EXPERIMENTAL STUDIES ON FROZEN SOIL

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
GEOTECHNICAL ENGINEERING

Submitted by:

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CANDIDATE'S DECLARATION

I, Kshitij Gaur, Roll No. 2K19/GTE/07, student of M.Tech (Geotechnical Engineering), hereby declare that the project dissertation entitled "Experimental Studies on Frozen Soil" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition. Responsibility of any plagiarism issue stands solely with me.

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Place: Delhi (**KSHITIJ GAUR)**

Date : August 2, 2021

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CERTIFICATE

I hereby certify that the Project Dissertation entitled “Experimentatal Studies on Frozen Soil” which is submitted by Kshitij Gaur, Roll No. 2K19/GTE/07, to Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by him under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
Date : AUGUST 2, 2021.

(ANIL KUMAR SAHU)
PROFESSOR & SUPERVISOR
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I would personally like to thank Prof. Anil Kumar Sahu Sir for his patience, insightful comments, practical advice and motivation which helped me tremendously in the project work. Without his guidance and support, this project would have not been completed.

In the times like this where whole world is fighting with the pandemic of COVID-19, I feel really blessed and thankful to my supervisor for his kind nature that helped and eased out the working of this project.

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ABSTRACT

Various studies have been carried out for soils at normal room temperature but the studies on frozen soils are meagre. For every construction, soil investigation is the most important and the primary step for a site selection. For constructions at normal room temperature, there are plenty of experimentation and research data on soil is available. But lack of research data exists for colder regions, where the ambient temperature is below zero degree Celsius for most of the time. It is therefore the need to study soil under frost condition to get a better idea about the behaviour of frozen soils. There are few research available on the mechanical behaviour of frozen soil but no study on the very basic parameters like void ratio, bulk density, porosity, and the degree of freezing. Also, how these parameters change as the soil temperature changes from normal room temperature to negative values. The main emphasis is on the study and experimentation on frozen soil and to formulate different relationships amongst individual soil parameters at various temperatures. The methodology used is to model the soil surface (open grounds in colder regions) by taking sand as the soil after sieving. The model samples are taken into beakers with different bulk densities to replicate real site condition in the freezer. Then by calculating factors like density, porosity, void ratio, etc at different negative temperatures (-5, -10, -15, -20 degree Celsius) and forming relationship with same parameters with that on room temperature. The experimental data obtained is used in “Eureqa software” that will utilize the input so provided and will find mathematical relationship that exist in the soil parameters.

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List of Symbols, abbreviations

γ Bulk density of soil
γ' Bulk density of frozen soil
C_c Coefficient of curvature
C_u Coefficient of uniformity
F Degree of freezing
H_t Height
h Height of sand in beaker
% Percentage
x Percentage change in void ratio
y Percentage change in bulk density
z Percentage change in porosity
n Porosity of soil at room temperature
n' Porosity of frozen soil
G_s Specific gravity of soil solids
T Temperature
γ_s Unit weight of soil solids
γ_w Unit weight of water
e Void ratio of soil at room temperature
e' Void ratio of frozen soil
V_I Volume of ice
V_s Volume of soil solids
V_v Volume of voids
V_w Volume of water
w Water content
W_t Weight
W Weight of soil at room temperature
W_s Weight of soil solids
W_w Weight of water
W' Weight of frozen soil
W_I Weight of Ice
SW Well graded Sand

Chapter 1: Introduction

The following chapters will help to understand frozen soil in a more better way while calculating and comparing soil parameters at different temperatures and establishing relationships among them. The parameters will be calculated at different temperatures based on the data obtained from the laboratory.

1.1 General

The world is expanding in terms of development and construction every day. From construction of high rise bridges to under water structures, the modern civil engineering is leaving no page unturned. The constructions on glacial soils or frozen soils is of concern as the detailed studies are not available similar to that of soils under normal room temperature. The glacial soils behave in a different manner than the usual soil at normal temperature. The properties vary significantly as the temperature changes from normal room temperature to negative values, tested and observed by Baker and Spaans [5]. All the experiments and relations are established for normal soils at room temperature while glacial soils have not been studied in detail as of now. The main objective is to study the behaviour of glacial soils or frozen soil and establish relationships between different characteristics of soil with variation of temperature, studied by Li et al. [15]. Just for example, when the voids of the soil get increased the chances of inter-connectivity also increase and thereby permeability of soil increases, observed by Zhu and Carbee [24]. But in case of glacial soil, the voids get occupied by ice instead of water, which acts as a barrier to flow of water and thereby permeability decreases. This example gives the idea that the governing factors and the formulae applicable to soil under normal room temperature doesn't hold good for frozen soil. In the present study, an attempt has been made to obtain actual data of soil under both room temperature as well as under frozen state. Then using those data as an input to "Eureqa" software[11] which will give the hidden mathematical relationship that exist between the parameter under varying temperature. For example, the porosity of soil sample will be calculated at both room temperature as well as at frozen state. Then by knowing the water content and temperature of frozen soil the relationship can be established. This will be done by taking frozen soil porosity to be a function of water content, porosity at room temperature and frozen soil temperature. The Eureqa software will then give the relationship between both the porosity of same soil sample with temperature variable. This will help geotechnical engineer to know different property of frozen soil if its data is given for room temperature.

1.2 Objectives of the study

The project deals with the following objectives:

- To classify the soil.
- To establish the relationship between parameters of unfrozen and frozen soil based on variation in temperature.
- To utilize the results for practical purposes.

1.3 Organisation of chapters

The following chapters have been incorporated in this project report:

In chapter 1, the project title have been introduced in detail. The main objectives and outlines of the work have been discussed.

In chapter 2, the study of the research papers and their findings are mentioned. After following various research papers and books, research gaps has been founded and mentioned.

In chapter 3, the materials used in this project and the methodology followed have been described.

In chapter 4, the results obtained in this project have been listed and discussed in detail, followed by solving an example using the formulae obtained.

In chapter 5, the conclusions have been summarized and the recommendations for future work is mentioned.

Chapter 2: Literature review

2.1 Introduction

The purpose of this research is to study the behaviour of glacial soils or frozen soil and establish relationships between different characteristics of soil. By going through several research papers on frozen soil, the lack of knowledge about basic parameters of iced soil can be observed. The parameters like void ratio, bulk density, degree of freezing, porosity of frozen soil and there study is absent creating a void that needs to be filled to get a complete idea about frozen soils. Glacial soils and soils which are frozen for a majority duration of the year can be dealt with the formulae so obtained in this research.

2.2 Literature review

Frozen soil is defined as the soil whose water content is converted partially or fully into ice. As the temperatures keeps going down, the water present in the soil converts into crystalline form and slowly it changes to solid ice, thereby, forming fully frozen soil. Glacial or frozen soils behaves in a different way then the soil at normal room temperature as observed by Smith et al. [20] and suggest that in depth study on frozen soil required. Andersland and Ladanyi [3], performed certain tests and observed that the surface area, expandable clay lattice and the activity ratio, was deviated to what assumed for frozen soils. Therefore, following different mechanism. Viklander [22] conducted triaxial drainage shearing test on remolded silt samples with different cycle times of freeze-thaw. It was concluded that the cohesion of remolded silt increases compared with that of non-freeze-thaw group after freeze-thaw cycle. This suggests that frozen soil are more cohesive in nature compared to unfrozen soil. Janoo and Shoop [13], grouped undisturbed fine-grained soil and remoulded them into saturated soil samples of various degrees, and measured the effects of water content and confining pressure on the mechanical properties of fine-grained remolded soil by applying different confining pressures on them. This article reference in Rock And Soil Engineering analysis method for silty clay, and in strict accordance with the Geo-technical Test Method Standard to test the soil sample. Edwards and Cresser [9], performed testing of the soil sample density, water content, particle composition, the basic parameters such as liquid limit and plastic limit is important. Through the analyzing of Grey Theory, this article finally analyses the shearing strength of the silty clay change rule, provide the reference to the following seasonal frozen area subgrade problems to lay the foundation, observed by Altuhafi and Baudet [1]. Tulaczyk et al. [21], inferred those studies on the behaviour of glacial sediments are limited, and those work are concentrated only on investigating ultimate strength of frozen soil and mechanical behaviour. This shows the importance of studying frozen soil mechanics as a different branch. An elaborative model considering the particle breakage and its plastic shear mechanisms is established by Chang et al. [8]. The model showed the failure planes of frozen soil.

The shear strength and elastic modulus of frozen soil as studied by Khoroshilov et al. [14], observed the shear strength parameters of frozen soil. Also, the influence of freezing and thawing cycles on wind erosion strength of black soil simulations done by Liu et al. [16]. Few other studies also include the three-dimensional compressibility anisotropy of a thawing soil and is determined by the cryogenic constitution of the frozen soil and affects primarily the value of the coefficient of thawing, Bakulin and Zhukov [6]. The mechanical properties of frozen soil, the stress-strains are discussed deeply in Qi et al. [18] the mechanical properties are studied in detail. Shen et al [19], studied the stress paths in frozen soil and how the stress path affects the mechanical properties of frozen soil. The books on the chemical properties, Edwards and Cresser [9], shows that after temperature of soil drops and reaches negative temperature, the chemical composition of frozen soil is also changed and different bonds are formed with greater attraction force between soil particles and water. The mechanical properties of frozen soil studied by Merzlyakov [17] suggests that the properties differ to a great extent and different approach should be use to study the soil in frost state. The creep in frozen soil studied by Fish [12], where he studied the creep by applying different loads for long duration and noted the deformations occurred. Similiar studies done by Eranti and Lee [10] to study the creep in frozen soil. Andersland and Ladanyi [2] suggest that the frozen soil acts in a complete strange way as the results obtained by creep study were challenging and different than those on soil at room temperature.

Further, various research has been done on flow throw partially frozen soil. For example, hydraulic conductivity calculated by Azmatch et al. [4] and found that the hydraulic conductivity of soil decrease sharply as the water content is converted into ice which acts as a barrier to flow of water. Burt and Williams [7] also studied the hydraulic conductivity in partially frozen soil and found the same trend.

Research works are also done on fully frozen soils. For example, strength and deformation characteristics of fully frozen soil by Xu et al. [23] and plotted various stress-strain curves of frozen soil and estimated its strength. The thermal effects and strain rates are also studied by Zhu et al. [25] in which he studied the thermal effects causing thermal strain on frozen soil. Previously the research on frozen soil was done for the analysis of the mechanical, physical, biological and chemical properties, however the main motive of this study is to obtain the relationship between characteristics of soil like its porosity, void ratio and bulk density, at varying temperature is forming a void in the studies that needs to be fulfilled to get the knowledge about how these characteristics changes as the temperature drops to negative values.

2.3 Research Gap

By going through various research papers and textbooks on frozen soil, the following research gaps came under light:

1. Lack of fundamentals of frozen soil: Frozen soils behave in a different way compared to the unfrozen soil. The basic formulae of normal soil for calculating its properties are not applicable for frozen soils. Therefore, its the need to understand frozen soil in a more detailed way similar to unfrozen soil. The gap is filled by establishing relationships to calculate the properties of frozen soil.
2. Lack of inter-relations: There are no formulae that relates the properties of frozen and unfrozen soil. In this study, this gap is filled by forming relationships of soil properties based on temperature variation.

Chapter 3 Materials & Methods

3.1 Materials and Equipment

1. Soil: locally available soil is used and sieve analysis is performed on it to classify the soil.
2. Beaker: Cylindrical borosil beakers are used to carry soil into it to create the samples.
3. Weighing balance: A digital weighing balance is used to measure weights of samples.
4. Deep freezer: It is used to freeze the soil sample. The temperatures used are -5, -10, and -15°C

3.2 Methodology

The methodology used in this project is simple and easy to understand. The soil is first oven dried to remove the natural water content of soil and then sieve analysis is done on the soil to find out the classification of soil. The soil available was found to be sand and it is used to find relationships between unfrozen and frozen state which can be further extended to other soil types as well. The soil is then mixed with certain amount of water(i.e., known water content) and then filled in 100ml cylindrical beakers with different bulk densities which can be obtained by temping different number of blows using a glass rod. Sample represents soil condition in open ground at normal room temperature. The sample is then placed in a freezer to replicate the temperature conditions of colder regions. In this study, the working temperatures are 25, -5, -10, -15, -20° Celsius which are achieved in a deep freezer in the laboratory. The soil factors like porosity, void ratio, bulk density, dry density, etc are calculated for frozen soil at above said temperatures. These are then related to the same properties under room temperature. For instance, porosity of frozen soil is a function of porosity at room temperature, water content and the temperature at which it is being calculated for. The degree of freezing is also be calculated using the same approach. After getting data of normal and frozen soil, different relations can be found using eureqa software.

