comparison between experimental and model values of moisture content for persimmon disks during osmotic treatment, solid lines indicate the model values, whereas symbols indicate the experimental data.




<u>Figure 19(a)-(i)</u> A comparison between experimental and model values of solid content for persimmon disks during osmotic treatment, solid lines indicate the model values, whereas symbols indicate the experimental data.

2.1.2 For Persimmon Cube

2.1.2.1 Change of Moisture and Solid Content for Persimmon Cube

It can be seen in Figure 20-21 that the decrease in moisture content and the increase in solid content of osmosed persimmon cube, with immersion time during osmotic treatment, show the same trend as osmosed persimmon disk. There is a high concentration difference between the solution and the fruit which accounts for the initial high rate. It was found that after 6 h of contact, the moisture content had fallen to values between 0.75 and 1.00 kg/kg, whereas the solid content had increased to values between 1.003 and 1.008 kg/kg in the case of cubes. The kinetics of moisture content reduction (Figure 20) confirms that osmotic treatment is a viable process for the removal of water from the persimmon. A driving force for water removal is set up because of a difference in osmotic pressure between the persimmon and its surrounding solution. On the other hand, the solid uptake kinetic (Figure 21) occurred simultaneous counters diffusion of solutes from the solution into the persimmon tissue during osmotic treatment.

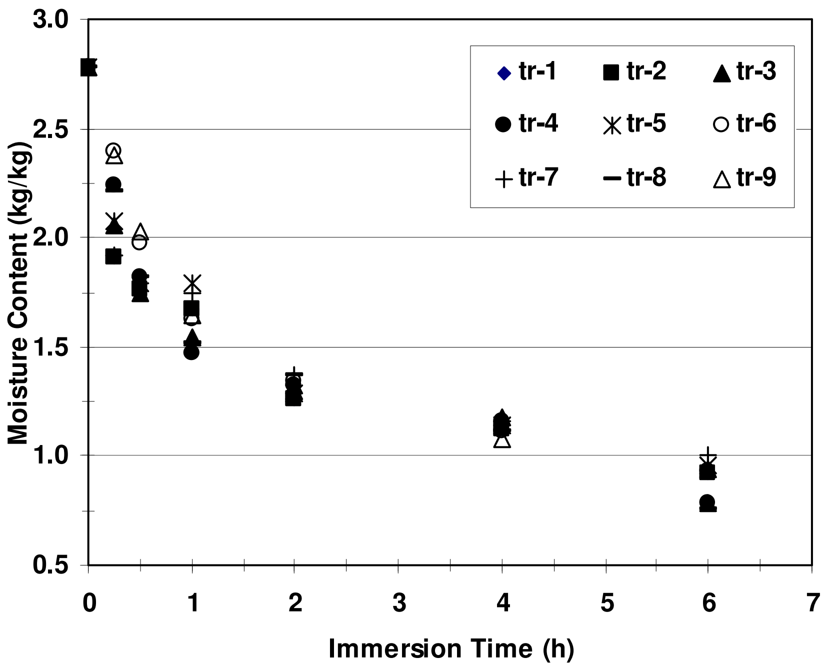



Figure 20 Change in moisture content with time during osmotic treatment of persimmon cubes.

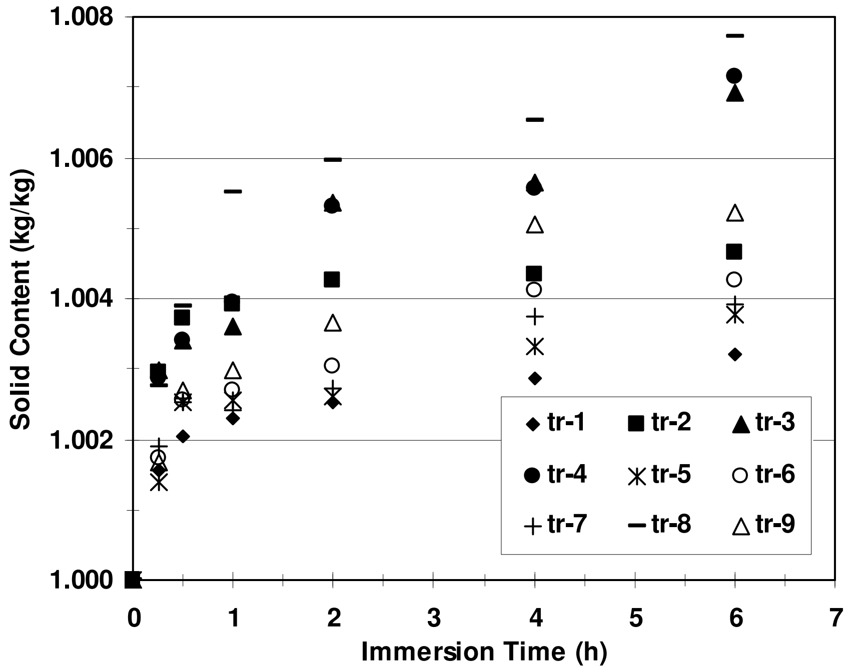



Figure 21 Change in solid content with time during osmotic treatment of persimmon cubes.

