BIABAN

BIABAN (Desert Journal)
Online at http://jbiaban.ut.ac.ir

BIABAN 12 (2007) 23-31

Validation of air freezing index (AFI), for determination of frost penetration depth in typical arid and semi-arid zones of Iran

A.Khalili[a*], H.Rahimi[a], Z. Agha Shariatmadari[b]

[a] *Proffesor, Irrigation Eng. Dept.,Soil and Water Eng. Faculty, University of Tehran, Iran*
[b]*Former graduate student, Irrigation Eng. Dept., Soil and Water Eng. Faculty, University of Tehran, Iran*

Received 21 January 2006; received in revised form 10 June 2007; accepted 11 July 2007

Abstract

Depth of frost penetration is one of the main indices in agriculture, civil and transportation engineering. Soil temperature is a function of several factors including: topography, solar radiation, air temperature, moisture content and other physical properties of soil such as thermal capacity, coefficient of heat conductivity, and specific heat. The main objective of the present paper is to determine the frost penetration depth in soils based on the air temperature. In this study the daily and hourly temperatures of air and soil at different depths of three climatology stations located at Shahr-e-Kord, Yazd and Urmia cities of Iran were collected and analyzed for a period of 11 years from 1992 to 2003. In the first stage, Air Freezing Indices (AFI) of the three named stations was calculated using three methods known as: American, Norwegian and Finn and then the results were compared with the observed values accordingly. Investigations showed that correlation between the results is significant at one percent level, but the three methods gave different figures. Based on other references, it has been shown that the American method is more suitable for regions located at the middle latitudes. Thus, the correlations between Frost Penetration Depth (FPD) and AFI based on the US method were calculated and found to be 0.88 and 0.82 for Shahr-e-Kord and Urmia stations respectively. However, the correlation for Yazd station was much lower (0.65), and significant ($P<0.05$). As a general, it was concluded that application of this method is more relevant to semi-arid rather than arid zones, but in the absence of a better method, the same index could be used for determination of FDP in arid zones as well.

Keywords: Soil freezing; Air Freezing Index; Frost Penetration Dept; Arid and Semi-arid Zones; Iran

1. Introduction

Soil frost penetration depth indices have many applications in agriculture, civil and transportation engineering. Frost Penetration Depth (FDP) has been defined as the depth of soil layer, where temperature reaches below 0 C^0. Soil temperature is normally related to several factors including topography, solar radiation, air temperature, moisture content, texture and some thermal properties of soil such as: thermal capacity, specific heat, and coefficient of thermal conductivity. Since the most important factor in determination of frost depth in soil is air temperature, thus, many researchers have attempted to correlate FPD and air temperature. Steuer (1995, 1996) was pioneer on this subject. Frost penetration depth is a factor which changes from year to year. In agriculture, the number of freezing periods and its return period is normally important, while in civil engineering, the maximum depth is needed for many design applications. One of the proposed methods for determination of FPD is Air Freezing Index, AFI, is the main governing factor, which has been proposed by, Agnieszka (1996) and Steuer (2003). In fact, AFI is the main factor which governs frost penetration of depth soil. Since this index is purely related to the air temperature, thus, its validity should be evaluated for any given region. The main objective of this paper is to investigate validity

* Corresponding author. Tel.: +98 261 2221119;
fax: +98 261 2221119
E-mail address: akhalili@ut.ac.ir

of AFI application for determination of FPD in some typical climates of Iran.

In the recent years, many attempts have been made to develop new methods or relationships for determination of soils frost penetration depth. After Jumikis investigation on using Stephan's analytical solution for determination of soils frost depth soils, Hass & Winters (1984) proposed an experimental relation based on the temperature of freezing days. Thomas & Trat (1984) also studied freezing and thawing of soils in two dimensional models. Mckeown & Clark (1988) studied the thermal regime and freezing process of gravels. McCormick (1993) investigated the frost action under road bases. Steuer & Crandlle (1995) have studied different methods of evaluation of air freezing index and found the US method (AFI_{US}) to be the most suitable for areas located in the middle latitudes. Steuer (1996) also studied probability density function of air freezing index with a return period of 100 years for the United States showed better fit by Weibull distribution in comparison to Gamble distribution. Degaethano & Cameron (2001) simulated soils maximum frost penetration, using the normal climatology data. Degaethano & Wills studied the limiting values of frost penetration depth in Contiguous, USA, (2002).

