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Moisture-dependent models for microwave complex permittivity and loss factor of spring oats kernels: A comparative study

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ABSTRACT

In the present work we have proposed two models namely, quadratic and cubic, for the variation of relative permittivity and dielectric loss factor of spring oats (*Avena sativa L.*) with decimal moisture content at 2.45 GHz. The results for relative permittivity and loss factor have been derived from the works of S.O. Nelson and the models chosen for comparison with the present models are also due to Nelson. The evaluation of constants for the models has been done using the method of least -squares-fit for non-linear regression analysis. The values of the coefficients of determination (r^2) too close to unity and lower average percentage errors in both of our models (~6.08 and 3.09 for relative permittivity and ~5.94 and 12.09 for the loss factor) compare our models favorably with the established models.

KEYWORDS

Permittivity;
Dielectric loss factor;
Nonlinear regression;
Agricultural products;
Microwave frequency;
Composite materials.

1. INTRODUCTION

The use of electrical properties of grains for moisture measurement has been one of the most prominent agricultural applications for dielectric properties data. The dielectric properties offer a potential means in making devices for sensing the moisture content of individual grain kernels, which help in preventing the spoilage of large blended lots stored in elevators, ships or mills[1-2].

Several efforts to model the dielectric properties of grains have been made[3-4]. The purpose of the present paper is to consider a more general approach towards modeling the dielectric properties of samples of spring oats (*Avena sativa L.*), using the data for them at a fixed frequency of 2.45 GHz at 24^{0}C, to present empirical expressions which allow predictions of permittivity and loss factor. The electrical properties of grains are influenced by ionic conductivities and bound-water- relaxations. The result of measured values is then a complicated function of the amount of water in the grain. However, all these effects disappear almost completely at higher microwave frequencies. Thus, microwaves offer a nondestructive, sensitive and feasible method for determining the water content in grains.

2. EXPERIMENTAL

Data for measured values of bulk density, decimal moisture content (m) and dielectric constant were taken from the TABLE 3[5]. For deriving the values of bulk density ρ_b, Kernel densities ρ_k and hence the volume fractions ($=\rho_b/\rho_k$) of the material in the mixture, the equations (7) and (8) of the same paper[5] were used. The general quadratic and cubic models given by Nelson and Kraszewski[2] connecting dielectric constant, moisture content and frequency of operation were used for their comparison with the corresponding new models proposed in the present study. The equations are:

$$\varepsilon' = [1+\{A_2 - B_2 \log f + (C_2 - D_2 \log f)\, M\}\, \rho]^2 \quad (1)$$

and

$$\varepsilon'' = [1+\{A_3 - B_3 \log f + (C_3 - D_3 \log f)\, M\}\, \rho]^3 \quad (2)$$

The solitary equation for the dielectric loss factor available for comparison is of the form:

$$\varepsilon''=0.146\rho^2 + 0.004615\, M^2\rho^2[0.32 \log f + 1.743/\log f - 1] \quad (3)$$

Where $\rho = \rho_b$ = bulk density of the material in gramxcm^{-3}, M = % moisture content, wet basis = 100 m, f = frequency of operation in MHz.

The values of constants viz. A_2, B_2, C_2, D_2 or A_3, B_3, C_3, and D_3 of equations (1) and (2) for spring oats were taken from the TABLE 6 of Nelson's paper[2].

3. Model development and evaluation of constants

Based on observations of almost linear plots obtained for the dependence of relative permittivity of grains and cereals with moisture content, especially in the microwave range, it was proposed to give quadratic as well as cubic models for such variations. On similar lines of the works of Noh and Nelson[6] on rice samples, the second and a new term, called moisture density (product of decimal moisture content and bulk density), was also used. The third and the new term, called moisture specific volume (ratio of decimal moisture content to bulk density, m_v), in addition to m and m_d was also proposed to be incorporated in the composite model proposed in the present study. The composite models are:

Quadratic

$$\varepsilon'=a_2 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + b_2 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_1 \quad (4a)$$

and

$$\varepsilon''=c_2 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + d_2 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_2 \quad (4b)$$