2.1.2.2 Weight Reduction (*WR*), Water Loss (*WL*) and Solid Gain (*SG*) for Persimmon Cube

The transient variation in *WR*, *WL* and *SG* for different solution concentrations are shown in Figure 22-24. The results showed that the water removal and weight reduction were always greater than the solid uptake. Very little solid was taken up by the sample which implies that the weight reduction simply mainly depended on the water loss. After immersion for 6 h, *WR* and *WL* attained values greater than 0.45 kg/kg for all treatment conditions. During the same period, the net *SG* was very small, ranging between 0.0005 and 0.0028 kg/kg. The rate of water loss was faster in the first two hours of the process, and decreased gradually while approaching the end of the experiment. The rapid *WL* in the beginning is due to the large osmotic driving force between the dilute sap of the fresh fruit and the hypertonic solution. The *SG* during the osmotic dehydration of persimmon cube is smaller in relation to the *WL*, because the cellular membrane not only allows the solvent to pass through, but also allow the passage of solute molecules, albeit to a lesser degree.

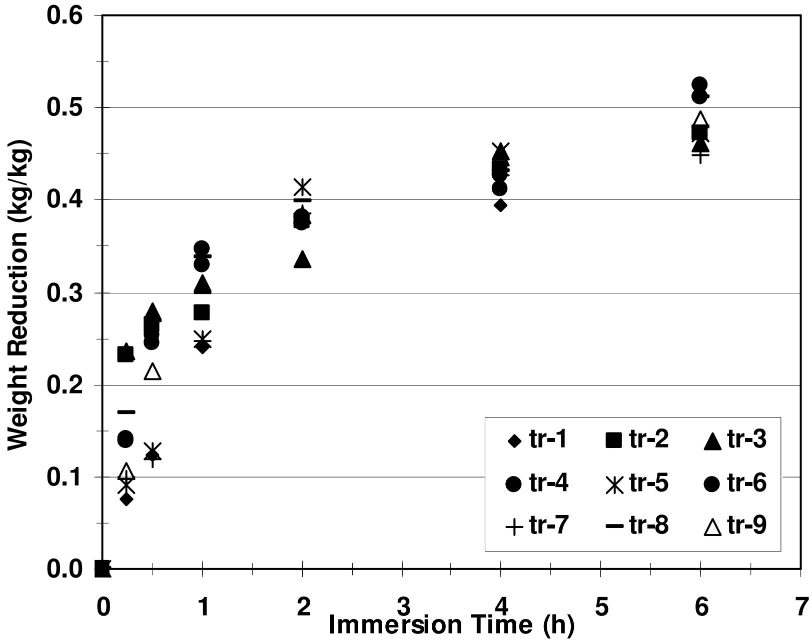



Figure 22 Variation of weight reduction with time for persimmon cubes.

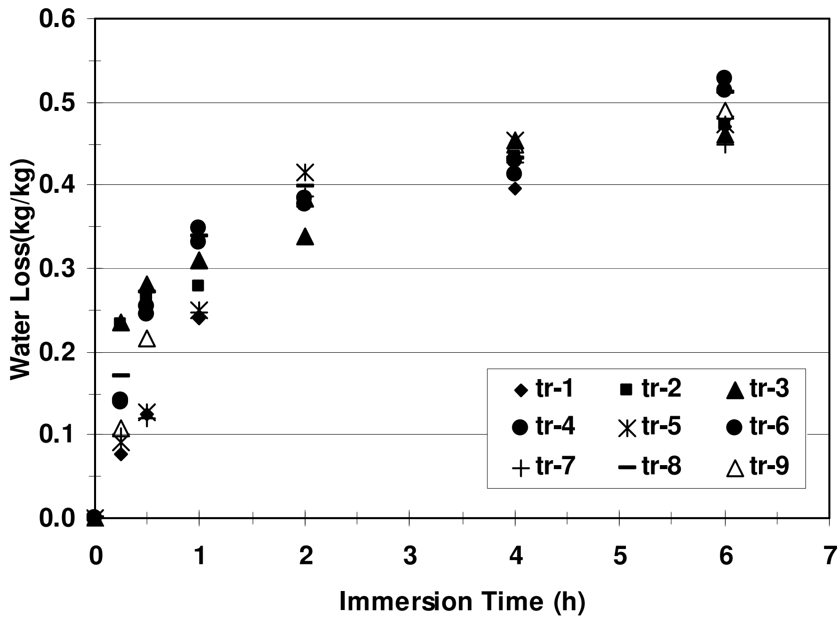



Figure 23 Variation of water loss with time for persimmon cubes.