2. Materials and Methods

2.1. Air Freezing Index

The air freezing index is indication of duration and magnitude of temperature above and below freezing in any region and cold season. In fact, this index is indication of air temperature potential to cause freezing of soil at a given depth. The main parameter used in this method is the average daily temperature. This parameter is calculated using the average value of the maximum and minimum daily temperatures as below:

$$\overline{T} = \frac{T_{\max} + T_{\min}}{2} \qquad (1)$$

For calculation of AFI several methods have been proposed by different researchers, among them the three most important are presented here. One of them is the American method (AFI_{US}), in which cumulative average daily temperature of cold season is calculated and plotted against time. AFI_{US}, is the distance between the maximum and the minimum points on this curve. The mathematical relationships for this method are shown as below:

$$S_i = \sum_{i=1}^{N} \overline{T}_i$$
$$AFI_{us} = \left(MaxS_i - MinS_i\right) \qquad (2)$$

Where:

N = number of cold days (°C)

$\overline{T}_i$ = average daily temperature (°C)

S_i = cumulative degree-days from the beginning of the cold season

$MaxS_i$ = maximum daily temperature (°C)

$MinS_i$ = minimum daily temperature (°C)

The graphical method for determination of AFI by the American method is shown in Figure (1).

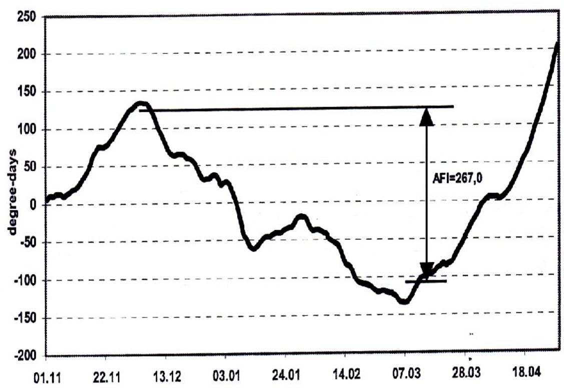

Fig. 1. Determination of AFI by the American method

In some cold season and some areas, there may be several points of maximum and minimum on the curve which is an indication of several cold periods. We found this case for current study areas. Since any sub-period is assumed as separate incident, therefore, only the difference between maximum and minimum of that period considered for calculation of the AFI, for one of the three under-studied stations (Shahr-e-Kord Station), as shown in figure (2).

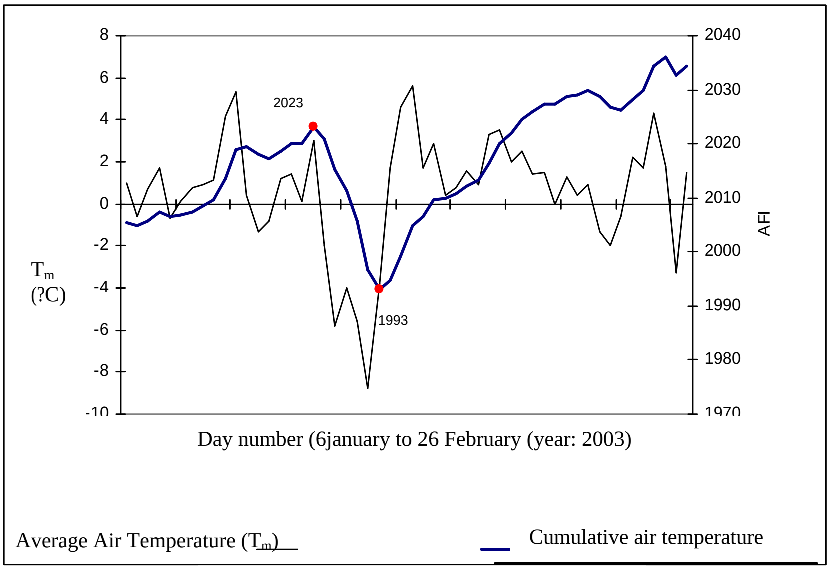

Fig. 2. Determination of AFI_{US} for Shahr-e-Kord Station, from Jan 6 to Feb 26, 2003

The second method is called Norwegian, where AFI_{NOR} is calculated by summing the negative average daily temperature in the winter season (Steuer, 1995). In this method the affirmative temperature values are not considered. The AFI calculated by this method is close to those calculated by the American method for cold regions, while for temperate regions; AFI is higher due to consideration of affirmative air temperature values. The main advantage of this method is its simplicity, where AFI is calculated by the following conditional equation:

$$AFI = \sum_{i=1}^{N} \left(\overline{T}_i \right) / \overline{T}_i \le 0 \qquad (3)$$

Where:
N is the number of freezing days in the cold period and $\overline{T}_i$ is the negative average daily temperature.