Cubic

$$\varepsilon'=a_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^3 + b_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + c_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_1 \quad (5a)$$

and

$$\varepsilon'' =d_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^3 + e_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + f_3 \begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_1 \quad (5b)$$

The value of the constant K_1 was taken to be equal to the average of the relative permittivities as derived from equations (1) and (2) by putting M = O in them. The corresponding value of ρ was derived from equation (7) of the Nelson's paper[5] by putting m = O in it. Similarly, the value of K_2 was taken to be equal to the value of the loss factor from equation (3) of the present paper by putting the abovementioned value of ρ corresponding to M=0. In this way

$$K_2 = (\varepsilon'')_{m=0} = 0.146\,(\rho_o)^2 \quad (6)$$

(ρ_0= bulk density at m=0)

From the data for relative permittivity at different decimal moisture contents and bulk densities, the constants for the first part of each of the sets of models were evaluated using the method of least-squares-fit for nonlinear regression.

The same method was adopted using the data for dielectric loss factor derived from the works of S.O. Nelson[7] i.e., from figure 1(b) for the operating frequency of 2450 MHz. The results have been presented in TABLE 1 and the evaluated constants are listed in TABLE 2.

In order to extend the applicability of the present models to grain kernels, the values of relative permittivity of the moist grain samples, (supposed to be an air-particle binary mixture), were proposed to be converted to those of solid materials (particles) with the help of eight dielectric mixture equations[8-14].

4. Brief Introduction of the dielectric mixture equations used

1. Rother-Lichtenecker formula or the logarithmic law of mixing for Chaotic mixture[8]

$$\ln \varepsilon_r = \sum_{i=1}^{n} f_i \ln \varepsilon_i \text{ (for n component mixture)} \quad (7a)$$

Thus for an asr-particle binary mixture

$$\ln \varepsilon_r = f_1 \ln \varepsilon_1 + f_2 \ln \varepsilon_2 \quad (7b)$$

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Thus, $\varepsilon_2 = \exp[1/f_2 \ln \varepsilon_r]$ **(7c)**

2. Taylor's formula for random angular distribution of needles[9]

$$3\varepsilon_r(\varepsilon_r - \varepsilon_H)/f = (\varepsilon_I - \varepsilon_H)(2\varepsilon_I + \varepsilon_r) \quad (8a)$$

$$\varepsilon_2 = 0.25\,[\{2+3/f\,(\varepsilon_r - 1) - \varepsilon_r\} + [\,[\{2+3/f\,(\varepsilon_r - 1)\} - \varepsilon_r]^2 + 8\varepsilon_r]^{1/2}] \quad (8b)$$

(Taking only the positive root of the quadratic equation which the relation yielded).

3. Taylor's formula for random angular distribution of disks[9]

$$[3(\varepsilon_r - \varepsilon_H)(\varepsilon_I + \varepsilon_r)]/f = (\varepsilon_I - \varepsilon_H)(5_r + \varepsilon_I) \quad (9a)$$

on similar pattern as 2

one gets,

$$\varepsilon_2 = 0.5\,[\,[(1-3/f) - (5-3/f)\,\varepsilon_r] + [\{(1-3/f) -(5-3/f)\varepsilon_r\}^2 + 4\{(3/f)\varepsilon_r^{\,2} + (5-3/f)\,\varepsilon_r\}]^{1/2}] \quad (9b)$$

4. Lewin's formula[10]

Lewin proposed a formula for the computation of permittivity and permeability of mixture consisting of a homogenous material in which spherical particles are embedded. The formula is given as :

$$(\varepsilon_r - \varepsilon_H)/\varepsilon H = 3f\,(\varepsilon_I - \varepsilon_H)/\{\varepsilon H\,(1+2f) + \varepsilon I\,(1-f)\} \quad (10a)$$

which in the present case simplifies as

$$\varepsilon_2 = [\varepsilon_r(1+2f) - (1-f)]/[(1+2f) - \varepsilon r\,(1-f)] \quad (10b)$$

5. Sillars formula[11]

$$\varepsilon_r = \varepsilon_H[\varepsilon_H + D(1-f) + f][\varepsilon_I - \varepsilon_H]/[\varepsilon H + D(1-f)\,(\varepsilon I - \varepsilon H)] \quad (11a)$$

where, D = depolarization factor depending on the shape of the particles.

$$\Rightarrow \varepsilon_2 = [\,\{\varepsilon_r - 1\}/\{\,f - D\,(1-f)\,(\varepsilon r - 1)\,\}\,] + 1 \quad (11b)$$

(where D= 0.2)

Surprisingly enough, the data give the best fit for the value of D = 0.2, as derived for rutile particles, suggesting that the shape of the particles were the same in both the cases. Other wise, other values of D were to be tried for best fit.