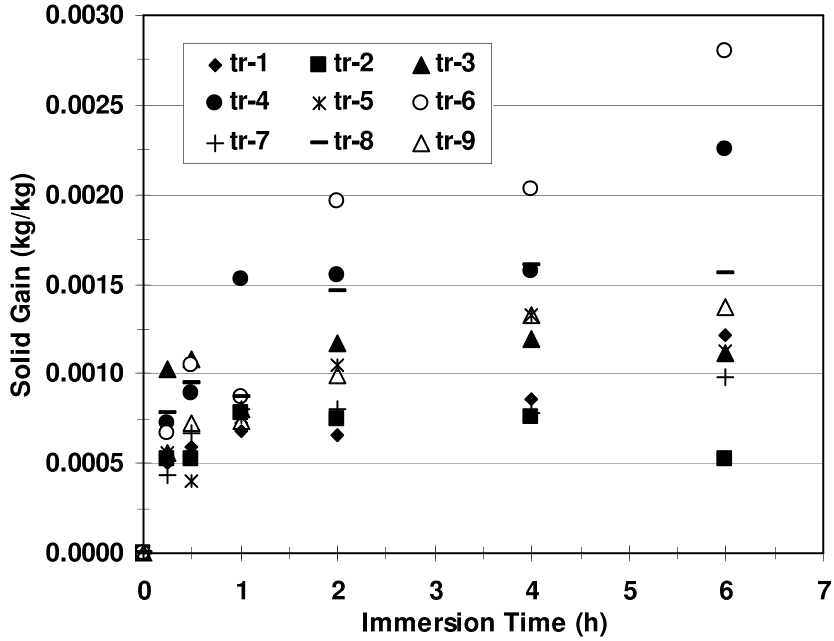



Figure 24 Variation of solid gain with time for persimmon cubes.

2.1.2.3 Water and Solute Diffusion Coefficient ($D_{ew}$ and $D_{es}$) and Equilibrium Moisture and Solid Content ($m_e$ and $s_e$) for Persimmon Cube

It is common practice to base on a diffusion analysis, the description of mass flows involved in osmotic dehydration (Beristain *et al.*, 1990; Rastogi *et al.*, 1997). As discussed earlier this fact has enabled the use of simplified versions of non-steady state form of Fick's second law, considering constant solution concentration and negligible external resistance to mass transfer (Crank, 1975; Hawkes and Flink, 1978). Here too, the diffusion coefficient was defined as the rate of transfer of the diffusing substance across unit area of a section divided by the space gradient of the concentration. Equilibrium was achieved at the end of the osmotic process, when the net rate of mass transport was equal to zero. The equilibrium moisture and solid contents of the fruits ($m_e$ and $s_e$) were estimated as the values of $m$ and $s$ at which d$m$/d$t$ and d$s$/d$t$ became zero. The two rates, deduced from the plots of moisture and solid content variation with time, were plotted against the moisture and solid content, respectively, and extrapolated to the point where the rates vanished. The example plots of rate of change of d*m*/d*t* and d*s*/d*t* with average moisture and solid contents, respectively, are shown in Figures 25 and 26. A constant average dimension was assumed in the calculation of water diffusion coefficient ($D_{ew}$) and solute diffusion coefficient ($D_{es}$). The estimated values of $m_e$, $s_e$, $D_{ew}$ and $D_{es}$ are shown in Table 5. The values of $m_e$ ranged from 0.807 to 0.970 kg/kg, and those for $s_e$ between 1.0034 and 1.0091 kg/kg of initial dry matter. The $D_{ew}$ and $D_{es}$ values were in the range $2.582\times10^{-10}$ to $3.437\times10^{-10}$ $m^2/s$ and$1.179\times10^{-10}$ to $4.311\times10^{-10}$ $m^2/s$, respectively. In the same trend with disk, it is clear that the highest $D_{ew}$ and $D_{es}$ values are observed when the highest concentration of sucrose and NaCl (treatment 4) are used and the lowest. It can explain that the higher osmotic pressure gradient can encourage the diffusion process. Whereas at the lowest concentration of sucrose and NaCl (treatment 1) is shown the lowest values of $D_{ew}$ and $D_{es}$. High values of $R^2$ (0.840-0.995) were noted in the estimation of $D_{ew}$ and $D_{es}$ values .The *E* values indicating the error between model prediction and experimental values of concentrations, are reported in Figures 27(a)-(i) and Figures 28(a)-(i). The *E* values ranged between 5.56% and 11.56% for moisture contents; and between 0.04% and 0.10% for solid content.