The third method for determination of AFI is called the Finn Method. This method is based on the average monthly temperature (Steuer, 1995). AFI in this method is calculated by multiplying the average monthly temperatures, provided to be negative, by the number of days in the month and summing up the obtained values. Due to using the average daily temperatures, this method is mainly applied to very cold regions having long freezing season, only. The following relationship is used for calculation of AFI in this method:

$$AFI = \sum_{i=1}^{12} \left[\left\{ \left(\overline{T}_{i_{month}} \right) / _{\overline{T}_{imonth} \le 0} \right\} \times N_i \right] \qquad (4)$$

where:
$\overline{T}_{i_{month}}$ = average monthly temperature (°C)
N_i = number of days in the i^{th} month

Based on the results of several investigations, it has been found that the US method is most suitable for temperate regions and therefore, it has been used as the main criteria for determination of frost depth penetration in under study areas (Steuer, 1995).

2.2. Field data

In the present study, air temperatures and soil parameters were collected for Shahr-e-Kord and Urmia as semi-arid regions and Yazd as an arid region of Iran, for an eleven years period of 1992-2003. The under screen air temperatures were collected at 3.00, 9:00 and 15:00 Greenwich hours and soil temperatures were collected for standard depths of 5, 10, 20, 30, 50 and 100 cm. Location of the three stations on the map of Iran is shown in Figure 3.

Fig. 3. Locations of meteorological stations on Iran map

Meteorological station of Shahr-e-Kord is located at 32^0, 20’ N and 50^0, 51’ E, in elevation of 2061m above the sea level (a.s.l.). Its aridity index is 14.6 and is classified as semi-arid cold climate according to De Martonne system. Surface soil texture is fine and for the subsurface layers is very fine, as indicated in Table (1) (Soil & Water Research Institute of Iran).

Table 1. Soil Texture of Shahr-e-Kord Station

Depth (cm)	Soil Texture
0-20	*Silty Clay Loam*
20-50	*Silty Clay*

Urmia Meteorological Station is located at 37^0, 32’ N and 45^0, 50’E, in elevation of 1315m a.s.l. Based on De Martonne’s Classification System, it has semi-arid climate and aridity index of 16.0. Based on the soil’s investigation reports, the texture of the surface soil is medium and in deeper layers is very fine, as shown in Table (2).

Table 2. Soil texture of Urmia Station

Depth (cm)	Soil Texture
0-50	*Sandy Loam*
50-85	*Clay*
85-120	*Clay*

Yazd Meteorological Station is located at a typical extra arid climate region of Iran with an aridity index of 2.1. Soil textures at different depths are shown in Table (3).

Table 3. Soil Texture of Yazd Station

Depth (cm)	Soil Texture
0-15	*Sandy Loam*
15-40	*Sandy Loam*
40-90	*Sandy Clay Loam*

Table (4), summarizes the important climatic elements of the three studied stations.

Table 4. Climatic elements for the period of 1955-2000

Station	Absolute Minimum Temperature (oC)	Absolute Maximum Temperature (oC)	Daily Mean Temperature (oC)	Sum Of Annual Precipitation (mm)	Average Relative Humidity	Number Of Freezing Days	Annual Average Of Sunny Hours	Number Of Perfect Cloudy Days
Shahr-e-Kord	-32	42	11.8	319	46%	124	3144	37.2
Urmia	-22.8	38	11.5	345	60%	110	2817	63
Yazd	-16	45.6	19.3	61.5	32%	52	3213	35

