APPENDIX G

BINDER AND MIXTURE PROPERTIES

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This program provides two ANN (Artificial Neural Network) models to calculate complex modulus which are 1999 ANN complex modulus model and 2006 ANN complex modulus model. These ANN models were developed from the Wictzak 1999 (2) and 2006 (3) models. Both models are available for the traffic case, and the 2006 ANN model is designed for use in the thermal case.

ANN 1999 Model – Traffic

Required Input Information:

- Gradation (3/4, 3/8, #4, #200)
- Volumetric (V_a, and V_{beff})
- Dynamic Viscosity (Log η, (poise))
- Frequency (ω(T), (Hz))

The frequency ω(T) (rad/sec.) is shown in (G-1). t_i is loading time.

$$\omega(T) = \frac{1}{2t_i} \left(\frac{rad.}{\text{sec.}}\right) \qquad \text{(G-1)}$$

The calculations of loading times t_i for each part are shown in the below:

- 292 loading times are calculated by tire length of each axle (single, tandem, triple, and quad) and desired velocity shown in the Table G-1. These loading times would be used to calculate ANN relaxation modulus and ANN SIF(Stress Intensity Factor).
- 18 loading times for $0.1 * t_{catetory}$, $t_{catetory}$, $10 * t_{catetory}$ are used to calculate m_{mix} for the calculation of Paris's law fracture properties A and n. The equations of loading time for each category are shown in Table G-2:
- 3 FWD loading times : $0.1 \times \frac{t_{FWD}}{a_T}$, $\frac{t_{FWD}}{a_T}$, and $10 \times \frac{t_{FWD}}{a_T}$ are used to calculate the E_1 in the fracture properties calculation.

$$a_T = 10^{\frac{-C_1(T_{FWD}-T_D)}{C_2+T_{FWD}-T_D}} \text{ , } t_{FWD} = 0.06 \text{ (sec.)}$$

The dynamic viscosity at the different temperatures is a function of the binder shear modulus, frequency of the master curve, and the slope of the G*(T) versus frequency curve.

$$\eta = \frac{\left|G^*(T)\right|}{m(T)\times\ 2\times\omega_0(T)^{\ 1-m(T)}}(Gpa\cdot s) \qquad \text{(G-2)}$$

Table G-1. Loading times for different axles.

Axles	Loading Times (sec.)
Single Axle	$\dfrac{10'+L_i\ \ (ft)}{Velocity\left(\dfrac{ft}{\text{sec.}}\right)}$
Tandem Axle	$\dfrac{14'+L_i\ \ (ft)}{Velocity\left(\dfrac{ft}{\text{sec.}}\right)}$
Tridem Axle	$\dfrac{18'+L_i\ \ (ft)}{Velocity\left(\dfrac{ft}{\text{sec.}}\right)}$
Quadrem Axle	$\dfrac{22'+L_i\ \ (ft)}{Velocity\left(\dfrac{ft}{\text{sec.}}\right)}$

Table G-2. Load times for different categories.

	$0.1{*}t_{category}$	$t_{category}$	$10{*}t_{category}$
Category 1	$0.1\times\dfrac{10'+0.99\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{10'+0.99\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{10'+0.99\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 2	$0.1\times\dfrac{10'+0.45\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{10'+0.45\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{10'+0.45\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 3	$0.1\times\dfrac{14'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{14'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{14'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 4	$0.1\times\dfrac{14'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{14'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{14'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 5	$0.1\times\dfrac{18'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{18'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{18'+0.9\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 6	$0.1\times\dfrac{18'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{18'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{18'+0.41\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 7	$0.1\times\dfrac{22'+0.68\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{22'+0.68\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{22'+0.68\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$
Category 8	$0.1\times\dfrac{22'+0.31\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$\dfrac{22'+0.31\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$	$10\times\dfrac{22'+0.31\ (ft)}{Velocity\left(\dfrac{ft}{sec.}\right)}$

where

$G^{*}(T)$ is the binder shear modulus (Gpa);

$\omega_0(T)$ is the frequency of the master curve;

$m(T)$ is the slope of the shear modulus ($G^{*}(T)$) versus frequency (ω) curve.