Table 5 Values of $m_e$, $s_e$, $D_{ew}$ and $D_{es}$ for variation treatments by persimmon cubes

| **Treatment** | $m_e$ **(kg kg$^{-1}$)** | $s_e$ **(kg kg$^{-1}$)** | $D_{ew}$**x10$^{10}$ (m$^2$ s$^{-1}$)** | $R^2$ | $D_{es}$**x10$^{13}$ (m$^2$ s$^{-1}$)** | $R^2$ |
|---|---|---|---|---|---|---|
| 1 | 0.970 | 1.0034 | 2.582 | 0.840 | 1.179 | 0.905 |
| 2 | 0.935 | 1.0040 | 2.858 | 0.907 | 2.393 | 0.977 |
| 3 | 0.879 | 1.0083 | 3.155 | 0.995 | 3.659 | 0.938 |
| 4 | 0.807 | 1.0091 | 3.437 | 0.893 | 4.311 | 0.827 |
| 5 | 0.939 | 1.0043 | 2.730 | 0.899 | 1.944 | 0.936 |
| 6 | 0.906 | 1.0045 | 2.999 | 0.993 | 2.514 | 0.834 |
| 7 | 0.955 | 1.0039 | 2.721 | 0.951 | 1.929 | 0.957 |
| 8 | 0.853 | 1.0079 | 3.273 | 0.979 | 3.691 | 0.848 |
| 9 | 0.901 | 1.0054 | 3.028 | 0.984 | 3.067 | 0.969 |

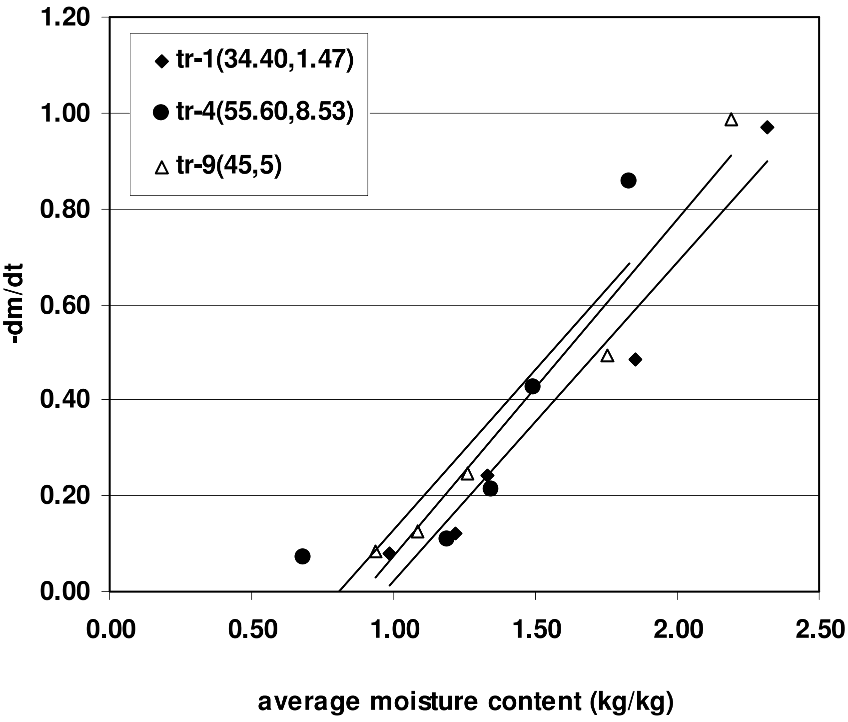



Figure 25 A Plot of rate of change of moisture (d*m*/d*t*) with average moisture content during osmotic dehydration of persimmon cubes.