3.3 Experimental Procedure

The test procedures performed in this experimental work is according to Indian Standard codes: IS 2720-2(1973), (IS-2720-PART-3-1980), ISO 11272:2017. The procedure is as follows:

A) Oven dry the soil at 105° Celsius for 24 hours as per **IS 2720-2(1973)**. Put this soil in plastic bags so that it may not get any moisture from surrounding as shown in Figure 3.1.

B) Take out samples from this soil bag. Sieve the soil for classification as shown in figure 3.2. For this project the soil gradation curve suggest the soil to be well graded soil as the value of C_c and C_u comes out to be 1.09 ad 8.33 respectively.

C) Let the dry weight of soil sample= W_s

Add known amount of water content (2%,4%,6%,8%,..,40%)

$w= (W_w/W_s)$ ……(1)

D) Separately, determine specific gravity(G_s) of soil solids using pycnometer test and relate it with equation (2) to get value of γ_s as shown in Figure 3.3. As per **IS-2720-PART-3-1980.**

$$Gs=(\gamma_s/\gamma_w) \quad ……(2)$$

Once, γ_s is calculated volume of soil solids will be further calculated by

$$\gamma_s=(W_s/V_s) \quad ……(3)$$

E) Now, calculate void ratio(e) as per IS : 2720 (Part 2)

$$e=(V_v/V_s) \quad ...…(4)$$

F) V_v can be calculated by first measuring the total volume(V_t) of soil sample having different bulk densities(γ_{t1}, γ_{t2}, γ_{t3}…) in measuring container as per **ISO 11272:2017** and then using:

$$V_v=(V_t - V_s) \quad ……(5)$$

G) Now, place the soil sample container in freezer for various temperatures to record data (-5,-10,-15,-20 degree Celsius) as shown in Figure 3.5.

H) After 24 hours, take the sample out and weigh it. Also measure heights at five different locations, and the average is taken as shown in Figure 3.4. Do this step as soon as possible to avoid error due to temperature change.

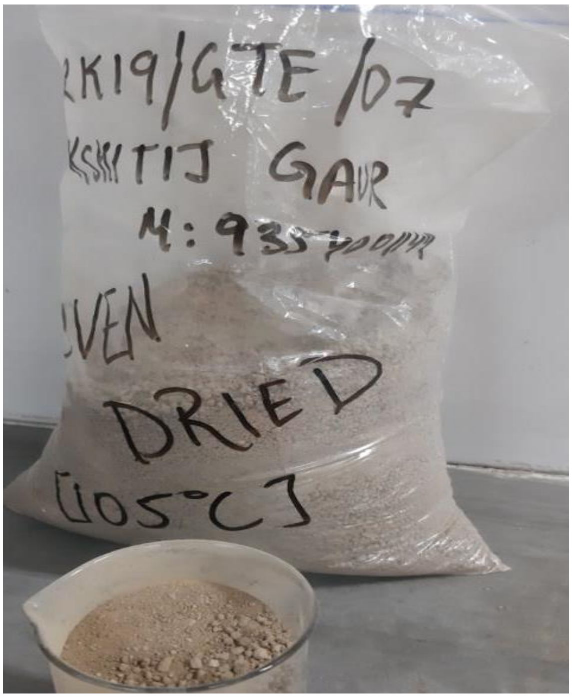


Figure 3.1: Oven dried soil

Figure 3.2: Soil sieving.

Figure 3.3: Pycnometer test

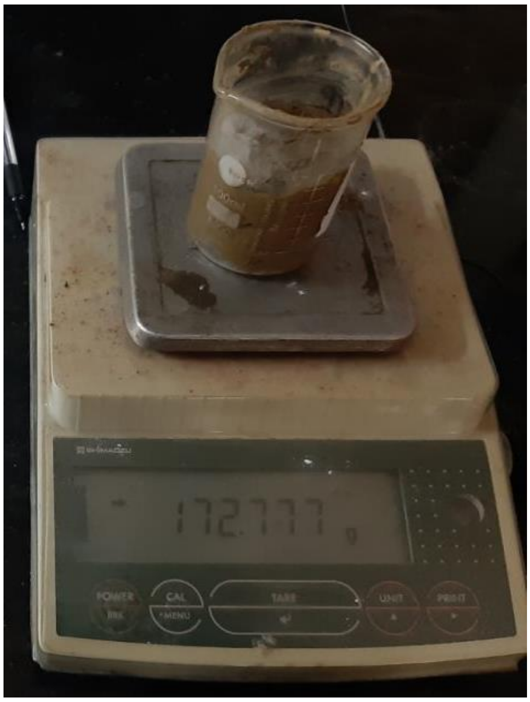


Figure 3.4: Frost soil sample weighing

Figure 3.5: Deep freezer with temperature controls.

I) Then the ice content of soil sample will be:

$$w' = (W_I / W_S) \quad \ldots\ldots..(6)$$

The water content will slowly change to ice content as the temperature is kept on decreasing. Therefore, the ice content is a function of initial water content and the temperature.

$$w' = f(w, T) \quad \ldots\ldots..(6A)$$

This ice content will reach a maximum value when all the water present in the soil gets converted into ice. The void ratio will also change as volume ice expands filling all the voids at first and then increasing the overall volume of soil sample as shown in Figure 3.6.

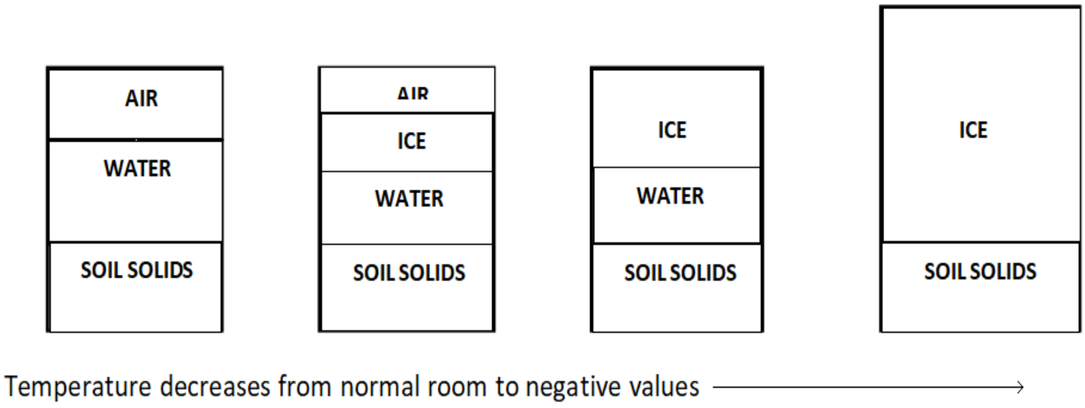


Figure 3.6: 4-Phase diagram of soil

J) Record the data of frozen weight of soil and the average height of frozen soil to form the observation tables.

K) Calculate void ratio, degree of freezing, bulk density, porosity of frozen soil from data so obtained for different temperature reading.

L) Utilize this raw data as input for Eureqa software and formulate different relationships by feeding both input and output parameter reading in the software.

3.4 Observations

The following observations were made during sieve analysis

Table 3.1 Sieve analysis observations

Sieve . No.	Diameter (mm)	Soil Retained (gm)	Accumulative Retain (gm)	% Mass Retain	% Passing
4	4.75	22.65	22.65	4.5426	95.4574
10	2.00	75.34	97.99	19.6526	80.3474
20	0.85	123.21	221.2	44.3633	55.6367
40	0.43	115.85	337.05	67.5979	32.4021
60	0.25	65.46	402.51	80.7264	19.2736
200	0.075	81.60	484.11	97.0919	2.9081
Pan		14.50	498.61		

In this project, the soil parameters at various temperature has been calculated. These parameters have been calculated using the data obtained in the laboratory by applying basic soil mechanics.

The observations and data recorded in lab are as follows:

1. The diameter of cylindrical beaker is 5cm.
2. The weight of dry soil taken for each reading is 100gm.
3. The least count of electronic weighing machine is 0.0001gm.
4. The least count of length measuring scale is 0.1cm.
5. The beakers are of different densities thereby resulting in different empty weights which are recorded accordingly in table 3.2.

Following are the readings recorded for unfrozen and frozen sand at different temperatures:

Table 3.2 Observation table for soil at room temperature

S. No.	Water content (%)	Empty wt. of cylinder (gm)	Wt. of dry sand (gm)	Ht. of sand [h] (cm)	Total volume (cc)
1	6	56.815	100	5.78	113.461
2	6	42.348	100	5.30	104.039
3	10	45.172	100	5.90	115.817
4	10	41.183	100	5.30	104.039
5	14	45.385	100	5.18	101.683
6	14	36.803	100	5.38	105.609
7	18	34.383	100	4.84	95.009
8	18	35.702	100	5.52	108.357
9	22	44.242	100	3.60	70.668
10	22	52.334	100	4.10	80.483
11	26	47.105	100	4.36	85.587
12	26	40.848	100	4.32	84.802
13	30	33.182	100	4.10	80.483
14	30	44.228	100	4.50	88.335

Chapter 4 Results and Discussion

4.1 Results

1. The soil gradation curve formed after sieve analysis is shown in figure 4.1.

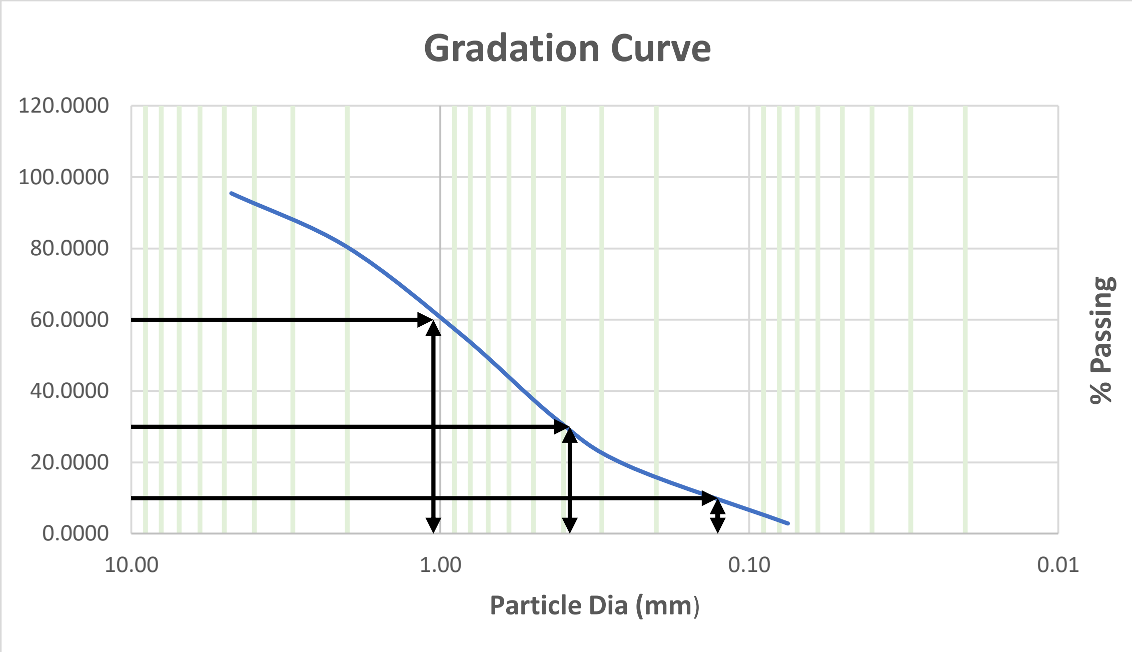


Fig. 4.1 Gradation curve for the soil.