The frequency of the master curve, $\omega_0(T)$ (rad/sec.) at the different temperatures is

$$\omega_0(T) = \omega(T) \times a_T = \omega(T) \times 10^{\frac{-C_1(T-T_D)}{C_2+T-T_D}} \left(\frac{rad.}{\text{sec.}}\right) \quad \text{(G-3)}$$

The slope of the log $G^*(T)$ versus log ω curve, $m(T)$ at the different temperatures is

$$m(T) = \frac{\left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}}{1+\left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}} \quad \text{(G-4)}$$

The binder shear modulus G*(T) at the different temperatures is

$$\left|G^*(T)\right| = \frac{G_g}{\left[1+\left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}\right]^{\frac{R}{\log 2}}} (Gpa) \quad \text{(G-5)}$$

where G_g, ω_{rm}, and R are coefficients that depend on the level we choose. Level 1: User input G_g, ω_{rm}, C_1, C_2, T_d, and R. Level 2: User input PG X-Y to find the G_g. Level 3: Parameters are varied by different climate zones (Wet-Freeze, Wet-No Freeze, Dry-Freeze, and Dry-No Freeze) in our database.

ANN 2006 Model – Thermal and Traffic Cases

Required Input Information:

- Gradation (3/4, 3/8, #4, #200)
- Volumetric (V_a, and V_{beff})
- Phase Angle (δ(T) (radians))
- Binder Shear Modulus ($G^*(T)$ (GPa))

The phase angle δ(T) (radians) and binder shear modulus $G^*(T)$ (GPa) at the different temperatures are shown in the equations (G-6) and (G-7).

$$\delta(T) = m(T) \times \frac{\pi}{2} (radians) \tag{G-6}$$

$$\left|G^*(T)\right| = \frac{G_g}{\left[1 + \left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}\right]^{\frac{R}{\log 2}}} (Gpa) \tag{G-7}$$

where

$m(T)$	is the slope of the log $G^*(T)$ versus frequency curve
$\omega_0(T)$	is frequency of the master curve;
G_g, ω_{rm}, and R	are coefficients based on input levels.

Level 1: User input G_g, ω_{rm}, C_1, C_2, T_d, and R.

Level 2: User input PG X-Y to find the G_g .

Level 3: Parameters are varied by different climate zones (Wet-Freeze, Wet-No Freeze, Dry-Freeze, and Dry-No Freeze).

The frequency of the master curve, $\omega_O(T)$ (rad/sec.) at the different temperatures is

$$\omega_0(T) = \omega(T) \times a_T = \omega(T) \times 10^{\frac{-C_1(T-T_D)}{C_2+T-T_D}} \left(\frac{rad.}{\sec.}\right) \tag{G-8}$$

$\omega(T)$ (rad/sec.) is frequency $=1/2t_i$

where a_T is the time-temperature shift factor; t_i is the loading time.

The loading times are different for traffic and thermal cases. For the thermal case, loading time was assumed to cover all the range of loading frequency (0.01 to 100,000 seconds). For the traffic case, loading times are related to the number of axles Table G-1 and traffic categories Table G-2.

The slope of the log $G^*(T)$ versus log ω curve, $m(T)$ at the different temperatures is in equation (G-9).

$$m(T) = \frac{\left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}}{1+\left[\frac{\omega_{rm}}{\omega_0(T)}\right]^{\frac{\log 2}{R}}} \qquad \text{(G-9)}$$

The format of the Artificial Neural Network (ANN) relaxation modulus program is shown in the Table G-3 and Table G-4. The comparison of the ANN and Witczak 1999 and 2006 models shows that the results from the ANN fit better than the Witczak models Figure G-1 and Figure G-2. The R^2 of the ANN are 0.98 for 1999 model and 0.96 for 2006 model, and R^2 of Witczak are 0.68 for 1999 model(2) and 0.77 for 2006 model(3).