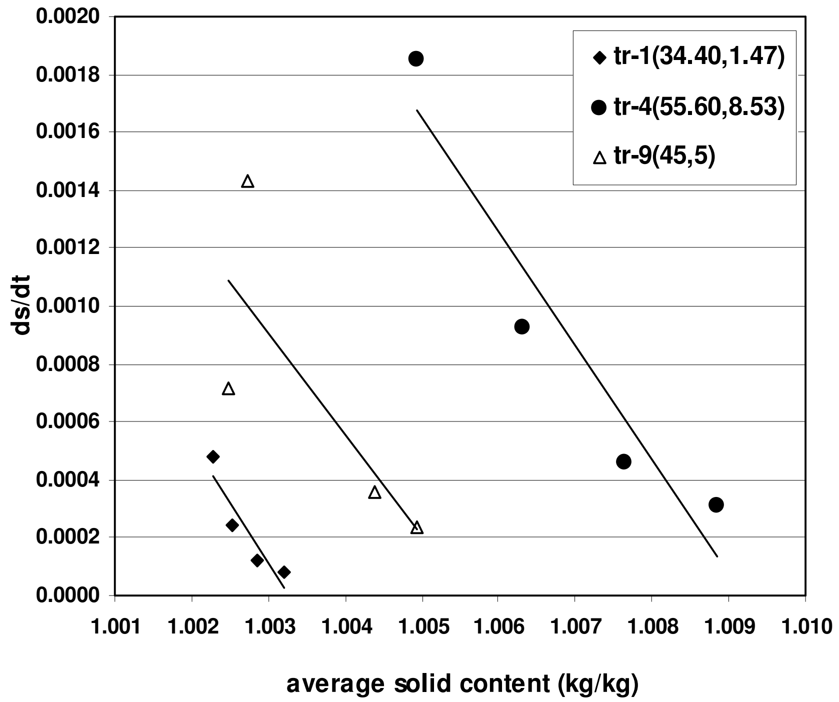
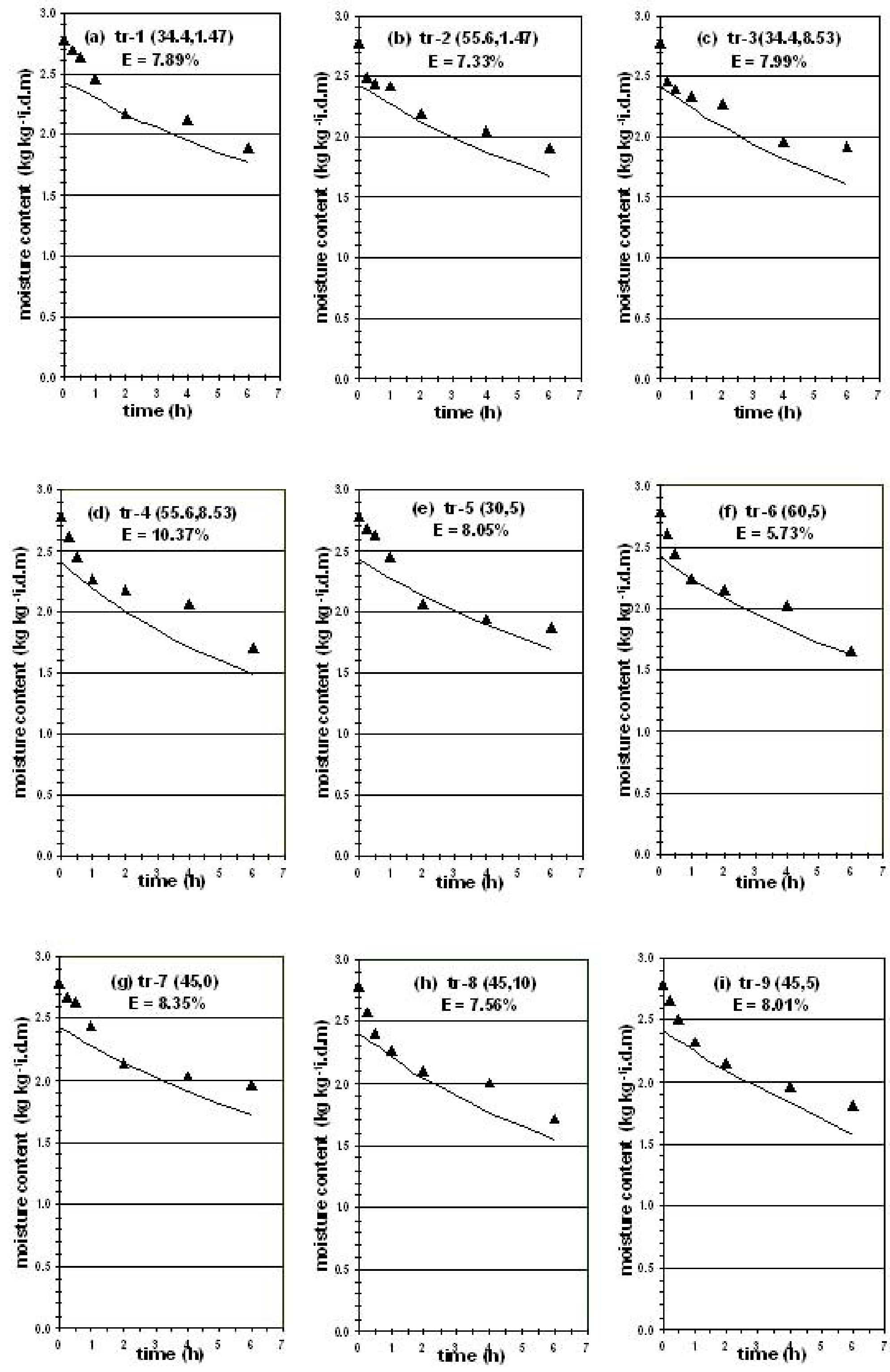



Figure 26 A Plot of rate of change of solid content (d*s*/d*t*) with average solid content during osmotic dehydration of persimmon cubes.




<u>Figure 27 (a)-(i)</u> A comparison between experimental and model values of moisture content for persimmon cubes during osmotic treatment, solid lines indicate the model values, whereas symbols indicate the experimental data.