6. Sadiku's formula[12]

$$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + u)} = \frac{f(\varepsilon_I - 1)}{(\varepsilon_2 + u)} + \frac{(1-f)(\varepsilon_H - 1)}{(\varepsilon_H + u)} \quad (12a)$$

$$\Rightarrow (\varepsilon_r - 1)/(\varepsilon_r + u) = f\,(\varepsilon_2 - 1)/(\varepsilon_2 + u) \quad (12b)$$

In the above formula u = form no., supposed to be depending on the shape of the particles and the values of u= 5 for snow or ice taken from the literature, gave the best fit as D = 0.2 for rutile in the previous formula. It also led us to suppose that there must be a relation like D = 1/u between D and u Thus, by putting u = 5, the formula finally reduces to:

$$\varepsilon_2 + 2 = 3\,[\varepsilon_r\,(1+f) + (5f-1)]\,/\,[(1+5f) - \varepsilon r\,(1-f)] \quad (12c)$$

Again, the limitation for the validity of the Weiner formula is that the particles should be small as compared to the wavelength used.

7. Formula obtained from effective medium theory[13]

$$\varepsilon_r = \varepsilon_H\,[(1+2f)\,\varepsilon_i + 2\,\varepsilon_H\,(1-f)]\,/[\,\varepsilon_i\,(1-f) + (2+f)\varepsilon_H] \quad (13a)$$

$$\varepsilon_2 = [(2+f)\,\varepsilon_r - 2(1-f)]\,/[(1+2f - \varepsilon_r\,(1-f)] \quad (13b)$$

In the above formula, particulate material has been taken as the first component and air as the second one under the limiting case of small concentration of the component A in the binary system AB-opposed to those taken in other formulae.

8. Skipetrov formula[14]

$$\varepsilon_{eff} = \varepsilon_1\,[1\{3f_2\,(\varepsilon_2 - \varepsilon_1)\}/\{1(2+f_2) + \varepsilon_2(1-f_2)\}] \quad (14a)$$

The equation finally gives :

$$\varepsilon_r = 1 + [3f\,(\varepsilon_2 - 1)]/[(2+f) + \varepsilon 2(1-f)] \quad (14b)$$

In all the above equations, $\varepsilon_H = 1$ and $\varepsilon_I = \varepsilon_2$.

The above expression has been claimed by the investigator to be an original expression for the effective dielectric function of dilute suspension of spherical beads of diameter d<< λ. Further, it has been claimed that the above formula is expected to be more appropriate for the interpretation of the experiments and behavior at higher volume fractions.

Using any measured value of ε_r, the corresponding value of volume fraction of the particle, f_2= (f), the value of the permittivity of the particles, ε_2 (=ε_2, say) was calculated choosing any of the eight equations, say the first one. The constants of the first set of equations concerning relative permittivity versus m (say) for the quadratic or the cubic model, as the case may be, were used to compute the value of m, (say). Using these values of m and the constants evaluated for the second set of equations (concerning loss factor versus moisture content, say), the value of loss factor of the particles (kernels), ε_2'' were calculated. Thus one gets the values of ε_2' and ε_2'' for a given computed value of m (say). The same process was repeated for different values of volume fractions of a given sample. A similar process was adopted by taking another dielectric mixture equation one by one, to get the data points. The same process was repeated for computation of ε_2' and

TABLE 1 : Data of measured values of relative permittivity and loss factor of spring oats (*Avena sativa L.*).at 24^{0}C and 2450 MHz at different bulk densities and moisture contents