Calculation of G_g for Level 2 Input

In the level 2 input, G_g is determined by the Superpave binder performance grading PG X-Y.

Determine G_g from X:

$$\text{Definition: } \frac{\left|G^*(x)\right|}{\sin\delta(x)} = 1.00\ kPa\ \ @\ \ \omega(x) = 10\,\frac{rad.}{\text{sec.}}$$

$$m(x) = m(\text{test temperature}) = \frac{\left[\frac{\omega_{rm}}{\omega(x)\cdot a_T}\right]^{\frac{\log 2}{R}}}{1+\left[\frac{\omega_{rm}}{\omega(x)\cdot a_T}\right]^{\frac{\log 2}{R}}}$$

Table G-3. 1999 ANN relaxation model input format.

Gradation				Volumetric		Log η(T)	ω(T)	Log E*(t,T)
3/4	**3/8**	**# 4**	**# 200**	**V_a**	**V_{beff}**			
(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(Poise)**	**(Hz)**	**(psi)**
4.00	20.00	56.00	6.00	6.30	8.95	9.68	25	6.45175
0	30	64.5	8.4	5.90	11.50	5.32	0.1	5.06911
0	23.4	48.9	5	8.95	9.92	11.79	25	6.63034
0	16	33	5	6.36	11.48	4.92	5	5.21269
0	16	33	5	6.36	11.48	6.48	5	5.87216
0	35	58.2	6.6	4.90	8.14	9.30	1	6.35392
10	35	51	3.5	7.17	8.91	4.56	0.1	4.42908
0.00	4.00	41.60	3.30	5.45	10.10	12.19	25	6.45609
0	13	42	6.1	7.17	11.09	4.21	0.5	4.89153
26.1	41	52.4	5.7	7.40	8.27	4.24	5	4.92430
10	35	51	3.5	10.77	8.12	7.03	0.1	5.56806
5.1	25.2	46.2	6.4	6.60	11.08	11.01	1	6.69364
0.00	2.60	39.90	5.70	7.95	10.80	5.47	0.1	4.86171
7.2	23.2	44.5	6.2	6.66	10.34	9.19	0.1	6.27103
0	23.4	48.9	5	12.45	6.08	9.30	0.1	6.17644

Table G-4. 2006 ANN relaxation model input format.

Gradation				Volumetric		Log |G*| X 10^6	δ(T)	Log E*(t,T)
3/4	**3/8**	**# 4**	**# 200**	**V_a**	**V_{beff}**			
(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(psi)**	**(deg)**	**(psi)**
1.3	38	56	5.1	7.38	11.00	8.18	60.5	5.90
1.3	38	56	5.1	6.10	10.80	9.15	17.2	6.66
6.2	38.5	58	3.1	7.00	8.90	8.15	52.6	5.96
22.00	39.00	73.00	4.00	6.10	7.80	9.17	12.0	6.53
22.00	39.00	73.00	4.00	6.45	9.65	7.70	61.3	5.40
2.6	22.2	30.7	2.8	4.09	18.87	9.44	41.9	6.19
7.0	22.0	35.0	5.0	4.39	9.81	7.81	67.0	5.80
0.00	4.00	41.60	3.30	1.90	12.68	6.09	73.0	4.69
0	30	64.5	8.4	5.90	11.50	8.40	53.8	6.21
0	16	32	5	6.32	11.17	8.46	56.5	6.20
0	21	62	2.6	11.13	18.24	7.09	72.3	5.48
10	35	51	3.5	7.05	10.02	8.86	62.1	6.19
0	23.4	48.9	5	9.30	6.47	6.03	84.1	4.91
26.1	41	52.4	5.7	7.40	8.27	9.22	53.3	6.13
22.00	39.00	73.00	4.00	5.60	7.70	9.20	20.8	6.59