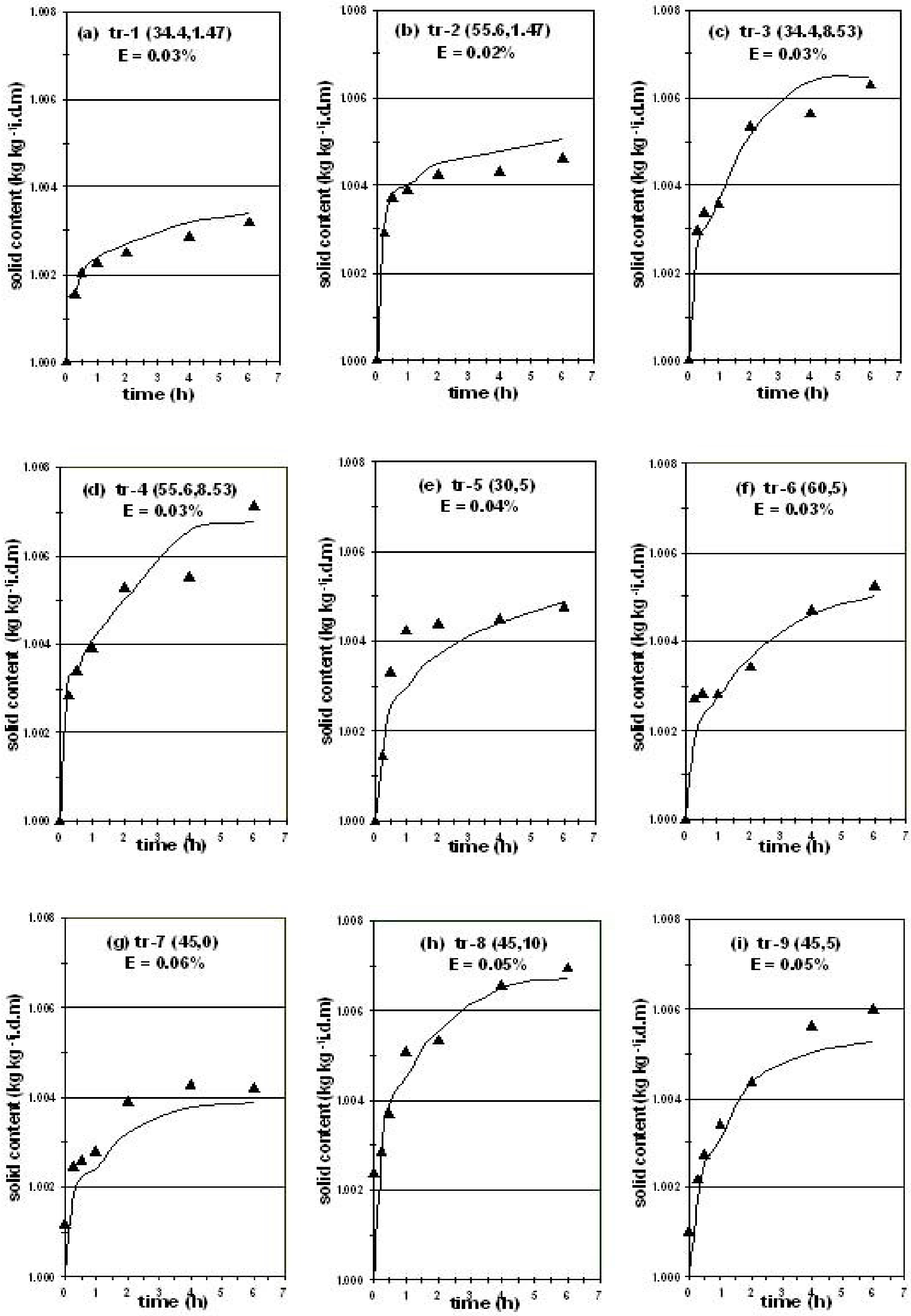



Figure 28 (a)-(i) A comparison between experimental and model values of solid content for persimmon cubes during osmotic treatment, solid lines indicate the model values, whereas symbols indicate the experimental data.

### 2.1.3 Osmotic Dehydration of the Whole Fruit

#### 2.1.3.1 Changes in Moisture and Solid Content

The variation in moisture content for the whole fruit is shown in Figure 29. It was found that after 48 h of osmotic treatment, the moisture content fell to between 0.3 and 0.8 kg/kg. It is evident from the figures that the variation pattern of moisture content is the same for all solutions. The initial decrease was rapid and subsequent decrease was slow as evidenced by the flattening of curves. At the beginning of the process, there was as osmotic transfer of water from fruit samples to osmotic solution caused by the difference in osmotic pressures. At the end of the osmotic process (after 48 hrs), the solid content increased to values between 1.2 and 1.5 kg/kg for all solution concentrations (Figure 30). It can be observed that the trend curves shown in Figures 21 and 30 also follow the same pattern. However, the final solid content achieved in each osmotic solution concentration was different.

