Asian Journal of Chemistry Vol. 21, No. 4 (2009), 2632-2642

Neural Network Based Modelling of Soil Particle Diameters Under Varying Quantity of Sodium Hexametaphosphate

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In this study, the particle diameter of the soil was simulated and modelled by using artificial neural network method. In order to determine the particle diameter of the soil based on passing time, hydrometer reading, temperature of the solution and the quantity of the sodium hexametaphosphate, the quantity of the sodium hexametaphosphate 0, 10, 20, 30, 40, 50 and 60 were respectively selected. As pointed out in the Turkish Standard 1900, the soil particle diameters in the solution prepared with 40 g sodium hexametaphosphate was taken as reference. It was found that the average soil grain diameter for 0 g sodium hexametaphosphate was about 4.5 times bigger than the reference grain diameter, for 10 g was 3.9 times, for 20 g 3.46 times, for 30 g 2.12 times bigger. However, the hydrometer reading could be done only up to the 260th min for 50 g sodium hexametaphosphate and for 60 g sodium hexametaphosphate the hydrometer couldn't be read. The relationships between experimental results and artificial neural network (ANN) model exhibited good correlation. The correlation coefficients square were found as $R^2 = 0.99$ for training set and $R^2 = 0.94$ for testing set with ANN. Based on the results of the study, it could be said that the ANN method could be used for modelling of the particle diameter of the soil according to the passing time, hydrometer reading, temperature of the solution and the quantity of the sodium hexametaphosphate.

Key Words: Artificial neural network, Hydrometer test, Particle diameter, Sodium hexametaphosphate.

INTRODUCTION

Being able to measure the soil grain diameter, which is smaller than 0.075 mm, is highly important for soil research; especially classification of the soil and for drawing the granülometrik curve correctly, *etc.* To determine the soil grain diameter, the most popular techniques are the hydrometer and the pipette methods[1]. For hydrometer testing 151H and 152H hydrometers defined in the ASTM E 100 are used[2]. In these methods, the diameters of the soil particles are calculated by using Stoke's Law. Sodium hexametaphosphate is the most popular solvent ($NaPO_3$) used to prevent the soil particles flock with together in the suspension. The hydrometer method provides multiple measurements in the same suspension[3] and ASTM[4]. For soil particles, the mass-size form of the equation used in this study is expressed as described by Tyler and Wheatcraft[5] and Frank[6] for the determination of the density of liquids for the testing of hydrometers. Several papers[7-9] have been devoted to the interactions between sodium hexametaphosphate and clay. Kura and Oashi[10] found that hexametaphosphate anion forms with calcium a strong 1:1 complex. The hexametaphosphate anions interact with the exposed atoms of aluminium, giving a complexed anion. Several investigations[3,11] have been devoted to the analysis of the behaviour of sodium hexametaphosphate in water. Sodium hexametaphosphate ($NaPO_3$) is a deflocculating widely used in clay industry[12]. It exerts a deflocculating action increasing the negative charge on the clay micelles being adsorbed as an anion[13,14]; Lagaly[15] investigated the effect of soda addition on the rheological properties of bentonit. Volzone and Garrido[16] studied the effect of Na_2CO_3 on several Argentine bentonite. Buchan *et al.*[17] obtained a detailed particle size distribution by using sieves and sedimentation of dispersed particles in a liquid[5,18,19]. Young *et al.*[20] and Bittelli *et al.*[21] used wet sieving, pipette and light-diffraction techniques in order to obtain particle size distribution of 19 soils.

Huertas *et al.*[22] studied the dissolution phenomena in an aqueous suspension of kaolinite at different pH of the solution. Yildiz *et al.*[23] investigated the influence of NaCl, Na-hexametaphosphate and pH on the rheological behaviour of the original and the activated Kütahya bentonite suspensions.

Hwang *et al.*[24] adjusted several models to experimental data. Filgueira *et al.*[25] presented an explicit relationship between time, soil suspension density and the fragmentation fractal dimension applied to particles with the fractal mass-size distribution. Fernanda *et al.*[9] assessed the effects caused by the addition of sodium hexametaphosphate to a standard kaolin suspension and compared the results with those obtained employing a kaolin.