2. The results obtained from sieve analysis are given in table 4.1.

Table 4.1 Results of soil gradation curve

Results					
% gravel	4.54	D_{60} (mm)	1.053063	$C_u = D_{60}/D_{10}$	8.33
% sand	92.56	D_{30} (mm)	0.381062	$C_c = D_{30}^2/D_{10}{*}\ D_{60}$	1.09
% fines	2.90	D_{10} (mm)	0.126385		

The soil type is found to be well graded sand (SW) as the coefficient of uniformity is greater than 6 (i.e., $C_u > 6$) and coefficient of curvature is greater than 1 (i.e., $C_c > 1$).

4.1.1 Weight Function

The weight of frozen soil can be found if weight of same soil at room temperature, its water content and the temperature at which weight is to be determined is known. By entering the data obtained in laboratory shown in table 4.2, Eureqa software gives the relationships that may exists between the data set. The weight function would be:

$$W' = f(W_s, w, T) \qquad \ldots\ldots..(7)$$

where w is the water content of soil at room temperature.

W_s is the weight of soil solids at room temperature

T is the temperature of frozen soil.

Table 4.2 Weight of dry vs frozen soil at given temperature and water content.

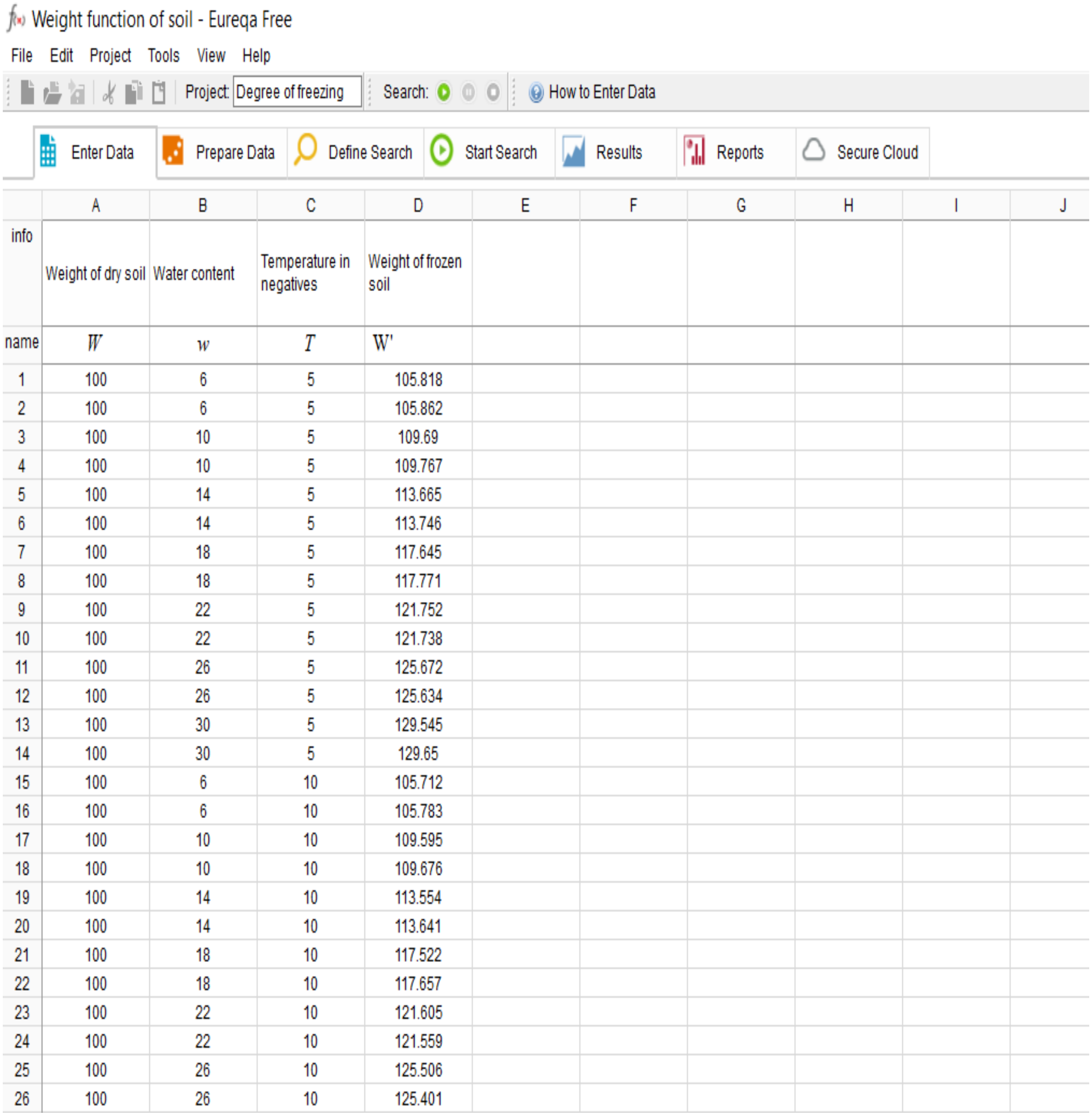
Wt. of dry soil (gm)	Water content (%)	Temperature (°C)	Wt. of frozen soil (gm)
W_s	w	T	W'
100	6	-5	105.818
100	6	-5	105.862
100	10	-5	109.69
100	10	-5	109.767
100	14	-5	113.665
100	14	-5	113.746
100	18	-5	117.645
100	18	-5	117.771
100	22	-5	121.752
100	22	-5	121.738
100	26	-5	125.672
100	26	-5	125.634
100	30	-5	129.545
100	30	-5	129.65
100	6	-10	105.712
100	6	-10	105.783
100	10	-10	109.595
100	10	-10	109.676
100	14	-10	113.554
100	14	-10	113.641
100	18	-10	117.522
100	18	-10	117.657
100	22	-10	121.605

100	22	-10	121.559
100	26	-10	125.506
100	26	-10	125.401
100	30	-10	129.399
100	30	-10	129.454
100	6	-15	105.635
100	6	-15	105.718
100	10	-15	109.432
100	10	-15	109.582
100	14	-15	113.445
100	14	-15	113.593
100	18	-15	117.41
100	18	-15	117.602
100	22	-15	121.45
100	22	-15	121.436
100	26	-15	125.4
100	26	-15	125.188
100	30	-15	129.352
100	30	-15	129.301

Steps to run search on software:

1. After creating a table of inputs and output for weight function, open eureqa software.
2. An excel sheet will gets open, enter the data in different columns like weight of dry soil at room temperature (W_s) in column 1, water content (w) in column 2, temperature (T) in column 3 and output (W’) in column 4 as shown in figure 4.2.
3. Now, click on “prepare data” tab to smoothen the data points if necessary as shown in figure 4.3.
4. Now, click on “Define data” tab to define the relationship between input and output data. For example, W’= f(W_s, w, T). Also, select the operators you want to use in your functions like add, subtract, divide, multiply, exponent, etc. as shown in figure 4.4
5. Now click on “start search” tab and click on “Run” to start the search as shown in figure 4.5.

6. Now, click on "Results" tab to see the formulae so obtained in the search with their amount of errors as shown in figure 4.6.



	A	B	C	D	E	F	G	H	I	J
info	Weight of dry soil	Water content	Temperature in negatives	Weight of frozen soil						
name	W	w	T	W'						
1	100	6	5	105.818						
2	100	6	5	105.862						
3	100	10	5	109.69						
4	100	10	5	109.767						
5	100	14	5	113.665						
6	100	14	5	113.746						
7	100	18	5	117.645						
8	100	18	5	117.771						
9	100	22	5	121.752						
10	100	22	5	121.738						
11	100	26	5	125.672						
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13	100	30	5	129.545						
14	100	30	5	129.65						
15	100	6	10	105.712						
16	100	6	10	105.783						
17	100	10	10	109.595						
18	100	10	10	109.676						
19	100	14	10	113.554						
20	100	14	10	113.641						
21	100	18	10	117.522						
22	100	18	10	117.657						
23	100	22	10	121.605						
24	100	22	10	121.559						
25	100	26	10	125.506						
26	100	26	10	125.401						

Figure 4.2: Data entering in eureqa software for weight function.

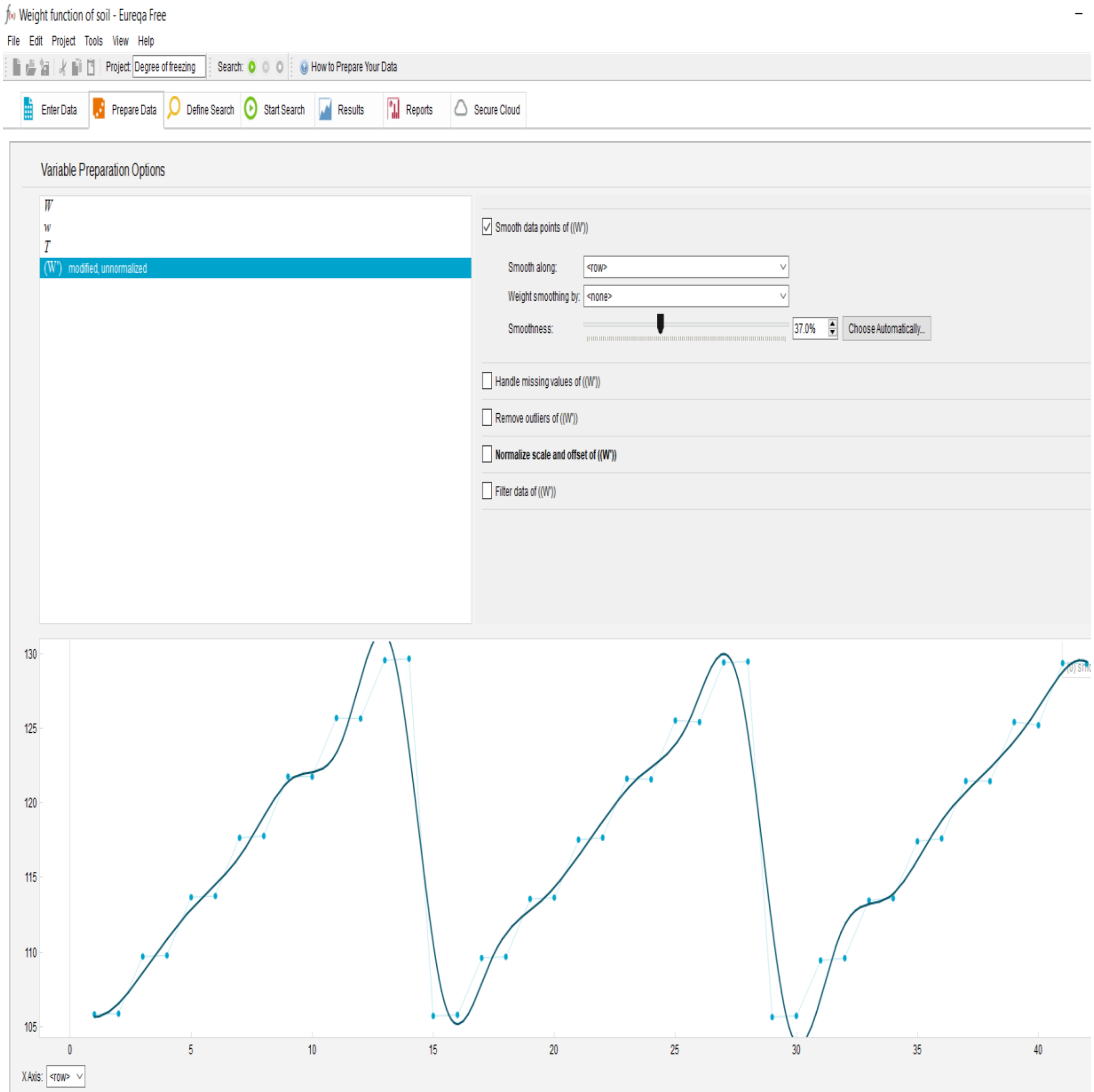

Figure 4.3: Preparing data in eureqa software for weight function.