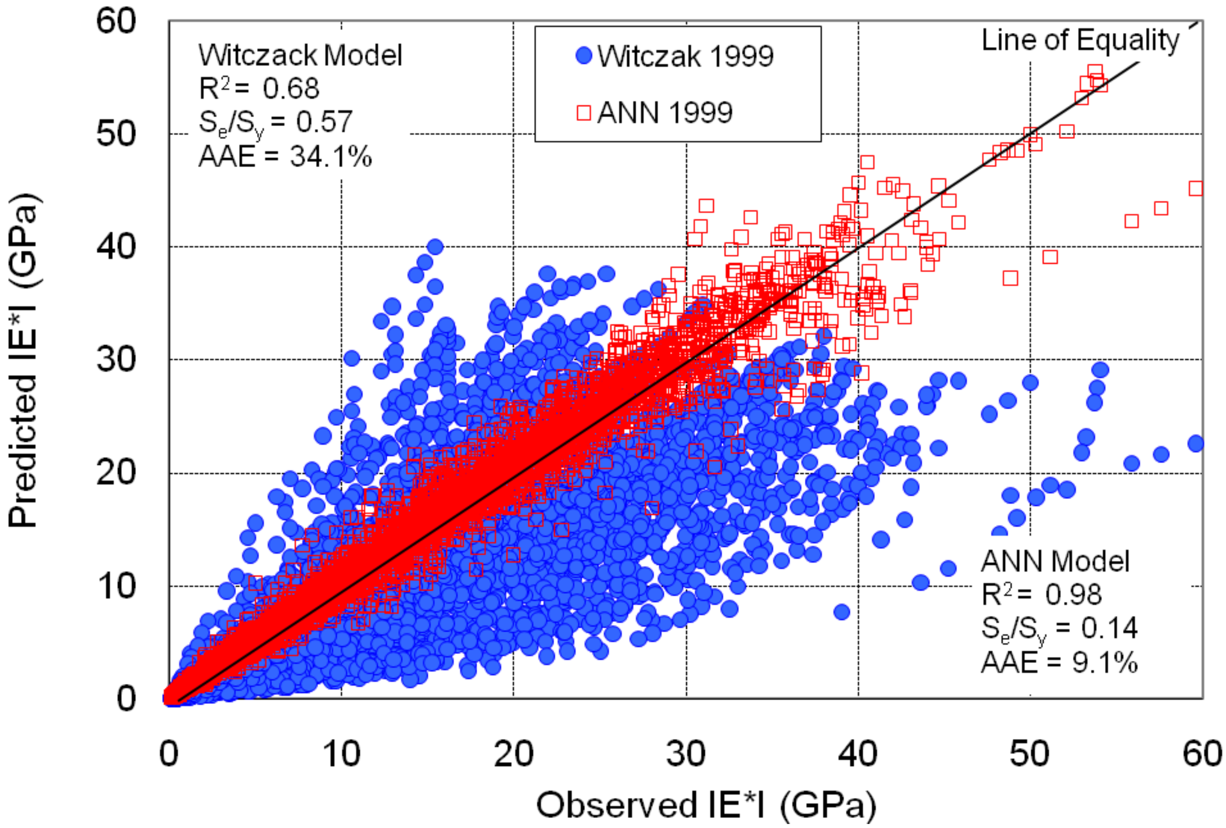

Figure G-1. Comparison between Witczak 1999 model and Artificial Neural Network (ANN) 1999 model.