In presented study, the effect of varying quantity of sodium hexametaphosphate ($NaPO_3$) to the soil particle' diameters were investigated as experimental and ANN method.

EXPERIMENTAL

The sample used in this study was taken from a brick factory's stocks randomly in Düzce. To determine soil particle' diameters that are smaller than 0.075 mm hydrometer test was conducted. The sodium hexametaphosphate was used as a solvent in the hydrometer tests. 151H type hydrometer was used in these tests. To determine the particle's microstructure, Olympus BX51 microscope was used. The sample was placed on to the micro slide with a drop of entellan and covered with the lamel. The obtained images from the microscope were enlarged 100 times for the sample and these images were shown in Fig. 1.

XRD analysis was also performed for the chemical composition of the sample and the results are given in Table-1.

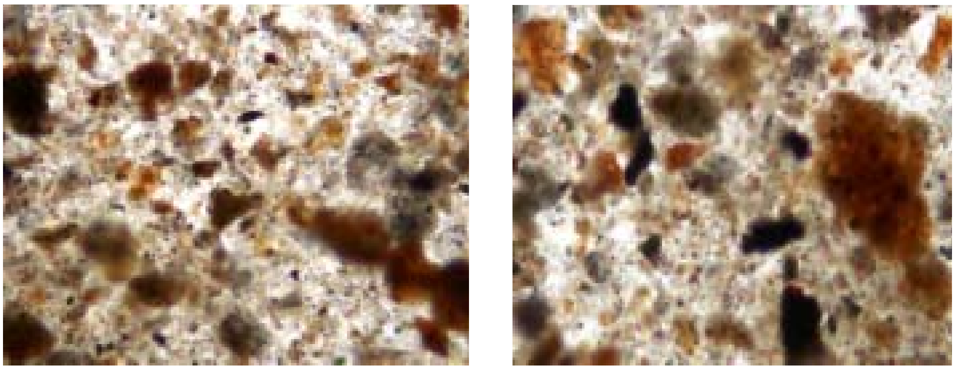

Fig. 1. Images of the sample obtained from the microscope enlarged 100 times

TABLE-1
XRD ANALYSIS RESULT FOR SAMPLES

Al_2O_3	SiO_2	Na_2O	K_2O	CaO	Fe_2O_3	MgO	SO_3	LOI	Total
20.73	51.82	0.74	3.71	3.74	6.50	1.74	1.19	9.40	99.57

According to the XRD, investigation there was montmorillonite, quartz, clinochlore, illite and calcite in clay mineral structure.

One of the most popular techniques is the hydrometer method based on the 'Stokes Law' which employs the relationship between time, travel distance and a coefficient named K (for solution temperature and sample's specific gravity). In the hydrometer test, it was found that the specific gravities of the soil particles were equal. In this test method, the bigger particles settling more quickly than the small particles. Stoke's Law was stated as below eqn. 1;

$$D = K\sqrt{\frac{L}{T}} \quad (1)$$

where; D = Radius of a spherical particle, (diameter of the equivalence sphere) mm; K = Coefficient (for solution temperature and specific gravity of soil sample); L = The travel distance of the spherical particle settling, (cm); T = Time (s).

Preparation of the experiments samples: The weight of the samples after passing through 0.075 mm (No. 200) sieve were 30 g in the hydrometer tests. Each samples placed into the glass pot and sodium hexametaphosphate ($NaPO_3$) was added and then mixed with a glass robe to wet for 5 min. The solution was left to dissolve all of the adhered soil particles in desiccators for 16 h. The samples were taken from the desiccators and after mixing them, they were poured into the mixer. Then, pure water was added to the samples about 2/3 ratio of the mixer and the mixer was fixed to its place and the solution was mixed for 1 min. The mixed solution was poured out to the glass measure and the pure water was filled to 1000 mL. Then, this measure was shaken for 1 min and started immediately to test. Hydrometer reading and temperature of the suspension were measured for each passing time for all of the hydrometer tests for varying quantity of sodium hexametaphosphate.