Moisture content %, wet basis	Bulk density in g/cm^3	Relative permittivity	Dielectric loss factor
8.2	0.444	1.336	1.79
10.7	0.445	1.319	1.86
12.5	0.447	1.313	1.98
15.3	0.433	1.310	2.09
17.6	0.423	1.316	2.18
19.1	0.430	1.323	2.46
21.3	0.439	1.340	2.46
23.1	0.421	1.358	2.53
25.4	0.410	1.389	2.60

TABLE 2: Data of evaluated constants for the different models for spring oats at 24^{0}C and 2.45GHz

Models	Nelson's models		Models from present study	
	Quadratic	Cubic	Quadratic	Cubic
(A) Models with decimal moisture content, m	A_2 = 0.3370 B_2 = -0.0199 C_2 = 0.0982 D_2 = 0.0154	A_3 = 0.2740 B_3 = 0.0000 C_3 = 0.0543 D_3 = 0.0081	a_2 = 5.7143 b_2= 5.7143 c_2 = -0.4286 d_2= 1.0714 K_1 = 1.0 K_2 = 0.03	a_3 = -18.7904 b_3 = 0.0235 c_3 = 7.5396 d_3 = 4.5294 e_3= 2.1351 f_3 = 0.4365 K_1 = 1.0, K_2 =0.03
(B) Models with moisture density, md	-	-	a_2= -56.2144 b_2=21.1022 c_2 = 24.8241 d_2= 0.2010 K_1 = 1.0 K_2 = 0.03	a_3 = 195.1700 b_3 = -85.3951 c_3 = 22.1091 d_3 = 122.4643 e_3= 9.0009 f_3 = 0.6204 K_1 = 1.0, K_2= 0.03
(C) Models with moisture specific volume, mv	-	-	a_2 =-2.6740 b_2=4.2447 c_2 = 0.5842 d_2= 0.1413 K_1 = 1.0 K_2 = 0.03	a_3 = 2.4141 b_3 = -4.8251 c_3 = 4.6882 d_3 = -0.1925 e_3= 0.7550 f_3 = 0.1059 K_1 = 1.0, K_2= 0.03

ε_2'' as functions of m_d and m_v for both types of the proposed models. It was expected to achieve the estimates of ε_2' and ε_2'' of spring oats kernels as functions of m, m_d and m_v.

3. RESULTS AND DISCUSSION

The data of measured values of relative permittivity and dielectric loss factor of spring oats (Avena sativa) L. bulk samples at nine different moisture contents ranging from 8.2 % to 25.4%, wet basis and bulk and kernel densities corresponding to 24^{0}C and 2.45 GHz as taken from the literature[5] are presented in TABLE 1. TABLE 2 presents the constants and model parameters for the present quadratic and cubic models relating relative permittivity and dielectric loss factor to m, m_d and m_v evaluated with the help of least-squares-fit method for non-linear regression analysis. The same TABLE also presents the constants for the moisture-dependent models for the dielectric properties namely, relative permittivity and loss factor. TABLE 3 presents the quantitative comparative performances of the Nelson's moisture-dependent quadratic and cubic models for relative permittivity and similar models proposed in the present study. The same TABLE also presents the same comparative performance analysis of the present models for dielectric loss factor with that of Kraszeweski-Nelson model for the same. It also presents the average percentage errors of prediction for the different models with respect to the measured values of two dielectric properties (ε' and ε'') along with the coefficients of determination (r^2). Graphical presen-

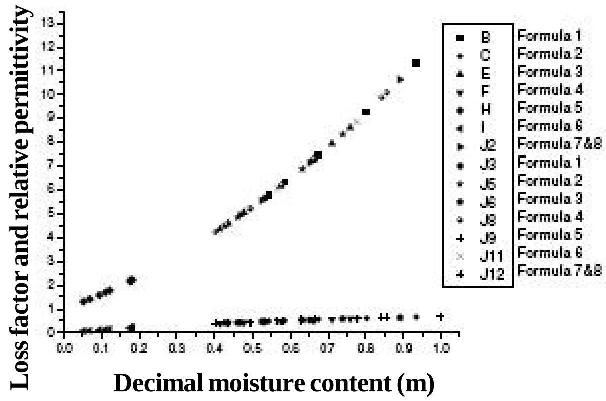

Figure 1(a): Variation of relative permittivity and loss factor of spring oats kernels at 2.45GHz and 24^{0}C as functions of decimal moisture content in the light of quadratic model