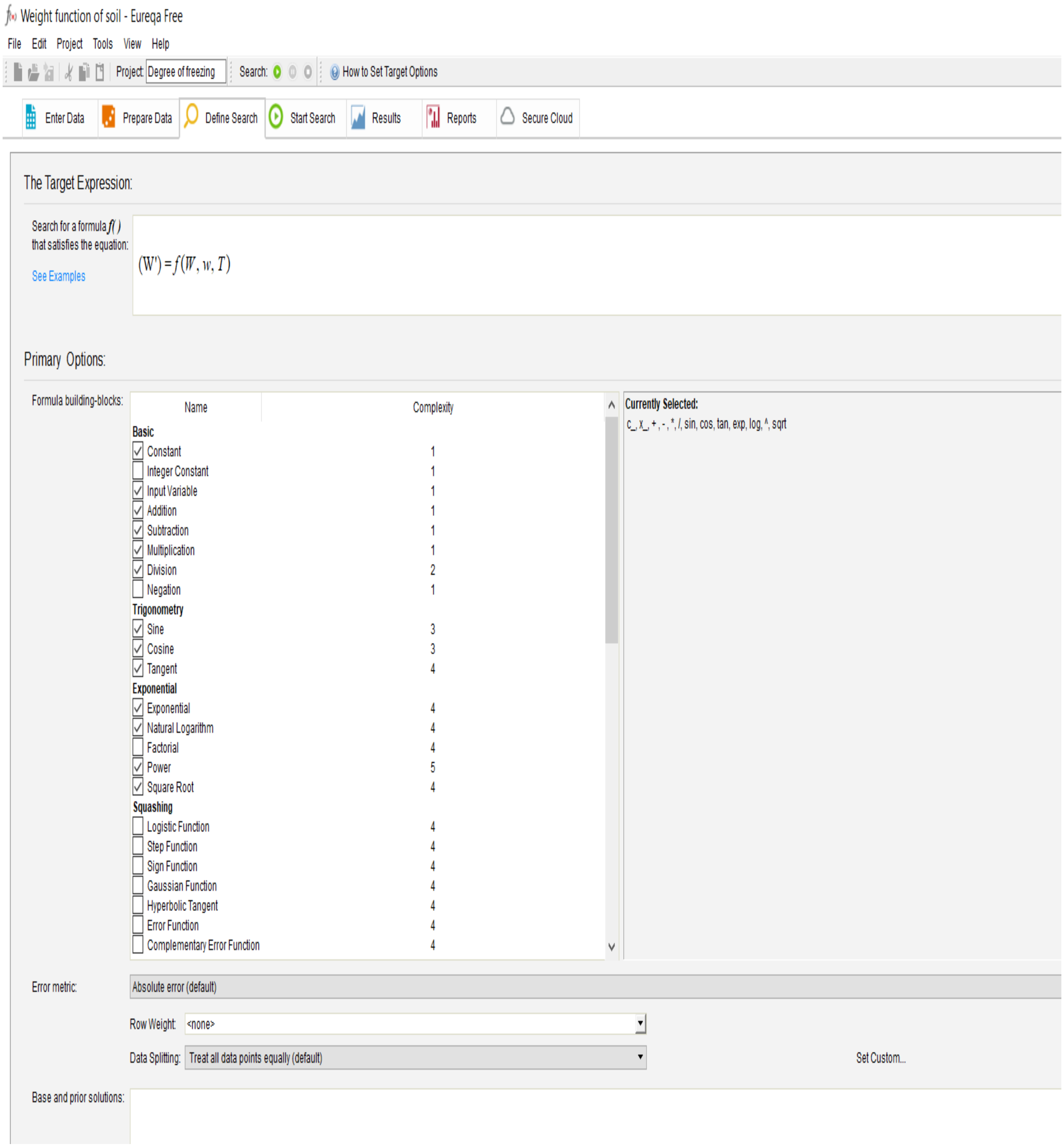

Figure 4.4: Defining search in eureqa software for weight function.

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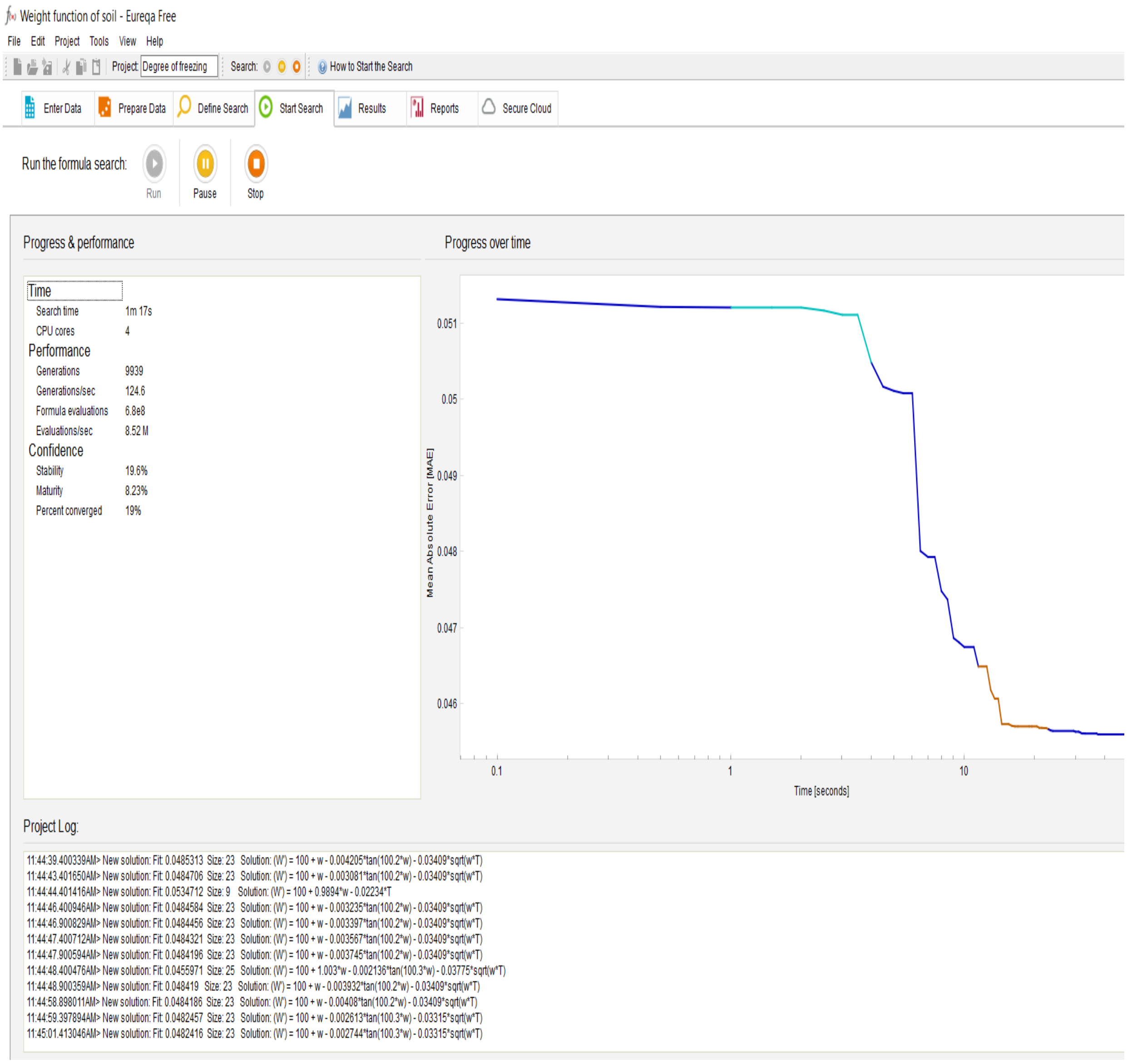


Figure 4.5: Starting search in eureqa software for weight function.

The relationship found is:

$$W' = W_s + 0.992w - 0.000208\, W_s(-T) \qquad \ldots\ldots..(7A)$$

This relationship has the maximum error of 0.18 units.

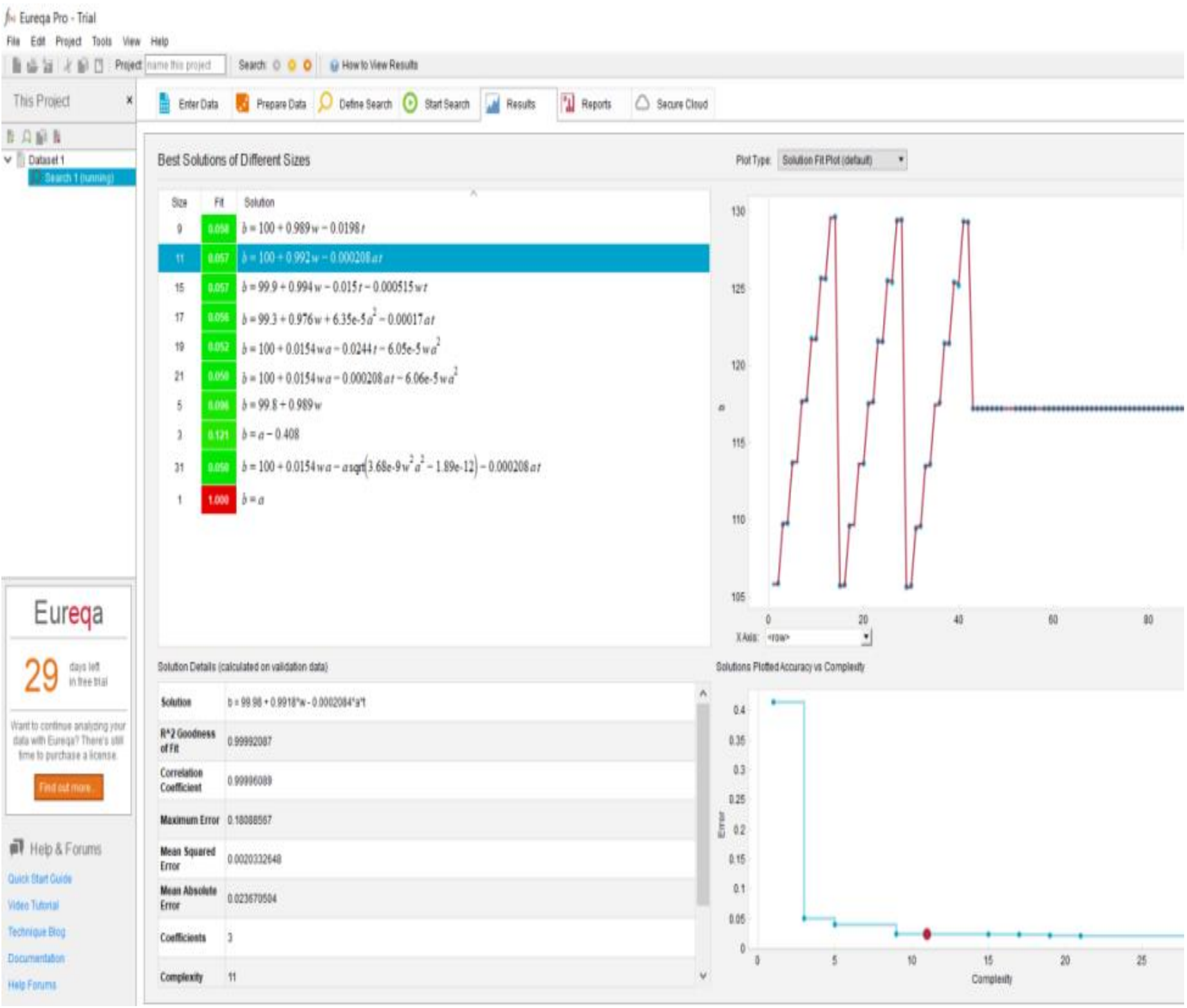


Figure 4.6: Results for weight function in eureqa software.

4.1.2 Void Ratio

Kindly assure that, the void ratio will change with temperature as the volume of water increased as it changes from liquid state to iced state. Thereby increasing the volume of voids while volume of soil solids remains same. Therefore, the void ratio will increase which is confirmed practically too. By entering data obtain in laboratory shown in table 4.3, the following relationship is obtained by the Eureqa Software.

$$e' = f(e, T) \quad \ldots\ldots..(8)$$

Where T is in degree Celsius.