Hydrometer test results: Hydrometer test results were grouped and tabulated according to the quantity of the sodium hexametaphosphate and passing times. The particles' diameter was shown as × 10^{-3} in table. Nevertheless, when 50 g sodium hexametaphosphate was added in to the solution, the hydrometer reading could be done only for 260th min and for 60 g sodium hexametaphosphate, hydrometer reading could not be done. The calculated particle diameters according to the passing times, hydrometer reading and temperature of the suspension values were shown for 0, 10, 20, 30 and 40 g sodium hexametaphosphate (Table-2).

TABLE-2
CALCULATED PARTICLE DIAMETERS ACCORDANCE TO THE PASSING TIMES, QUANTITY OF THE SODIUM HEXAMETAPHOSPHATE, HYDROMETER READING AND TEMPERATURE OF THE SUSPENSION

Hydrometer test parameters	Passing time (min)										Quantity of sodium hex. (g)
	0	1	2	5	10	15	30	60	120	260	
Hydrometer reading	1.02	1.017	1.014	1.012	1.007	1.005	1.004	1.003	1.002	1.001	
Temperature of the suspension (ºC)	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.4	18.5	18.8	0
Particles diameter (×10^{-3}) mm	–	47.66	34.74	22.39	16.56	13.75	9.80	6.98	4.97	3.25	
Hydrometer reading	1.024	1.022	1.021	1.020	1.019	1.019	1.018	1.016	1.015	1.008	
Temperature of the suspension (ºC)	19.6	19.6	19.3	19.3	19.6	19.9	19.9	20.3	20.6	21.2	10
Particles diameter (×10^{-3}) mm	–	42.37	30.39	19.46	13.90	11.40	8.10	5.81	4.14	2.99	
Hydrometer reading	1.032	1.031	1.030	1.029	1.028	1.028	1.026	1.025	1.023	1.022	
Temperature of the suspension (ºC)	19.4	19.2	19.1	19.4	19.2	18.9	18.7	19.8	19.8	20.2	20
Particles diameter (×10^{-3}) mm	–	37.23	26.80	17.19	12.35	10.17	7.41	5.25	3.81	2.60	
Hydrometer reading	–	–	1.039	1.038	1.035	1.034	1.033	1.031	1.030	1.028	
Temperature of the suspension (ºC)	18.7	18.9	18.5	19.1	18.4	19.1	18.7	19.5	19.9	20.6	30
Particles diameter (×10^{-3}) mm	–	–	23.09	14.62	11.10	9.14	6.47	4.88	3.44	2.38	
Hydrometer reading	–	–	–	–	1.390	1.380	1.036	1.035	1.033	1.029	
Temperature of the suspension (ºC)	18.3	18.3	18.2	18.2	18.3	18.2	18.2	18.4	18.6	19.1	40
Particles diameter (×10^{-3}) mm	–	–	–	–	10.38	8.54	6.29	4.53	3.32	2.38	

– = Couldn't be calculated.

The effects of the solvent to the particle diameters were shown on the graph together with the reference solvent value (40 g) and the other calculated values for 1 h (Fig. 2).