2.3. Calculation Method

When the required data were collected, maximum depth of frost penetration in soil for three stations were calculated based on the required inputs for eleven years period from 1992 to 2003. In this process, air temperatures and soil temperatures at different depths were first tabulated separately and then, the maximum depth of frost penetration was calculated based on analysis of hourly soil temperature of each station. For this purpose, the three dimensional variations of soil temperature (time, depth, temperature) were analyzed. The graphical examples of this method for the three stations in a 31 and 32 days period are shown in Figures (4) to (6). For determination of temperature at a given depth of soil located between depths of Z_1 and Z_2, with temperatures of $T_1$and T_2, linear interpolation technique was used and where temperature sign changes from positive to negative, is taken as the depth of frost penetration. The FPD value obtained in this process is considered as thermal property of the soil at the time of measurement and its maximum yearly value is taken as Maximum Frost Penetration Depth (MFPD) in the year of study (Agnieszka, 2003). To facilitate the process, a computer program was written and used for calculation of maximum yearly FPD, using hourly soil temperatures. AFI of each station was calculated by the American, Norwegian and Finn methods, based on the mean daily air temperature, using equations (2) to (4).

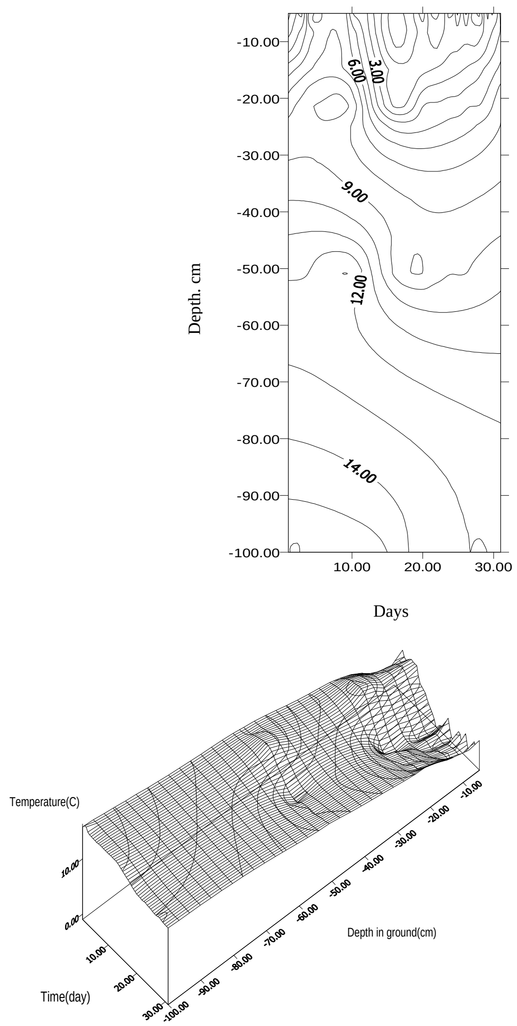

Fig. 4. Three dimensional model of daily temperature at soil different depths for Yazd Station at 3.00 am (Greenwich), Jan. 1996

3. Results

The results of calculations for the maximum frost penetration depth of the three stations based on the above mentioned analysis are summarized in Table (5). Air freezing indices calculated using American, Norwegian and Finn methods are also given in Tables (6) to (8).

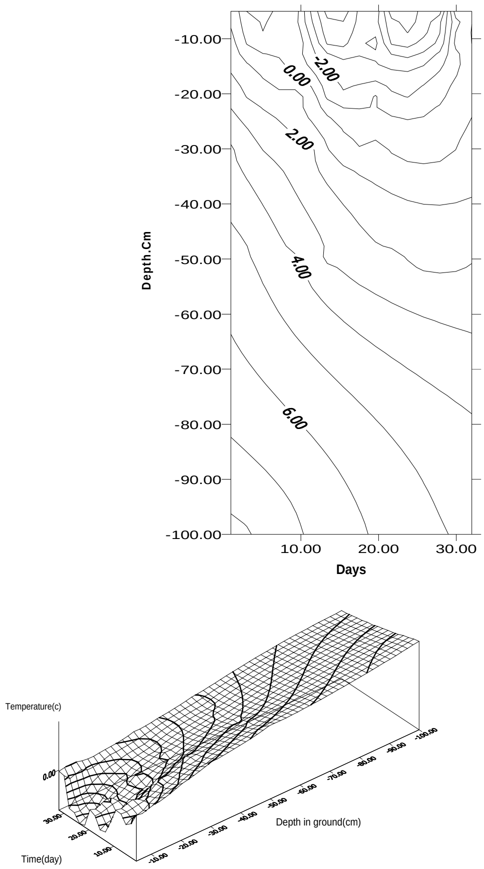

Fig. 5. Three dimensional model of daily temperature at soil different depths for Urmia Station at 3.00 am (Greenwich), Jan. 1996