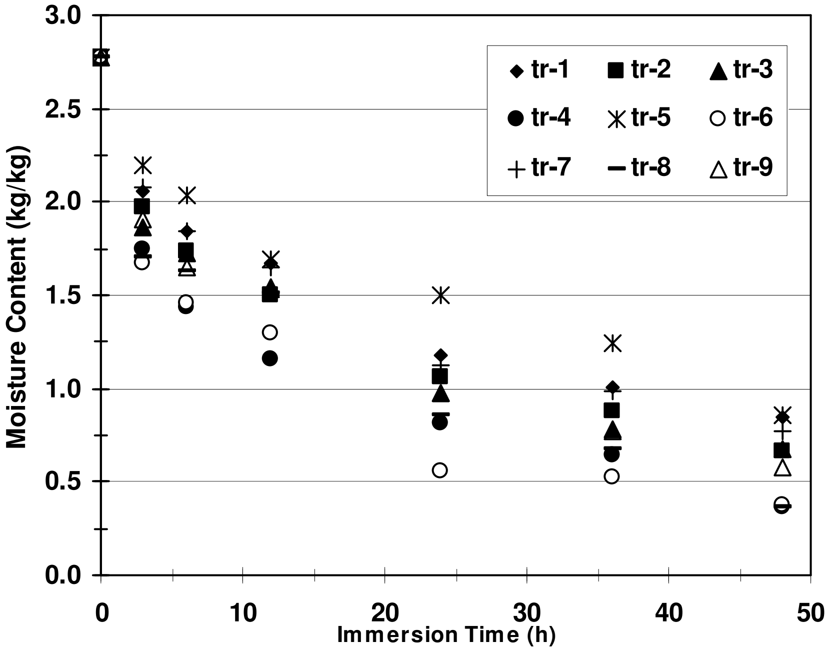



Figure 29 Change in moisture content with time during osmotic treatment of persimmon whole fruit.

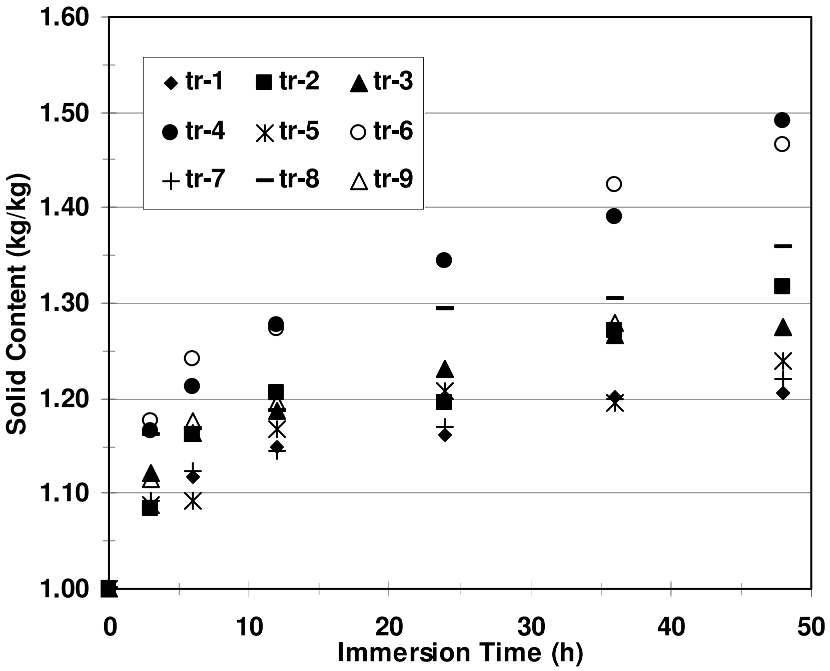



Figure 30 Change in solid content with time during osmotic treatment of persimmon whole fruit.

2.1.3.2 Weight Reduction (*WR*), Water Loss (*WL*) and Solid Gain (*SG*) for the Whole Fruit

Figures 31 - 33 show the variation of weight reduction, water loss and solid gain as a function of sucrose and NaCl concentration in the osmotic solution during 48 hr of contact. The final weight reduction and water loss values ranged between 0.4 to 0.5 and 0.45 to 0.6 kg/kg, respectively. Solid gain in the same time period showed wide variation between 0.055 to 0.13 kg/kg. Here too, the amount of water loss was much greater than the amount of solid gain. In fact, sucrose and NaCl are selectively incorporated into the cell and can not freely cross the membrane of the cells. Moreover, since sucrose molecules are larger, they could not diffuse easily through the cell membrane, thus the approach to osmotic equilibrium was achieved primary by water loss from the fruit tissue (Shi *et al*., 1995).