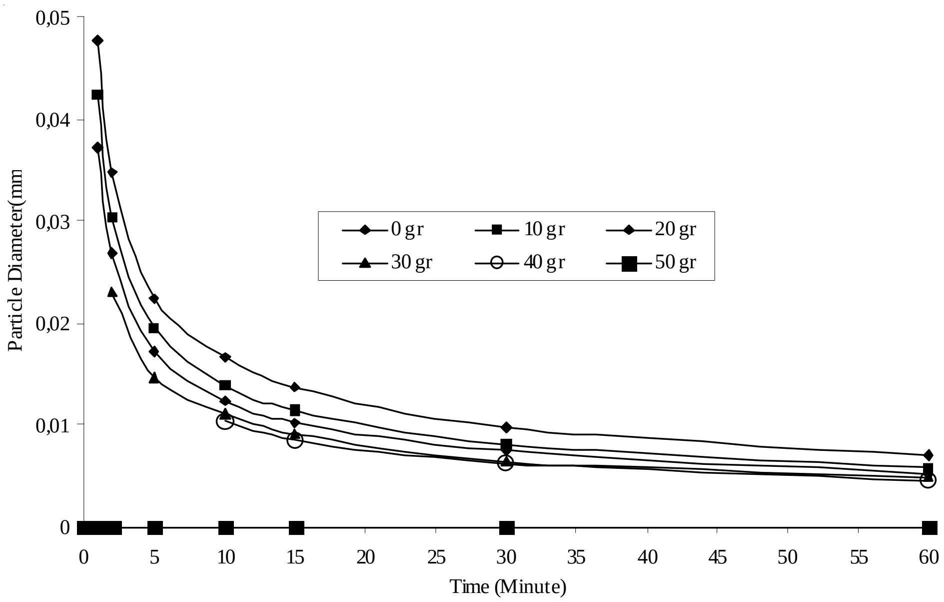

Fig. 2. Particle diameters and passing times according to the quantity of sodium hexametaphosphate

It was seen from this figure that, the biggest particle diameter was calculated as 48×10^{-3} mm for 0 g solvent and this value was obtained within 1st min. All the particle diameters were calculated for the 1st min for the other quantities of the solvent except for 30 g solvent, which was calculated for 2nd min. For 40 g solvent, the particle diameters were calculated for the 10th min and for 50 g, the particle diameters were calculated for only 260th min. The general appearances of the tendency lines on the graphs are looks like with together.

Artificial neural networks (ANN): A general structure of a multi-layer ANN was shown in Fig. 3. Such a neural network contains three layers: input layer, hidden layer(s) and output layer[26]. Each layer is composed of several neurons. The number of neurons in the input and output layers depends on the system dynamics and the desired accuracy. All the neurons in adjacent layers are interconnected. The strength of the interconnection was determined by weighting vector of neural network[26]. Each neuron performs two functions as shown below Figs. 3 and 4. The first is to sum all the inputs from lower layer based on their weighting factors as given in eqn. 1. The second is to process this sum by a nonlinear sigmoid function as shown in eqn. 2. The input and output neurons may not contain nonlinear functions. The basic equations described the dynamics of each neuron were given in below:

$$net_j = \sum_i W_{ij} O_i \quad (2)$$

$$O_j = f\left(net_j + \theta_j\right) \quad (3)$$

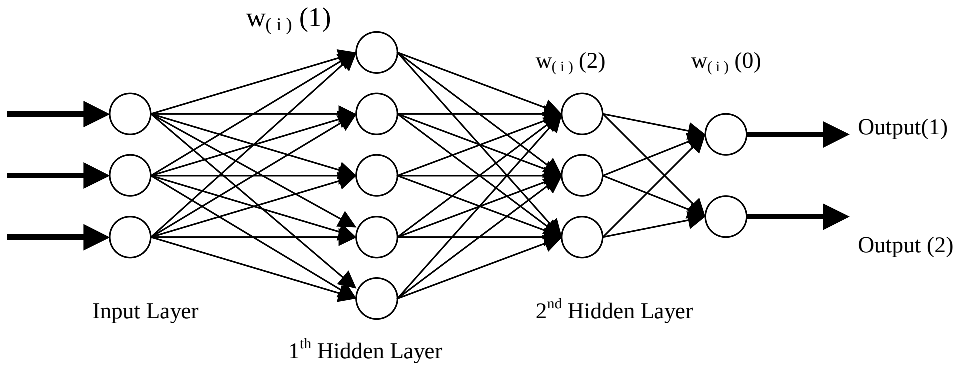

Fig. 3. General structure of the multi-layer neural networks

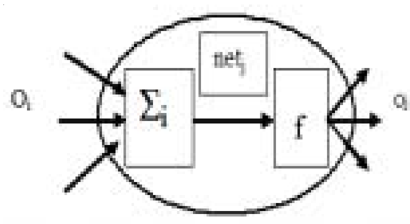

Fig. 4. A single neuron structure

where; W_{ij} = weight between the jth neuron and the ith neuron in two adjacent layers; θ_j = threshold of the jth neuron; O_i = output of the ith neuron; O_j = output of the jth neuron; f(.) = sigmoid function.