Table 4.3 Void ratios for normal (e) and frozen soil (e')

Unfrozen soil void ratio	Temperature	Water content (%)	Frozen soil void ratio	% change in void ratio
e	T	w	e'	y
1.909	-5	6	1.949	2.05
1.667	-5	6	1.688	1.24
1.969	-5	10	1.985	0.81
1.667	-5	10	1.688	1.24
1.607	-5	14	1.708	5.91
1.708	-5	14	1.748	2.29
1.436	-5	18	1.532	6.27
1.778	-5	18	1.829	2.79
0.812	-5	22	0.922	11.93
1.063	-5	22	1.073	0.93
1.194	-5	26	1.204	0.83
1.174	-5	26	1.199	2.09
1.063	-5	30	1.073	0.93
1.265	-5	30	1.386	8.73
1.909	-10	6	1.98	3.59
1.667	-10	6	1.698	1.83
1.969	-10	10	1.99	1.06
1.667	-10	10	1.718	2.97
1.607	-10	14	1.713	6.19
1.708	-10	14	1.808	5.53
1.436	-10	18	1.547	7.18
1.778	-10	18	1.829	2.79
0.812	-10	22	1.033	21.39
1.063	-10	22	1.124	5.43
1.194	-10	26	1.104	8.15
1.173	-10	26	1.174	0.09
1.063	-10	30	1.114	4.58
1.265	-10	30	1.476	14.3
1.909	-15	6	1.98	3.59
1.667	-15	6	1.698	1.83
1.969	-15	10	1.99	1.06
1.667	-15	10	1.718	2.97
1.607	-15	14	1.718	6.46
1.708	-15	14	1.813	5.79
1.436	-15	18	1.567	8.36
1.778	-15	18	1.834	3.05
0.812	-15	22	1.033	21.39
1.063	-15	22	1.124	5.43
1.194	-15	26	1.114	7.18
1.174	-15	26	1.179	0.42
1.063	-15	30	1.114	4.58

1.265	-15	30	1.481	14.58

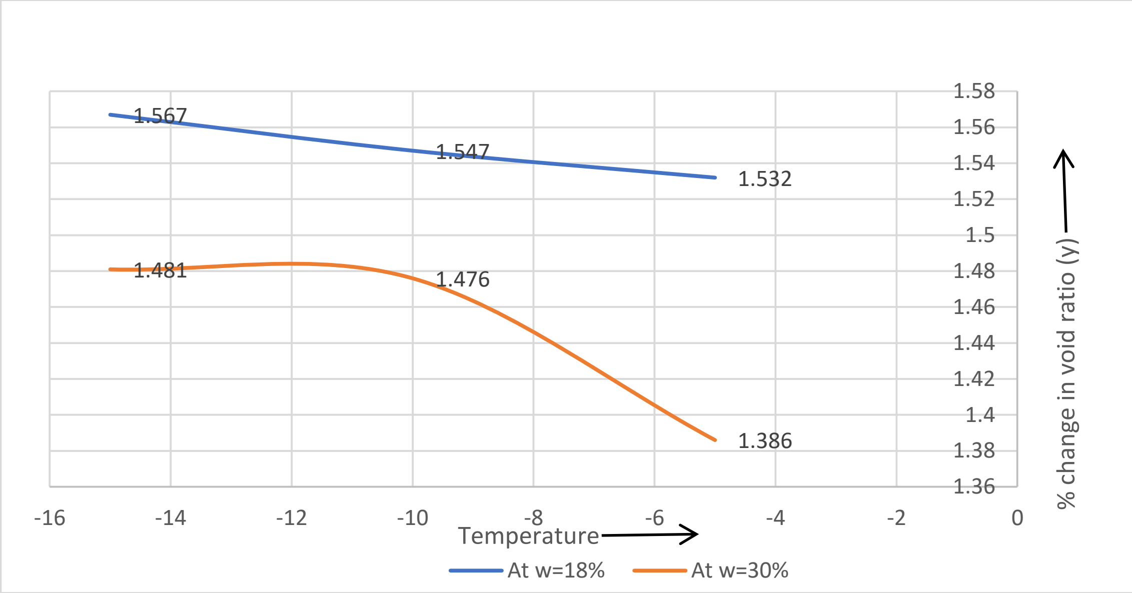
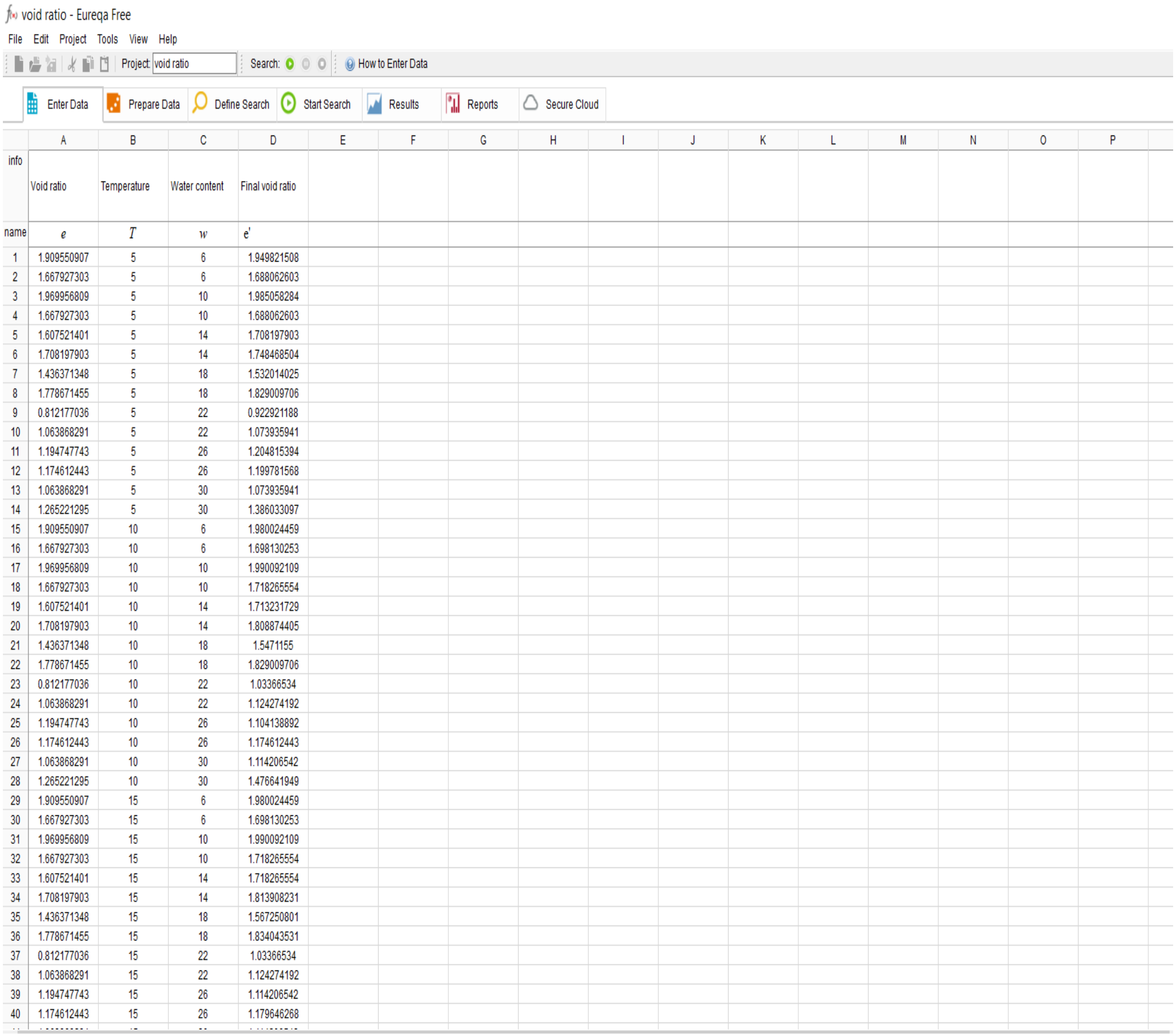


Fig. 4.7 Graph of % change in void ratio (y) vs Temperature

The graph between percentage change in void ratio vs temperature suggests that at higher water content the change in void ratio is more and steep curve is obtained as compared to lower water content as shown in figure 4.7. This is because more water will convert into ice and volume of voids will increase sharply in case of higher water content and volume of ice will be greater than the initial volume of voids.

Steps to run search on software:

1. After creating a table of inputs and output for void ratio function, open eureqa software.
2. An excel sheet will gets open, enter the data in different columns like void ratio of soil at room temperature (e) in column 1, temperature (T) in column 2, water content (w) in column 3 and output (e') in column 4 as shown in figure as 4.8.
3. Now, click on "prepare data" tab to smoothen the data points if necessary as shown in figure 4.9.
4. Now, click on "Define data" tab to define the relationship between input and output data. For example, e'= f(e, w, T). Also, select the operators you want to use in your functions like add, subtract, divide, multiply, exponent, etc. as shown in figure 4.10.
5. Now click on "start search" tab and click on "Run" to start the search as shown in figure 4.11.
6. Now, click on "Results" tab to see the formulae so obtained in the search with their amount of errors as shown in figure 4.12.



	A	B	C	D
info	Void ratio	Temperature	Water content	Final void ratio
name	e	T	w	e'
1	1.909550907	5	6	1.949821508
2	1.667927303	5	6	1.688062603
3	1.969956809	5	10	1.985058284
4	1.667927303	5	10	1.688062603
5	1.607521401	5	14	1.708197903
6	1.708197903	5	14	1.748468504
7	1.436371348	5	18	1.532014025
8	1.778671455	5	18	1.829009706
9	0.812177036	5	22	0.922921188
10	1.063868291	5	22	1.073935941
11	1.194747743	5	26	1.204815394
12	1.174612443	5	26	1.199781568
13	1.063868291	5	30	1.073935941
14	1.265221295	5	30	1.386033097
15	1.909550907	10	6	1.980024459
16	1.667927303	10	6	1.698130253
17	1.969956809	10	10	1.990092109
18	1.667927303	10	10	1.718265554
19	1.607521401	10	14	1.713231729
20	1.708197903	10	14	1.808874405
21	1.436371348	10	18	1.5471155
22	1.778671455	10	18	1.829009706
23	0.812177036	10	22	1.03366534
24	1.063868291	10	22	1.124274192
25	1.194747743	10	26	1.104138892
26	1.174612443	10	26	1.174612443
27	1.063868291	10	30	1.114206542
28	1.265221295	10	30	1.476641949
29	1.909550907	15	6	1.980024459
30	1.667927303	15	6	1.698130253
31	1.969956809	15	10	1.990092109
32	1.667927303	15	10	1.718265554
33	1.607521401	15	14	1.718265554
34	1.708197903	15	14	1.813908231
35	1.436371348	15	18	1.567250801
36	1.778671455	15	18	1.834043531
37	0.812177036	15	22	1.03366534
38	1.063868291	15	22	1.124274192
39	1.194747743	15	26	1.114206542
40	1.174612443	15	26	1.179646268

Figure 4.8: Data entering in eureqa software for void ratio function.