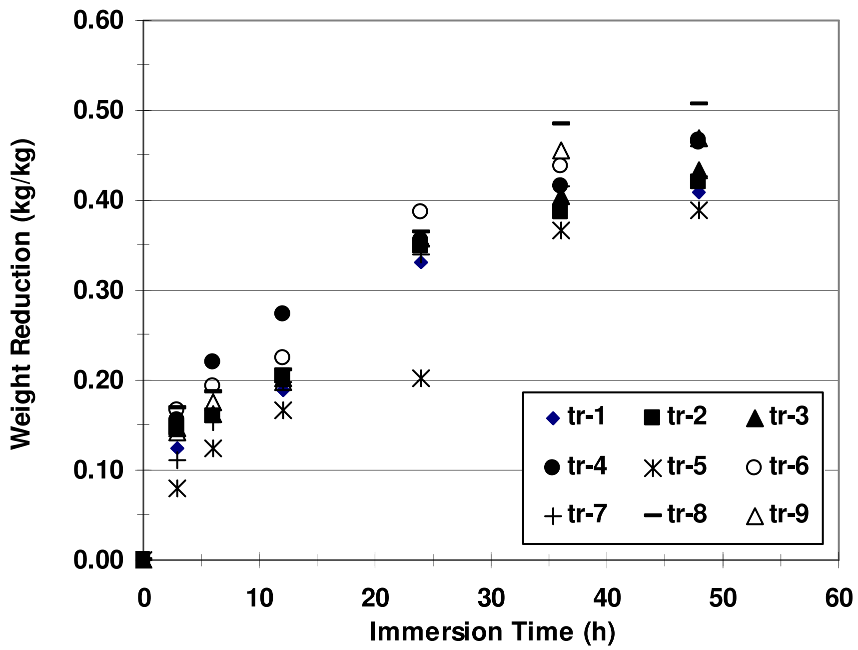



Figure 31 Variation of weight reduction with time for persimmon whole fruit.

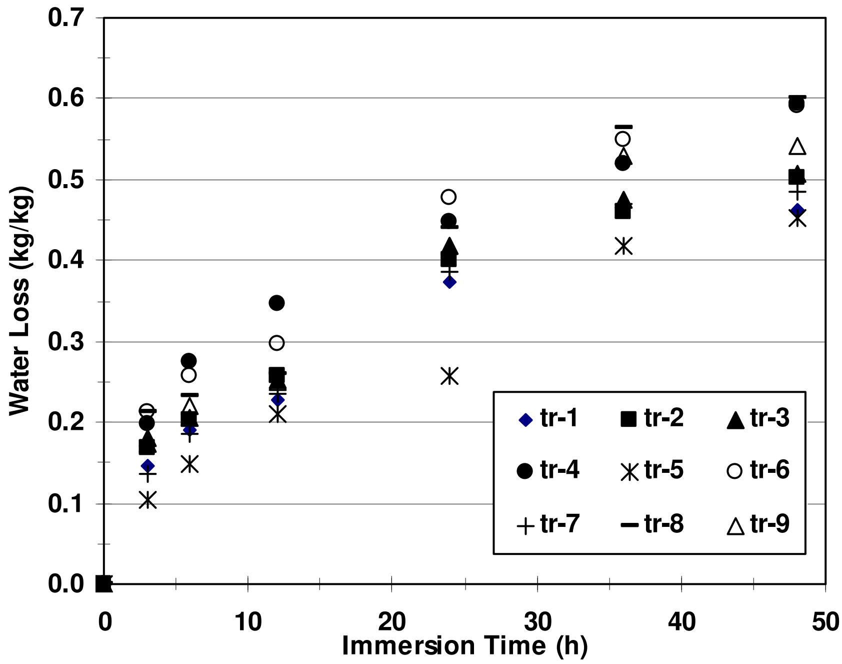



Figure 32 Variation of water loss with time for persimmon whole fruit.

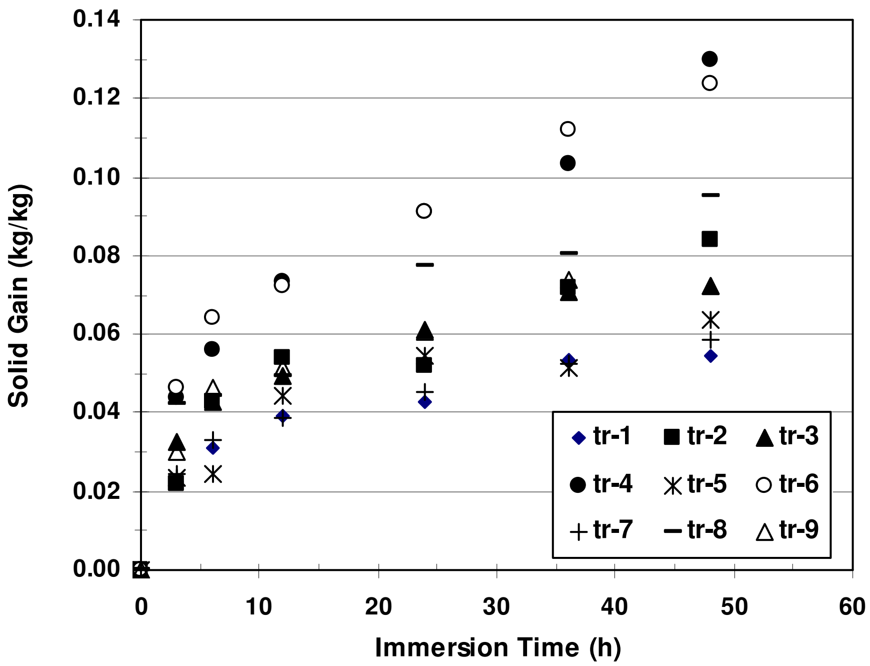



Figure 33 Variation of solid gain with time for persimmon whole fruit.