Training of neuron network: The most common method of neural network training is back error propagation algorithm. The algorithm is based on the gradient search technique that minimization process is done by adjusting the weighting vector of the neural network[27]. Let the objective function (E) could be write as;

$$E = \frac{1}{2}\sum_{p}\sum_{j}\left(T_{pj} - O_{pj}\right)^2 \quad (4)$$

where, T_{pj} = target output of neuron j due to input pattern p; O_{pj} = neural network output of the same neuron and for the same pattern.

Minimizing eqn. 3 leads to a sequence of update of the weight vector. The weights of the interconnections between two adjacent layers could be updated based on the following formula:

$$W_{ij}(k+1) = W_{ij}(k) + \eta\frac{\delta E}{\delta W_{ij}(k)} + \alpha\,\Delta W_{ij}(k) \quad (4)$$

where; k = iteration number, h = step size, a = momentum gain and ΔW_{ij} (k) = weight change based on the gradient of the cost function[28-30].

Application of the developed ANN model: Developed the ANN model has 5 neurons (variables) in the input layer and one neuron in the output layer as illustrated in Fig. 5. One hidden layer with 8 neurons was used in the architecture because of its minimum percentage error values for training and testing sets.

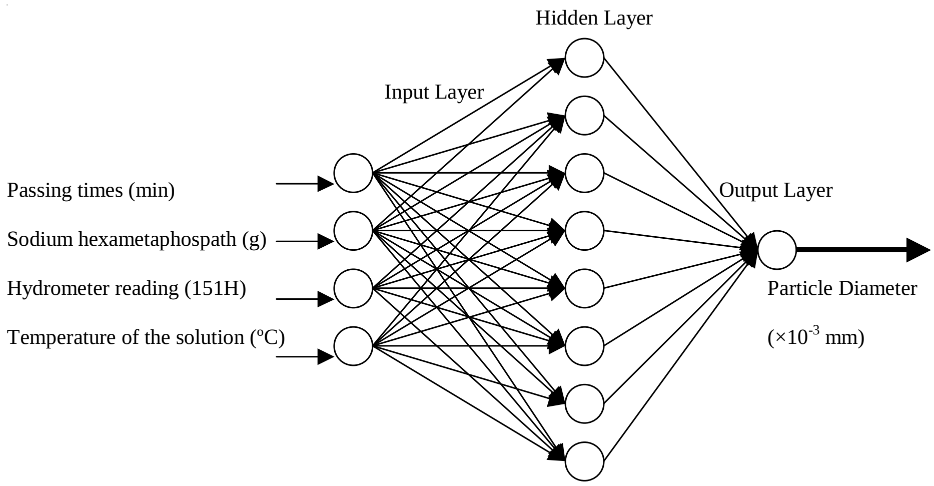

Fig. 5. Developed ANN model architecture

Some of the architectures with different number of neurons studied here in hidden layer and their correlations with experimental results investigated. While modelling networks, passing time (min), sodium hexametaphosphate (g), hydrometer reading (151H) and temperature of the solution (°C) were used as inputs and particle diameter (10^{-3} mm) was used as output.

For training set 56 samples (80 % of all samples) were selected and the residual data 14 samples (20 % of all samples) were selected as test set. The values of the training and test data were normalized between 0 and 1 by using in below equation.

$$F = (F_i - F_{min})/(F_{max} - F_{min}) \tag{5}$$

where, F = represents the normalized value, F_i = represents i. value of the measured values, F_{max} and F_{min} represent maximum and minimum values of the measured values.

The back-propagation learning algorithm was used in feed-forward with one hidden layer. Logarithmic sigmoid transfer function was used as the activation function for hidden layers and output layers. The learning rate and momentum are the parameters that affect the speed of convergence of the back-propagation algorithm. Stopping criteria is employed 5,000 for training on all networks. A learning rate of 0,001 and momentum 0,1 were fixed for selected network after training and model selection was completed for training set. The trained networks were used to run a set of test data. All of the developed networks were compared with experimental results. The developed ANN has the best correlation with the experimental results both training and testing sets that are displayed in Figs 6-9.