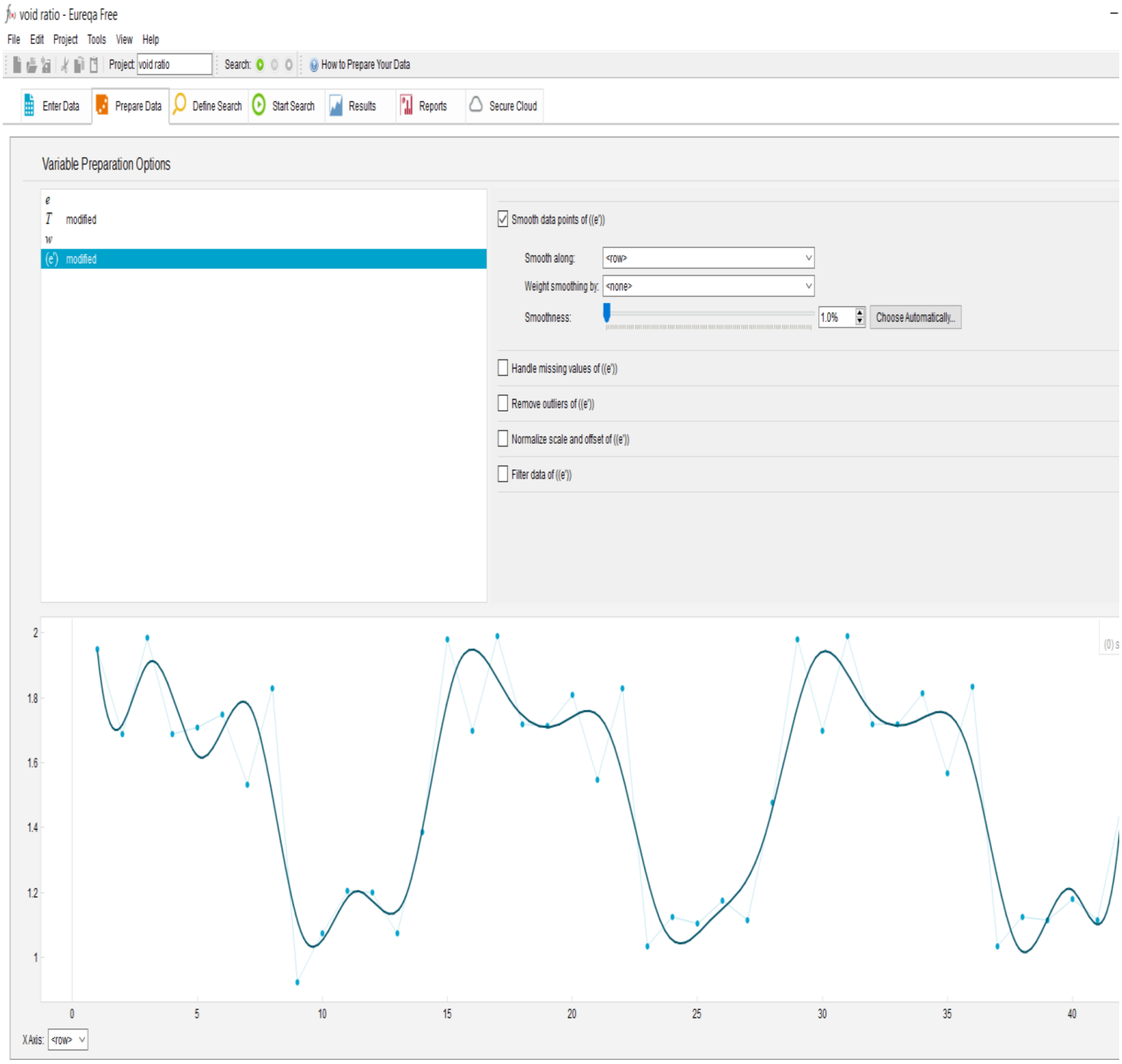


Figure 4.9: Preparing data in eureqa software for void ratio function.

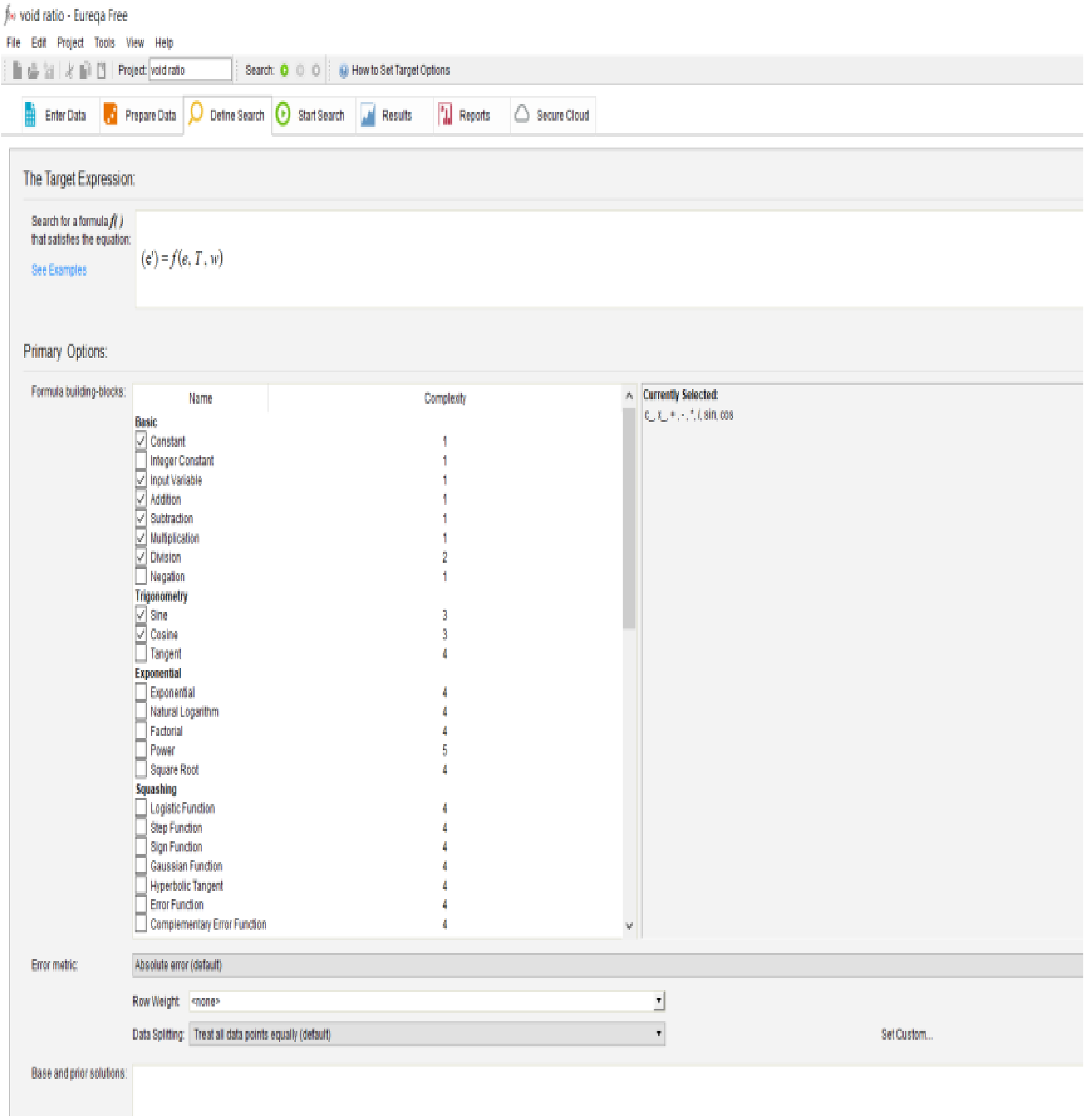


Figure 4.10: Defining search in eureqa software for void ratio function.

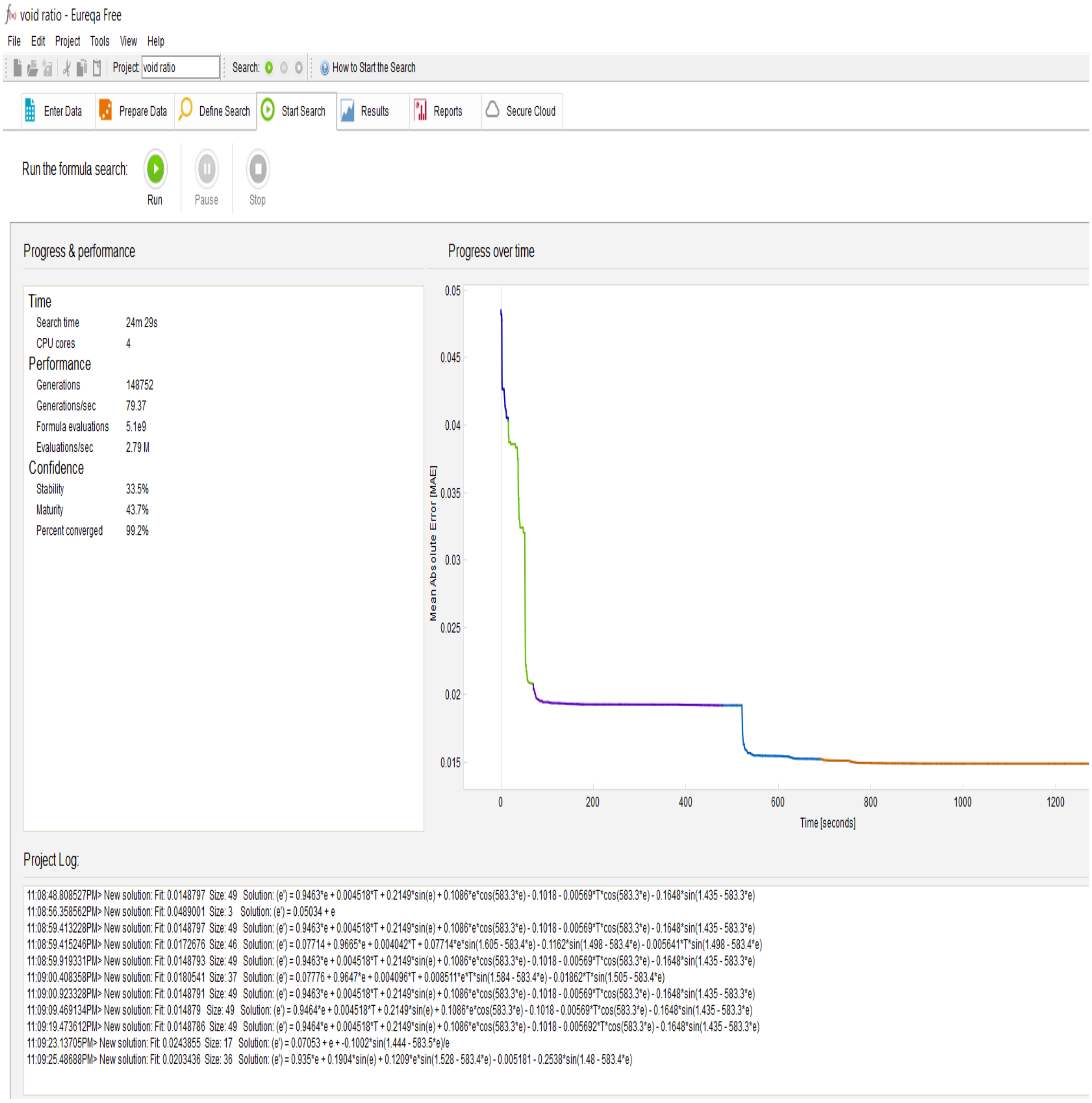


Figure 4.11: Starting search in eureqa software for void ratio function.