where ω_{rm} and R are the coefficient varied by different climate zones;

$$a_T \text{ is shift factor } = 10^{\frac{-C_1(T_x - T_D)}{C_2 + T_x - T_D}}$$

$$\delta(x) = m(x) \times \frac{\pi}{2} (radians)$$

$$\left|G^*(x)\right| = \frac{G_g}{\left[1 + \left[\frac{\omega_{rm}}{\omega(x) \cdot a_T}\right]^{\frac{\log 2}{R}}\right]^{\frac{R}{\log 2}}} (Kpa)$$

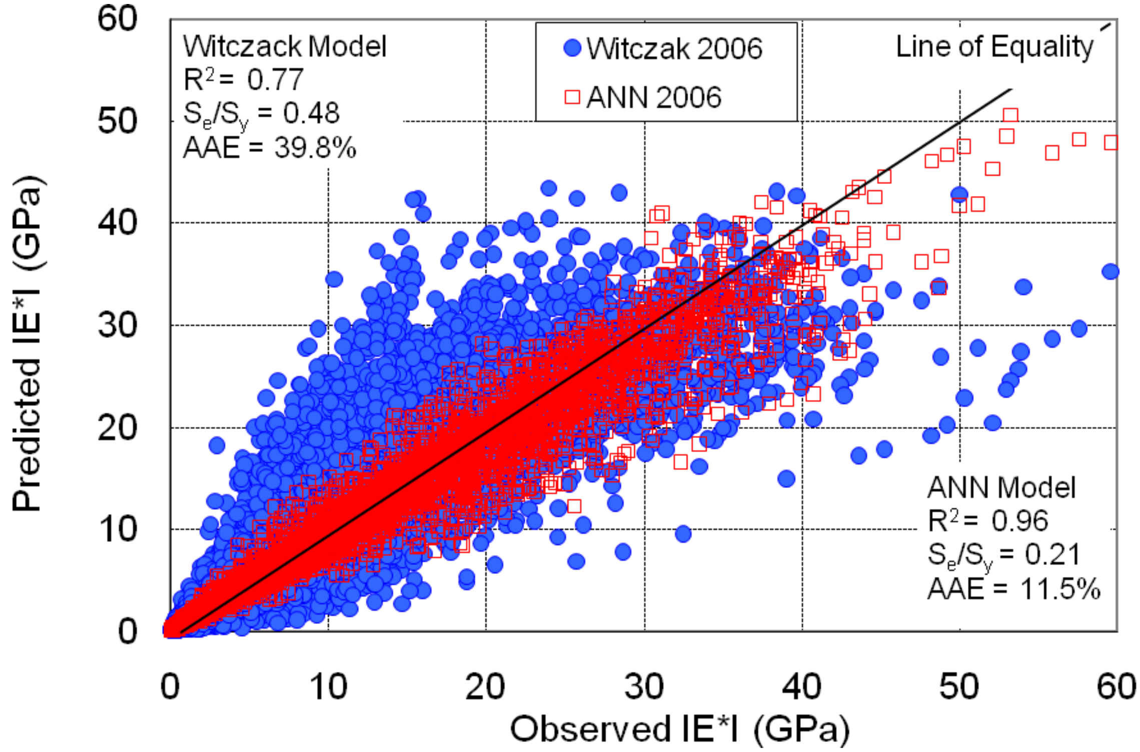

Figure G-2. Comparison between Witczak 2006 model and Artificial Neural Network (ANN) 2006 model.

$$G_g = \left|G^*(x)\right| \times \left[1 + \left[\frac{\omega_{rm}}{\omega(x)\cdot a_T}\right]^{\frac{\log 2}{R}}\right]^{\frac{R}{\log 2}} \quad (Kpa)$$

Dectermine Gg from Y:

Use the dynamic shear test temperature corresponding to the Y temperature.