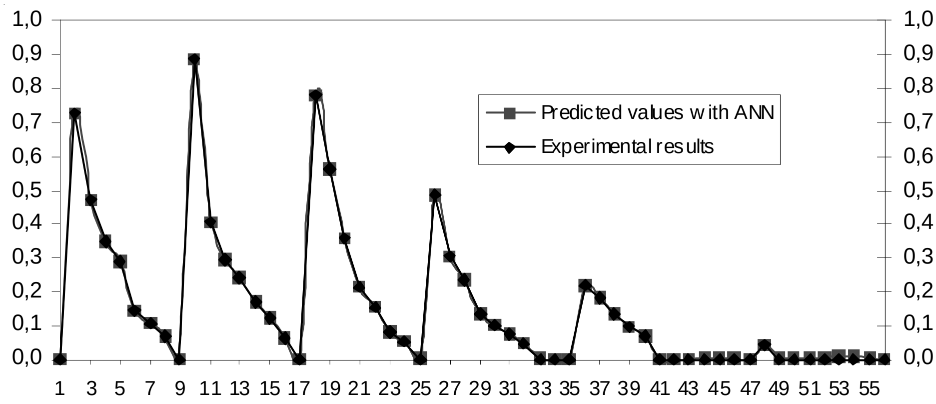

Fig. 6. Matching the experimental and predicted values for training set on particle diameter

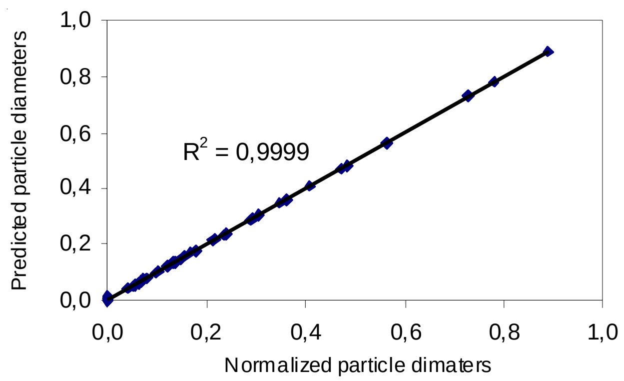

Fig. 7. Correlation coefficient between normalized and predicted particle diameters for training set

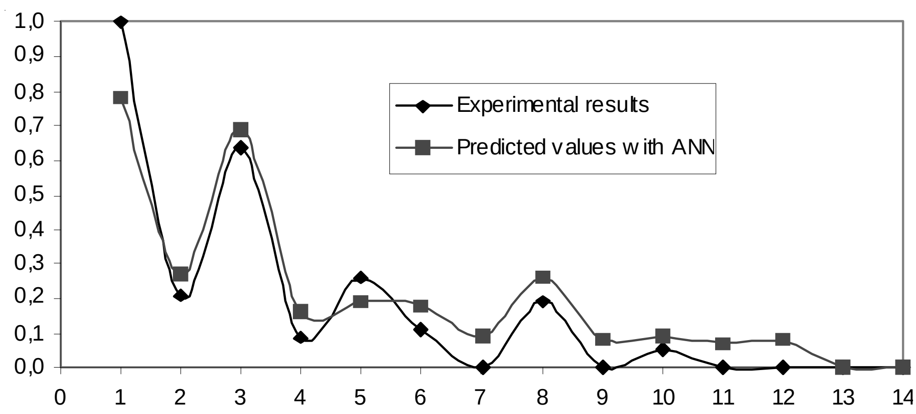

Fig. 8. Matching the experimental and predicted values for testing set on particle diameter

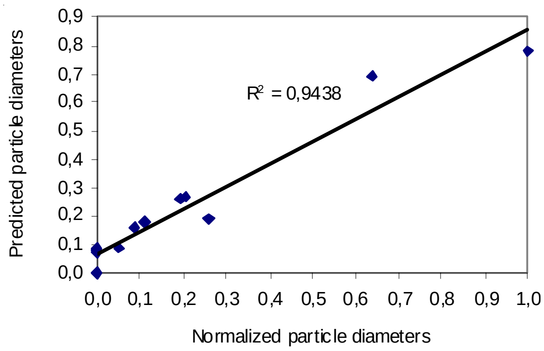

Fig. 9. Correlation coefficient between normalized and predicted particle diameters for testing set