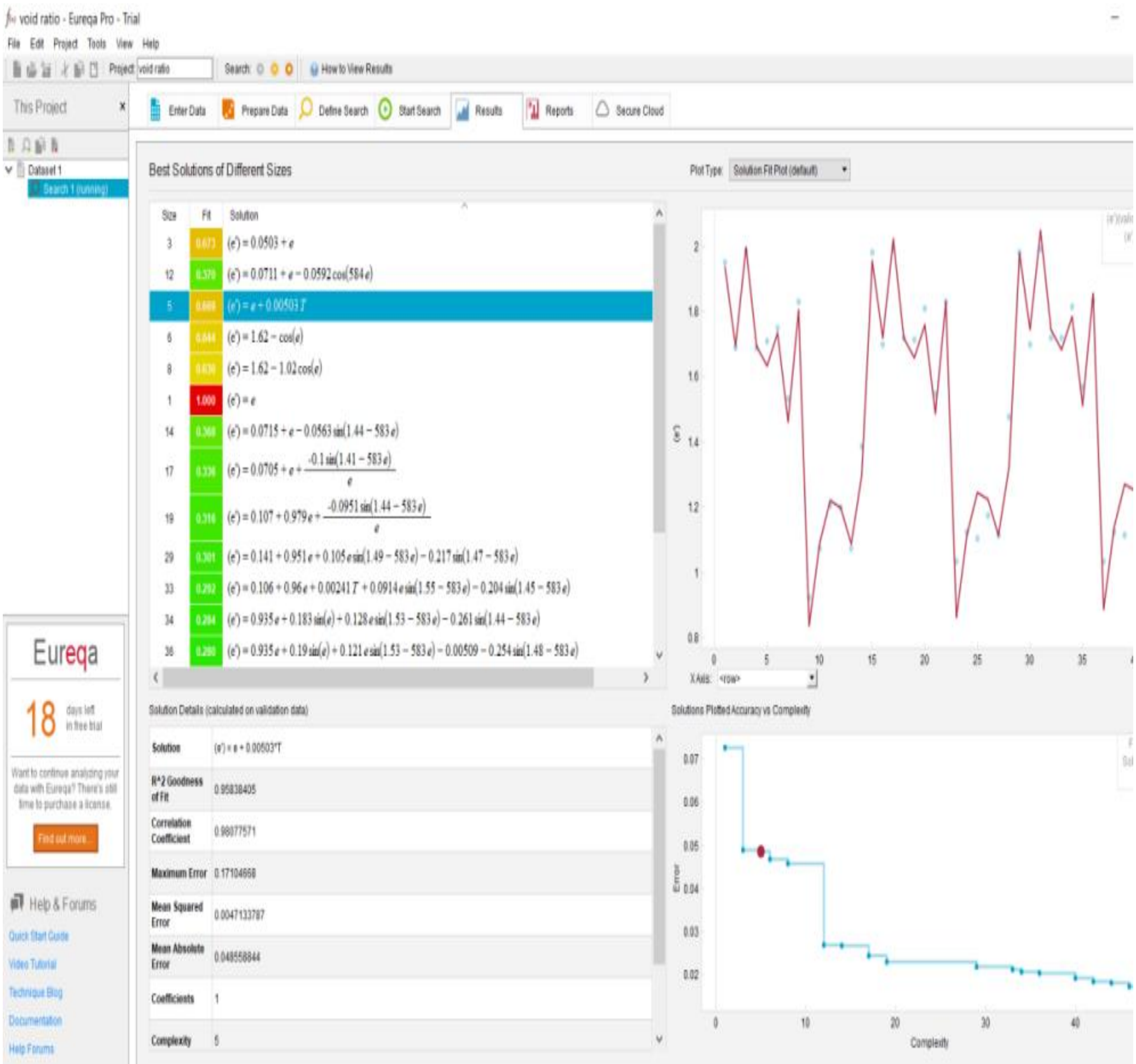


Figure 4.12: Results for void ratio function in eureqa software.

The relationship found is:

$$e' = e + 0.00503(-T) \qquad \ldots\ldots..(8A)$$

4.1.3 Bulk Density of Soil

The weight of soil solids remains constant but the weight of water changes with change of temperature thereby changing the bulk density of soil. Therefore, a relationship may exist between the bulk density at room temperature to the bulk density at frozen temperature.

After entering the data obtained in laboratory shown in table 4.4, the relationship can be obtained in Eureqa software.

The function is expected to be:

$$\gamma_t'=f(\gamma_t,w,T) \qquad \ldots\ldots..(9)$$

Table 4.4 Bulk densities for normal (γ) and frozen soil (γ')

Bulk Density (KN/m^3)	water content (%)	Temperature (°C)	Bulk Density of frozen soil (KN/m3)	% Change in bulk density
γ	w	T	γ'	x
9.161	6	-5	9.020	1.54
9.991	6	-5	9.903	0.88
9.313	10	-5	9.240	0.78
10.368	10	-5	10.268	0.96
10.994	14	-5	10.554	4.00
10.585	14	-5	10.406	1.69
12.179	18	-5	11.684	4.06
10.679	18	-5	10.468	1.97
16.929	22	-5	15.921	5.95
14.864	22	-5	14.760	0.69
14.436	26	-5	14.333	0.71
14.569	26	-5	14.361	1.43
15.839	30	-5	15.707	0.83
14.431	30	-5	13.664	5.31
9.161	6	-10	8.920	2.63
9.991	6	-10	9.859	1.32
9.313	10	-10	9.217	1.03
10.368	10	-10	10.146	2.14
10.994	14	-10	10.524	4.27
10.585	14	-10	10.173	3.89
12.1789	18	-10	11.602	4.74
10.679	18	-10	10.458	2.07
16.929	22	-10	15.036	11.18
14.864	22	-10	14.389	3.19
14.436	26	-10	14.999	3.89
14.569	26	-10	14.500	0.47
15.839	30	-10	15.390	2.83
14.431	30	-10	13.144	8.92
9.161	6	-15	8.914	2.70
9.991	6	-15	9.853	1.38
9.313	10	-15	9.203	1.18
10.368	10	-15	10.137	2.23
10.994	14	-15	10.495	4.54
10.585	14	-15	10.151	4.10
12.179	18	-15	11.500	5.57

10.679	18	-15	10.435	2.28
16.929	22	-15	15.017	11.29
14.864	22	-15	14.375	3.29
14.436	26	-15	14.915	3.32
14.569	26	-15	14.443	0.86
15.839	30	-15	15.385	2.86
14.431	30	-15	13.102	9.21

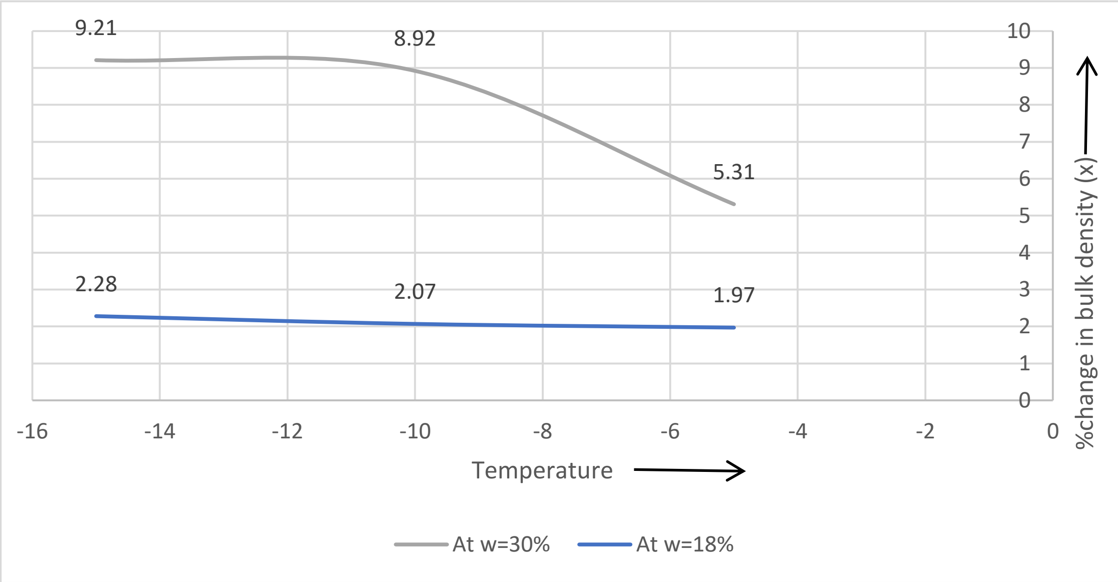


Fig. 4.13 Percentage change in Bulk density Vs Temperature

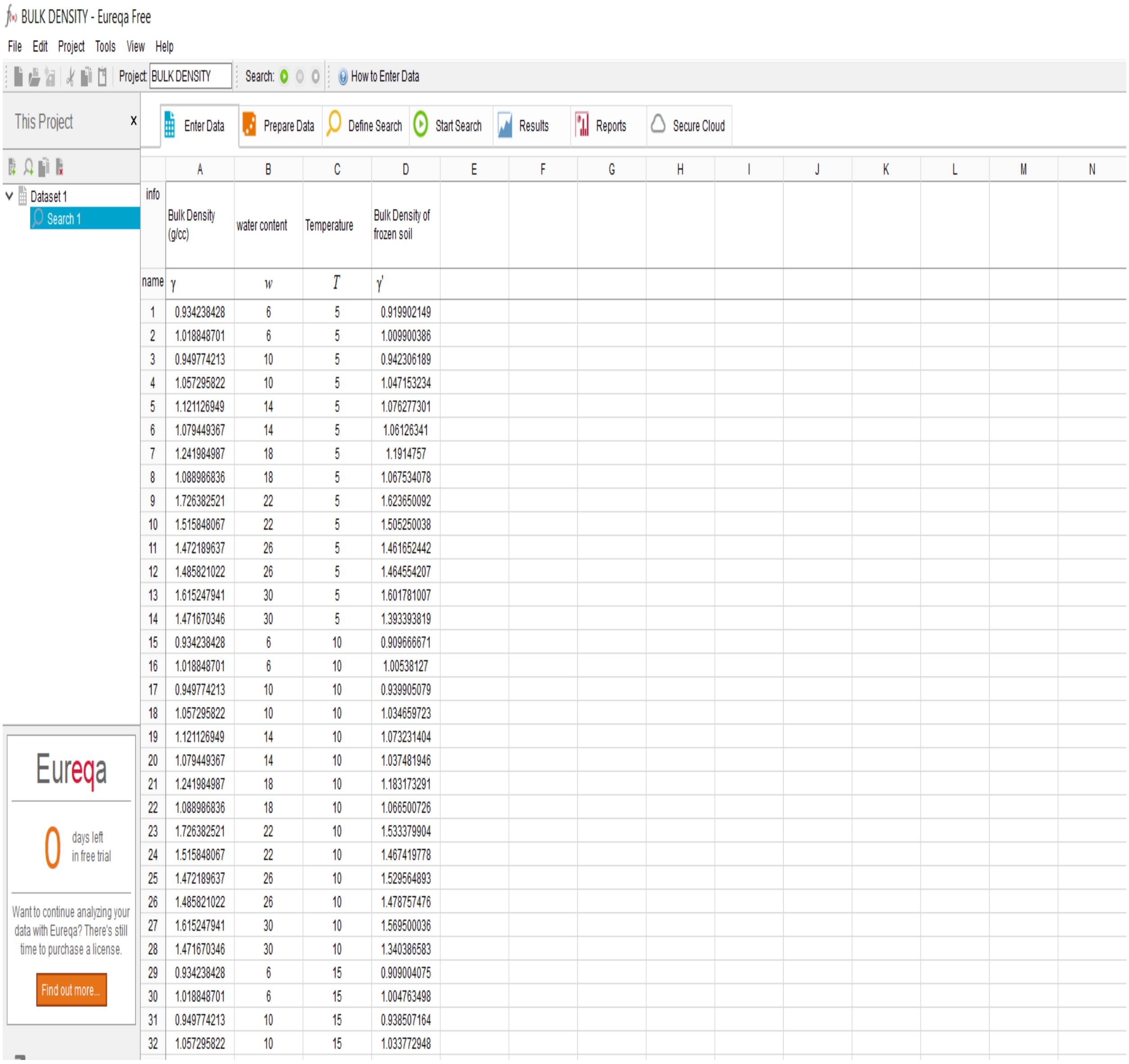
As the graph in Fig. 4.13 suggests that the change in bulk density will be more steep when working with higher water content. Also, the rate of change in bulk density with temperature decreases as the temperature is decreasing. This is because the density of ice is smaller than that of water.

Steps to run search on software:

1. After creating a table of inputs and output for bulk density function, open eureqa software.
2. An excel sheet will gets open, enter the data in different columns like bulk density of soil at room temperature (γ) in column 1, water content (w) in column 2, temperature (T) in column 3 and output (γ') in column 4 as shown in figure 4.14.
3. Now, click on "prepare data" tab to smoothen the data points if necessary as shown in figure 4.15.
4. Now, click on "Define data" tab to define the relationship between input and output data. For example, γ'= f(γ, w, T). Also, select the operators you want to use in your functions like add, subtract, divide, multiply, exponent, etc. as shown in figure 4.16.

5. Now click on “start search” tab and click on “Run” to start the search as shown in figure 4.17.

6. Now, click on “Results” tab to see the formulae so obtained in the search with their amount of errors as shown in figure 4.18.