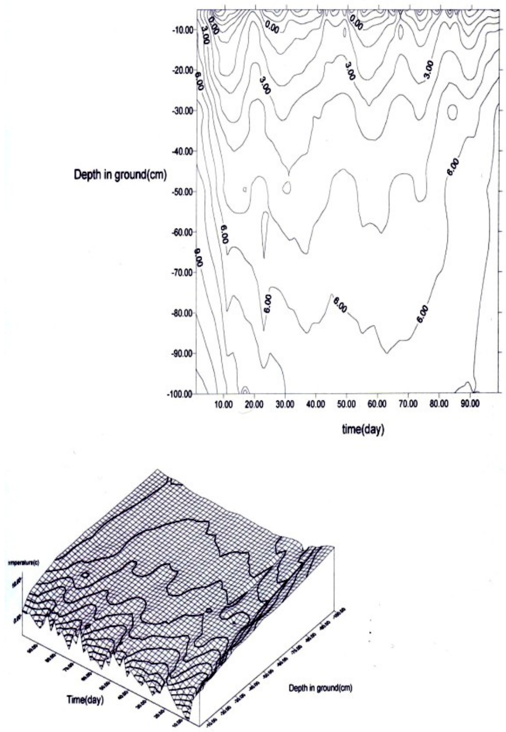

Fig. 6. Three dimensional model of daily temperature at soil different depths for Shahr-e-Kord Station at 3.00 am (Greenwich), Jan. 1996

Table 6. Air Freezing Index, (AFI), for Shahr-e-Kord Station

Year	$AFI_{(US)}$	$AFI_{(NOR)}$	$AFI_{(FIN)}$	**Average Temperatures of Dec., Jan. and Feb. (°C)**
1992-93	79.9	150.5	72.0	0.2
1993-94	28.0	40.6	0.0	2.6
1994-95	14.1	40.6	0.0	1.9
1995-96	160.2	258.9	207.8	-1.1
1996-97	47.2	81.8	0.0	1.5
1997-98	117.5	213.4	117.2	-0.8
1998-99	24.9	36.6	0.0	3.9
1999-2000	38.9	58.5	0.0	1.6
2000-2001	50.5	74.8	17.8	1.3
2001-2002	30.6	38.9	0.0	2.9
2002-2003	68.6	105.5	24.8	1.1
Mean	60.0	100.0	40.0	1.4
SD	44.4	76.3	67.4	1.5
CV	74.0	76.3	168.7	110

Table 7. Air Freezing Index, (AFI), for Urmia Station

Year	$AFI_{(US)}$	$AFI_{(NOR)}$	$AFI_{(FIN)}$	**Average Temperatures of Dec., Jan. and Feb. (°C)**
19992-93	254.1	265.3	213.7	-2.2
1993-94	35.7	79.8	16.0	0.2
1994-95	35.4	64.8	17.3	1.1
1995-96	89.7	103.7	40.9	0.4
1996-97	116.1	129.9	34.5	1.5
1997-98	106.9	133.2	98.5	-0.4
1998-99	3.1	7.6	0.0	3.3
1999-2000	60.0	74.6	14.7	1.1
2000-2001	19.5	55.1	8.1	1.5
2001-2002	65.2	85.7	38.8	1.4
2002-2003	106.5	139.4	57.9	0.0
Mean	83.8	103.6	49.1	0.7
SD	66.6	66.2	61.1	1.4
CV	79.5	63.9	124.4	190

Table 8. Air Freezing Index, (AFI), for Yazd Station

Year	$AFI_{(US)}$	$AFI_{(NOR)}$	$AFI_{(FIN)}$	**Average Temperatures of Dec., Jan. and Feb. (°C)**
1992-93	1.6	1.6	0.0	7.1
1993-94	0.0	0.0	0.0	8.3
1994-95	0.0	2.3	0.0	8.1
1995-96	23.8	23.8	0.0	10.8
1996-97	0.0	0.0	0.0	8.5
1997-98	0.0	0.0	0.0	7.7
1998-99	0.0	0.0	0.0	10.1
1999-2000	0.0	0.0	0.0	7.9
2000-2001	3.4	3.4	0.0	8.2
2001-2002	0.0	0.0	0.0	9.4
2002-2003	0.0	0.0	0.0	8.9
Mean	2.6	2.8	0.0	8.6
SD	7.1	7.1	0.0	1.1
CV	371.5	249.6	0.0	10.0