Definition: $\omega(y) = 10\,\frac{rad.}{\sec.}$

Definition: $G^*(y) \times \sin\delta(y) \leq 5000\ kPa$

$$a_T = 10^{\frac{-C_1(T_y - T_D)}{C_2 + T_y - T_D}}$$

$$m(y) = m(\text{test temperature}) = \frac{\left[\frac{\omega_{rm}}{\omega(y)\cdot a_T}\right]^{\frac{\log 2}{R}}}{1+\left[\frac{\omega_{rm}}{\omega(y)\cdot a_T}\right]^{\frac{\log 2}{R}}}$$

$$\delta(y) = m(y) \times \frac{\pi}{2} (radians)$$

$$G^*(y) \le \frac{5000}{\sin\delta(y)} (Kpa)$$

$$G_g = \left|G^*(y)\right| \times \left[1+\left[\frac{\omega_{rm}}{\omega(y)\cdot a_T}\right]^{\frac{\log 2}{R}}\right]^{\frac{R}{\log 2}} (Kpa)$$

Comparison:

1. Compare G_g(x) with G_g(y), and choose the larger one
2. Compare this larger G_g with the regional G_g

If G_g,region > G_g,PGx-y > 0.5* G_g,region use G_g,PGx-y
Otherwise use G_g,region

The results of G_g at different PG grading and different climate zones are shown in the Table G-5. This table is one of our databases. When a user chooses level 2 and inputs a PG grading, this program will be able to select a G_g in the specified climate zone.

Table G-5. G_g database at different PG grading and climate zones.

PG		Test temp. (°C)	Gg (Gpa)			
X (°C)	Y (°C)		WF	WNF	DF	DNF
46	-34	10	0.79428	0.90583	1.570837	0.301117
46	-40	7	0.552329	0.90583	1.570837	0.531575
46	-46	4	0.861218	0.90583	1.570837	0.531575
52	-10	25	0.861218	0.751501	1.570837	0.531575
52	-16	22	0.861218	0.533385	1.570837	0.531575
52	-22	19	0.861218	0.90583	1.103578	0.531575
52	-28	16	0.861218	0.90583	1.570837	0.531575
52	-34	13	0.861218	0.90583	1.570837	0.404961
52	-40	10	0.79428	0.90583	1.570837	0.301117
52	-46	7	0.552329	0.90583	1.570837	0.531575
58	-16	25	0.861218	0.751501	1.570837	0.531575
58	-22	22	0.861218	0.533385	1.570837	0.531575
58	-28	19	0.861218	0.90583	1.103578	0.531575
58	-34	16	0.861218	0.90583	1.570837	0.531575
58	-40	13	0.861218	0.90583	1.570837	0.404961
64	-10	31	0.861218	0.90583	1.570837	0.531575
64	-16	28	0.861218	0.90583	1.570837	0.531575
64	-22	25	0.861218	0.751501	1.570837	0.531575
64	-28	22	0.861218	0.533385	1.570837	0.531575
64	-34	19	0.861218	0.90583	1.103578	0.531575
64	-40	16	0.861218	0.90583	1.570837	0.531575
70	-10	34	0.861218	0.90583	1.570837	0.531575
70	-16	31	0.861218	0.90583	1.570837	0.531575
70	-22	28	0.861218	0.90583	1.570837	0.531575
70	-28	25	0.861218	0.751501	1.570837	0.531575
70	-34	22	0.861218	0.533385	1.570837	0.531575
70	-40	19	0.861218	0.90583	1.103578	0.531575
76	-10	37	0.861218	0.90583	1.570837	0.531575
76	-16	34	0.861218	0.90583	1.570837	0.531575
76	-22	31	0.861218	0.90583	1.570837	0.531575
76	-28	28	0.861218	0.90583	1.570837	0.531575
76	-34	22	0.861218	0.533385	1.570837	0.531575
82	-10	40	0.861218	0.90583	1.570837	0.531575
82	-16	37	0.861218	0.90583	1.570837	0.531575
82	-22	34	0.861218	0.90583	1.570837	0.531575
82	-28	31	0.861218	0.90583	1.570837	0.531575
82	-34	28	0.861218	0.90583	1.570837	0.531575