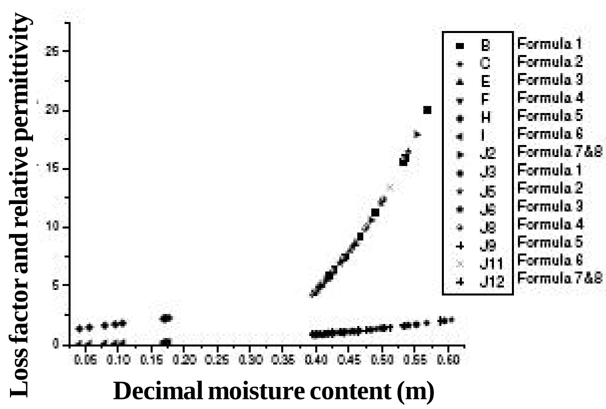

Figure 1(b): Variation of relative permittivity and loss factor of spring oats kernels at 2.45GHz and 24^{0}C as functions of decimal moisture content in the light of cubic model

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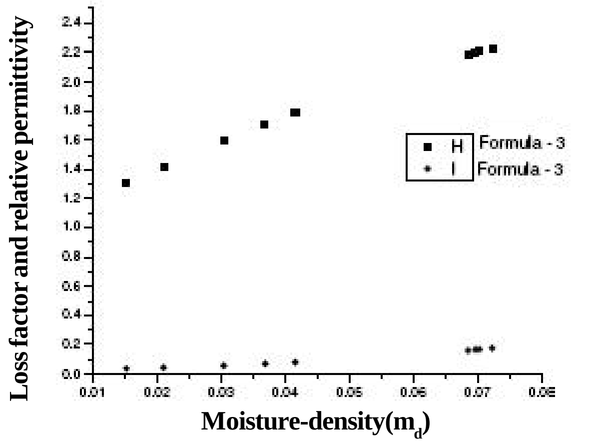


Figure 2(a): Variation of relative permittivity and loss factor of spring oats kernels at 2.45GHz and 24⁰C as functions of moisture-density in the light of quadratic mode

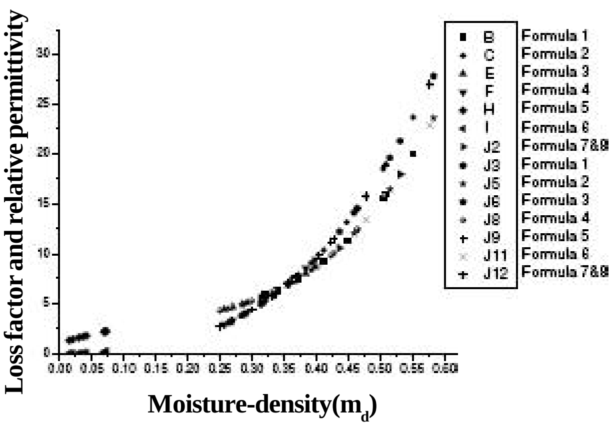
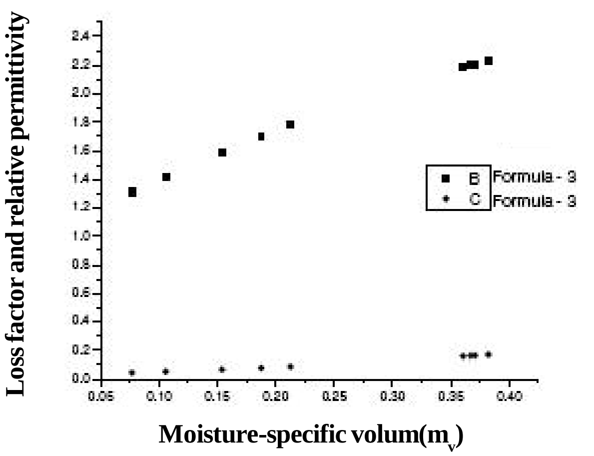


Figure 2(b): Variation of relative permittivity and loss factor of spring oats kernels at 2.45GHz and 24⁰C as functions of moisture-density in the light of cubic model



Figgure 3(a): Variation of relative permittivity and loss factor of spring oats kernels at 2.45GHz and 24⁰C as functions of moisture-specific volume in the light of quadratic model

(Figure 3b)??

tation for the ε'_2 and ε''_2 as function of decimal moisture content (m) have been given in Figures 1a and 1b. Graphical presentation of data points for moisture–density(m_d) dependent quadratic and cubic models for ε'_2 and ε''_2 are given in figures 2a and 2b, respectively. Similar graphical presentations of respective data points for moisture-specific volume (m_v) dependent quadratic and cubic models are given in figures 3a and 3b.