As the results of calculations presented in the above mentioned tables show, AFI values obtained by Norwegian method, (AFI_{Nor}), are greater than the values obtained by the other methods, while the Finn method, (AFI_{Finn}), shows the lowest amount. The results of linear correlation test of AFI methods for Urmia and Shahr-e-Kord Stations, by all three methods have significant affirmative correlation at ($P<0.01$), while for Yazd Station, values calculated by AFI_{US} and AFI_{Nor} methods have powerful correlation but they are weakly correlated with AFI_{Fin}. It means that for regions like Yazd, where there is less possibility for prevailing freezing conditions, the AFI_{Fin} method is not suitable and AFI_{US} the best method for determination of the maximum frost depth.Variations of maximum observed frost penetration depths versus AFI_{US} for the three stations are presented in Figures (7) to (9).

The regression equations and coefficients of correlation are shown on the same figures. The linear correlation analysis shows a powerful and significant affirmative correlation ($P<0.01$) between the results for Urmia and Shahr-e-Kord Stations, while for the Yazd Station the results are correlated at ($P<0.05$) significant level, which shows weaker correlation. Figure (10) shows that AFI_{US} and FPD of December, January and February for Urmia and Shahr-e-Kord Stations have powerful significant correlation ($P<0.01$), while for Yazd, they are correlated only at 5 significant level, which indicates a weaker correlation.

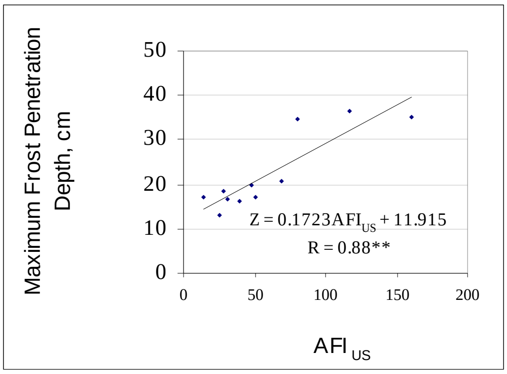

Fig. 7. AFI_{US} versus maximum observed frost penetration depth (Shahr-e-Kord Station)

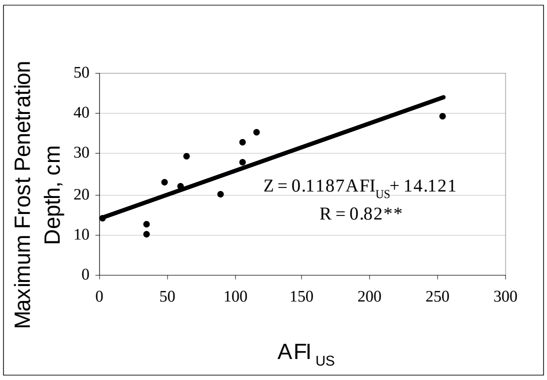

Fig. 8. AFIUS versus maximum observed frost penetration depth (Urmia Station)

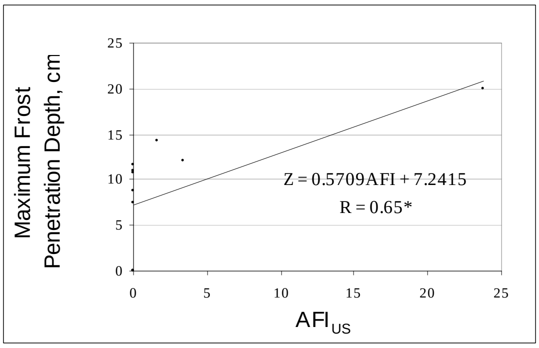

Fig. 9. AFIUS versus maximum observed frost penetration depth (Yazd Station)

4. Conclusion

The results show, AFI_{US} can be used for determination of maximum frost penetration depths in semi-arid regions such as Urmia and Shahr-e-Kord, and FPD can be calculated based on mean daily temperatures (P<0.01). In arid regions like Yazd, the correlation is weaker (P<0.05).

It is suggested for some regions that the correlation between mean daily air temperatures and soil temperatures at different depths to be monitored for a given climatic period. Having the results, maximum frost penetration depth for any year can be calculated based on the AFI of the same year. As the correlation between AFI and FPD is a function of soil texture and climate type, it is suggested that such relationship study different regions, where the three methods discussed in this paper are not applicable. By using this method, it possible to plot the climatology map of maximum frost penetration depth.