RESULTS AND DISCUSSION

In this study, it was seen that the quantity of the sodium hexametaphosphate directly affects particle diameters of the soil. As pointed out in the TS 1900[31], the soil grain diameter in the suspension prepared with 40 g sodium hexametaphosphate was taken as reference. It was found that the average soil grain diameter for 0 g sodium hexametaphosphate was about 4.5 times bigger than the reference grain diameter, for 10 g was 3.9 times, for 20 g 3.46 times, for 30 g 2.12 times bigger. However, the hydrometer reading could be done only up to the 260th min for 50 g sodium hexametaphosphate and for 60 g sodium hexametaphosphate the hydrometer couldn't be read. It was clearly seen that sodium hexametaphosphate prevented adhering of the particles together. Increasing the quantity of the sodium hexametaphosphate increased the specific gravity of the solution. As a result, when 50 g sodium hexametaphosphate was used, hydrometer reading could be done only for 260th min. When 60 g sodium hexametaphosphate was used, hydrometer did not sink into the solution and so there were no hydrometer readings.

When the solution was prepared with 40 g sodium hexametaphosphate (It was pointed out in Turkish Standard 1900 as reference[31]) and hydrometer reading steps was chosen as 1, 2, 5, 10, 15, 30, 60, 120 and 260 min, hydrometer readings couldn't be done for 1, 2, 5 and 10th min. Therefore, hydrometer test readings were completed with about 44 % of the readings missing. When the solution was prepared with 30 g sodium hexametaphosphate, the hydrometer reading couldn't be done for only first minute. Therefore, the hydrometer test reading was completed with about 11 % missing. However, when the suspension was prepared with 20, 10 and 0 g sodium hexametaphosphate, the hydrometer reading could be done for all time steps. Therefore, it could be said that the quantity of the sodium hexametaphosphate should be less than 40 g for all the hydrometer readings.

If the hydrometer tests are wanted to be completed with at least limited number of missing readings, quantity of the sodium hexametaphosphate could be selected 30 g. In this way, calculated particle diameters could be used directly for 2th, 5th and 10th min, for 15th, 30th, 60th, 120th and 260th readings the calculated particle diameters could be turned to the reference particle diameter by multiplying with proposed coefficients (which has to be calculated for 40 g sodium hexametaphosphate).

If the hydrometer tests are wanted to be completed with any missing reading, the quantity of the sodium hexametaphosphate could be select as 20 g, 10 g or 0 g. In this way, calculated particle diameters could be use directly for 1th, 2th, 5th and 10th min. The calculated particle diameters for 15th, 30th, 60th, 120th and 260th readings could be turned to reference particle diameter by multiplication with proposed coefficients (Table-3).

TABLE-3
PROPOSED CORRECTION COEFFICIENTS FOR PARTICLE DIAMETERS TO TURNING REFERENCE VALUES

Passing time (min)	Quantity of sodium hexametaphosphate (g)				
	0	10	20	30	40 (reference)
1	Use read value as is	Use read value as is	Use read value as is	Unreadable	Unreadable
2	Use read value as is	Use read value as is	Use read value as is	Use read value as is	Unreadable
5	Use read value as is	Use read value as is	Use read value as is	Use read value as is	Unreadable
10	0.63	0.75	0.84	0.94	Unreadable
15	0.62	0.75	0.84	0.93	1.00
30	0.64	0.78	0.85	0.97	1.00
60	0.65	0.78	0.86	0.93	1.00
120	0.67	0.80	0.87	0.97	1.00
260	0.73	0.80	0.92	1.00	1.00
Missing read ratio (%)	0.00	0.00	0.00	11.11	44.44

In this work, an ANN model has been developed to determine the particle diameter under varying quantity of the sodium hexametaphosphate. Despite the particle diameters are nonlinear; the proposed ANN approach has ability to model the particle diameter. This methodology could helped the prediction of the particle diameter of the soil and the other same materials.

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(*Received*: 7 March 2008; *Accepted*: 9 January 2009) AJC-7100