Examination of data in TABLE 3(A) reveals that Nelson's moisture-dependent quadratic and cubic models for relative permittivity provided values of average percentage errors ≈3-4. Corresponding values for the new cubic and quadratic models are ≈3-6. The r^2-values for the two old models are almost similar (≈0.99) whereas they are ~1 for both the new models (quadratic and cubic). Solitary Kraszewski–Nelson Model (KNM) as well as the new cubic model (PSM) for loss factor provides higher average percentage errors ≈ 15 and 12 and almost the same order of values for r^2 (≈ 0.993 – 0.994). On the contrary, the present quadratic model (PSM) provides best fit with experimental data in having r^2=1 and average error ≈ 6 %.

The cubic model for the variation of ε'_2 and ε''_2 as function of decimal moisture content (m) provided a poorer fitting as compared with the similar quadratic model, but the trend of variation is the same as in the density-dependent models. As regards the moisture-density dependent quadratic model, none other than the third formula provided accepTABLE data points for computed values of m_d and hence for ε''_2 for different computed values of ε'_2, corresponding to different values for bulk material samples, though seven different dielectric mixture equations were tried in the present study(Figure 2a). However, the trend of variation is similar as above. As regards the plot corresponding to the cubic model for m_v (**Figure 3b**), it is seen that although the trend of variation is similar as in other plots, a critical computed value of m_d (≈ 0.35) is reached beyond which the dielectric loss factor became too large so that it overtook the relative permittivity and then continued to be ahead of relative permittivity for subsequent vales of m_d.

TABLE 3 : Comparative Performances of different models for the variation of relative permittivity and loss factor with moisture content of spring oats at 24^{0}C and 2.45GHz

TABLE 3(A)

Nelson's model (NM) for relative permittivity				Prasad - Singh Model (PSM) for relative permittivity			
QM*		CM**		QM		CM	
Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error
1.81	-	1.82	-	1.52	-	1.62	-
1.96	-	1.95	-	1.68	-	1.78	-
2.07	0.9956	2.06	0.9955	1.80	1	1.91	1
2.21	-	2.20	-	2.02	-	2.09	-
2.29	4.01	2.28	3.85	2.18	6.08	2.22	3.19
2.40	-	2.40	-	2.31	-	2.31	-
2.58	-	2.58	-	2.49	-	2.42	-
2.61	-	2.61	-	2.62	-	2.51	-
2.70	-	2.70	-	2.82	-	2.61	-

TABLE 3(B)

Kraszewski-Nelsons model (KNM) for loss factor		Prasad - Singh Model (PSM) for loss factor			
		QM		CM	
Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error
0.071	-	0.115	-	-	-
0.068	-	0.139	-	-	-
0.091	0.9929	0.157	1	-	0.9936
0.182	-	0.184	-	0.163	-
0.204	14.96	0.205	5.94	0.198	12.09
0.273	-	0.219	-	0.223	-
0.261	-	0.238	-	0.264	-
0.261	-	0.255	-	0.300	-
0.283	-	0.274	-	0.353	-

*Quadratic model, **Cubic model

In case of m_v-dependent quadratic model for ε'_2 and ε''_2 similar to the m_d-dependent quadratic model, it was found that none other than the third formula provided acceptable data points for computed values of m_v and hence for ε''_2 corresponding to different computed values of ε'_2. Further, the trend of variation was similar to that for m_d-dependent quadratic model. As regards the last model i.e., the cubic model for the variation of computed values of ε'_2 and ε''_2 corresponding to different values of m_v(computed), the trend of variation is similar to that offered in the other models and the fitting was excellent over the entire range of variation of m_v.

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