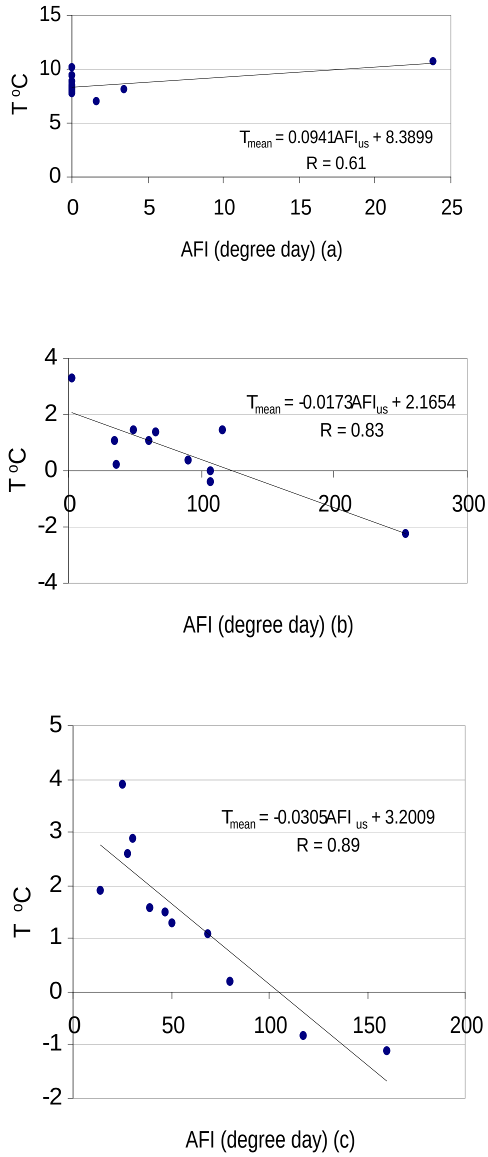

Fig. 10. Linear correlation between AFI and the mean temperature of Dec. to Feb. for the three stations, (a) Yazd, (b) Urmia and (c) Sharr-e-kord

Acknowledgements

The authors wish to express their deepest gratitude to the Vice Chancellors for Research Affairs of University of Tehran and Agricultural Campus of Karaj for their financial support of the research.

References

Agnieszka, G., 2003. Comparison of Calculated and Observed Depth of Frost Penetration in West Poland. Faculty of Civil and Environmental Engineering, Instute of Structural Engin. ASCE, New York, NY.

Degaethano, A. T., Cameron, D. C., 2001. Physical Simulation of Maximum Seasonal Soil Freezing Depth in the United States Using Routine Weather Observation. Jour. App. Meteorology. Vol.40, pages 546-556.

Degaethano, A. T., Wilks, D. S., 2002. Extreme Value Climatology of Maximum Soil Freezing Depth in Contiguous United States. Jour. Cold Reg. Eng. Vol.16, No.2, Pages 51-71.

Haas, W. M., Winters, L. H., 1984. Freezing Degree-days and Frost Penetration under Roads. In proceedings, 3rd International Specialty Conference on Cold Regions Engineering, Edmonton, Alberta. pages 1151-1165.

McCorMick G., 1993. Frost Penetration beneath Cleared Pavements, In Frost in Geotechnical Engineering. Balkema, Rotterdam. pages 117-126, ISBN 9054103191.

Mc Keown, S., Clark, J. I., Matheson, D., 1988 Frost Penetration and Thermal Regime in Dry Gravel. Jour. Cold Reg. Eng. Vol.2, pages 111-123.

Steuer P. M., 1996. Probability Distribution Used in 100 years Return Period of Air Freezing Index. Jour. Cold Reg. Eng. Vol. 10, no.1, Pages 25-35.

Steuer P. M., Crandell J.H., 1995. Comparison of Methods Used to Create Estimate of Air-Freezing Index. Jour. Cold Reg. Eng. Vol.9, no 2, Pages 64-75.

Thomas H.P., Trat R.G., 1984. Two-dimensional Simulation of Freezing and Thawing in Soils". Proceedings, 3rd nternational Specialty Conference on Cold Regions Engineering, Edmonton, Alberta. 1984. Pages 265-274.