	A	B	C	D
info	Bulk Density (g/cc)	water content	Temperature	Bulk Density of frozen soil
name	γ	w	T	γ'
1	0.934238428	6	5	0.919902149
2	1.018848701	6	5	1.009900386
3	0.949774213	10	5	0.942306189
4	1.057295822	10	5	1.047153234
5	1.121126949	14	5	1.076277301
6	1.079449367	14	5	1.06126341
7	1.241984987	18	5	1.1914757
8	1.088986836	18	5	1.067534078
9	1.726382521	22	5	1.623650092
10	1.515848067	22	5	1.505250038
11	1.472189637	26	5	1.461652442
12	1.485821022	26	5	1.464554207
13	1.615247941	30	5	1.601781007
14	1.471670346	30	5	1.393393819
15	0.934238428	6	10	0.909666671
16	1.018848701	6	10	1.00538127
17	0.949774213	10	10	0.939905079
18	1.057295822	10	10	1.034659723
19	1.121126949	14	10	1.073231404
20	1.079449367	14	10	1.037481946
21	1.241984987	18	10	1.183173291
22	1.088986836	18	10	1.066500726
23	1.726382521	22	10	1.533379904
24	1.515848067	22	10	1.467419778
25	1.472189637	26	10	1.529564893
26	1.485821022	26	10	1.478757476
27	1.615247941	30	10	1.569500036
28	1.471670346	30	10	1.340386583
29	0.934238428	6	15	0.909004075
30	1.018848701	6	15	1.004763498
31	0.949774213	10	15	0.938507164
32	1.057295822	10	15	1.033772948

Figure 4.14: Data entering in eureqa software for bulk density function.

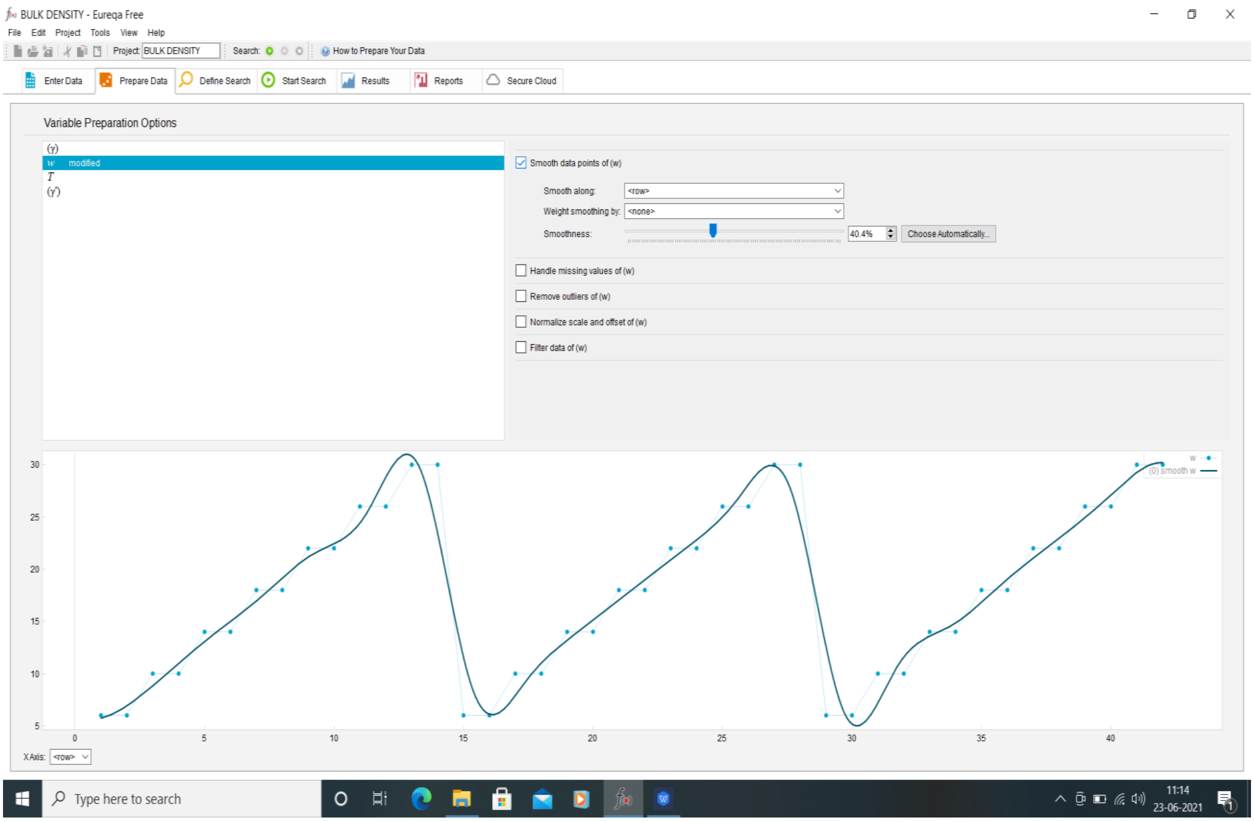


Figure 4.15: Preparing data in eureqa software for bulk density function.

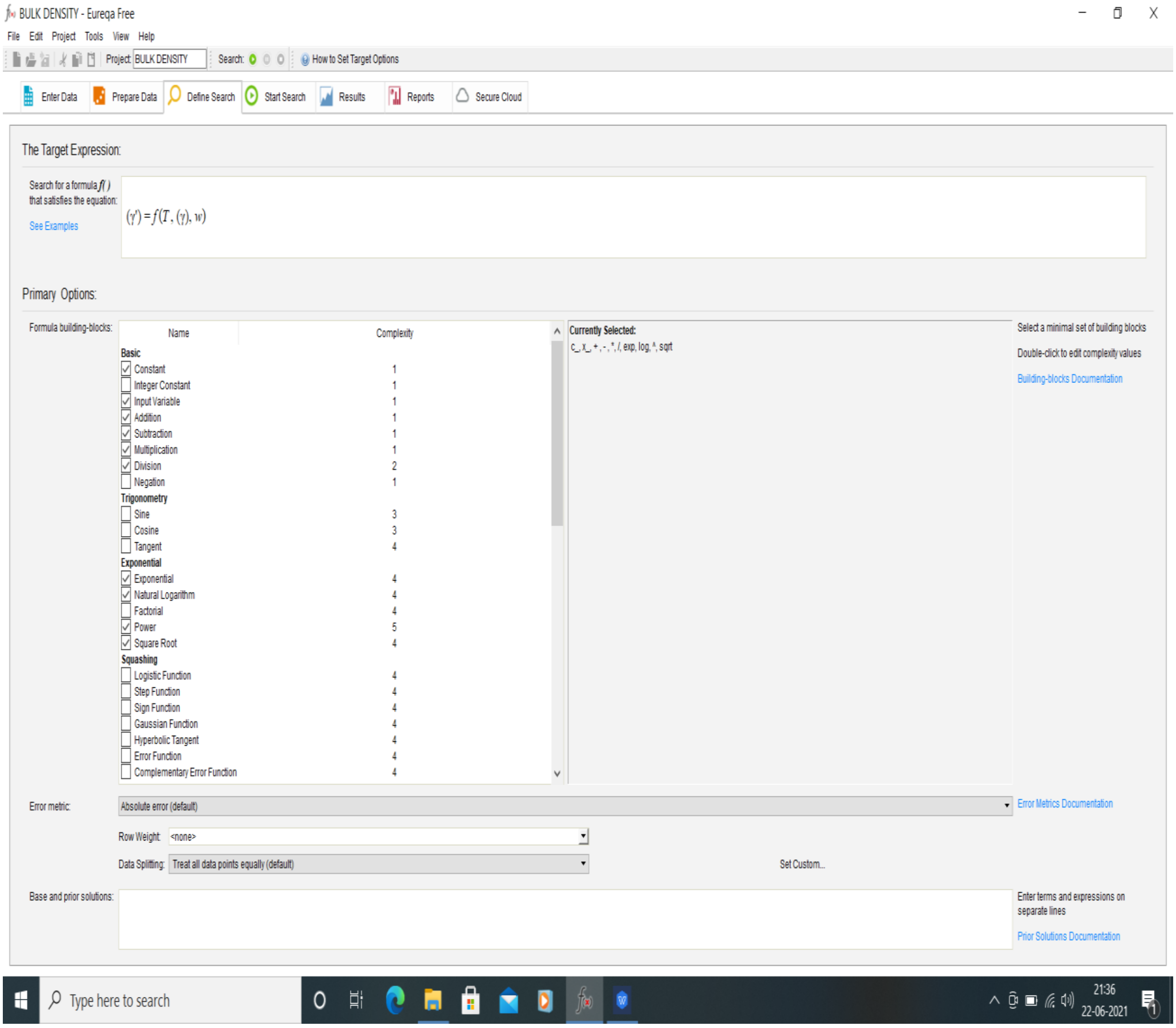


Figure 4.16: Defining search in eureqa software for bulk density function.

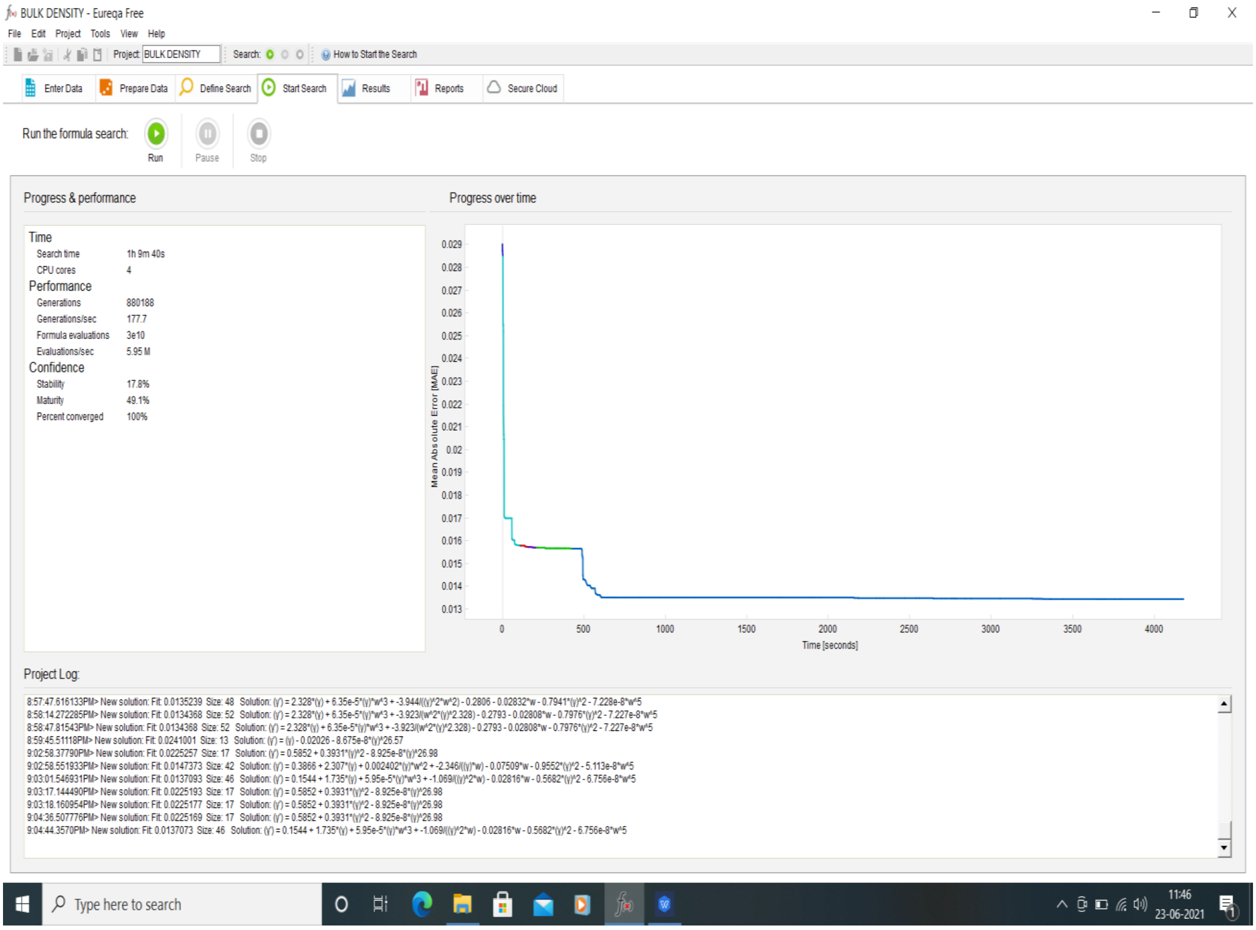


Figure 4.17: Starting search in eureqa software for bulk density function.

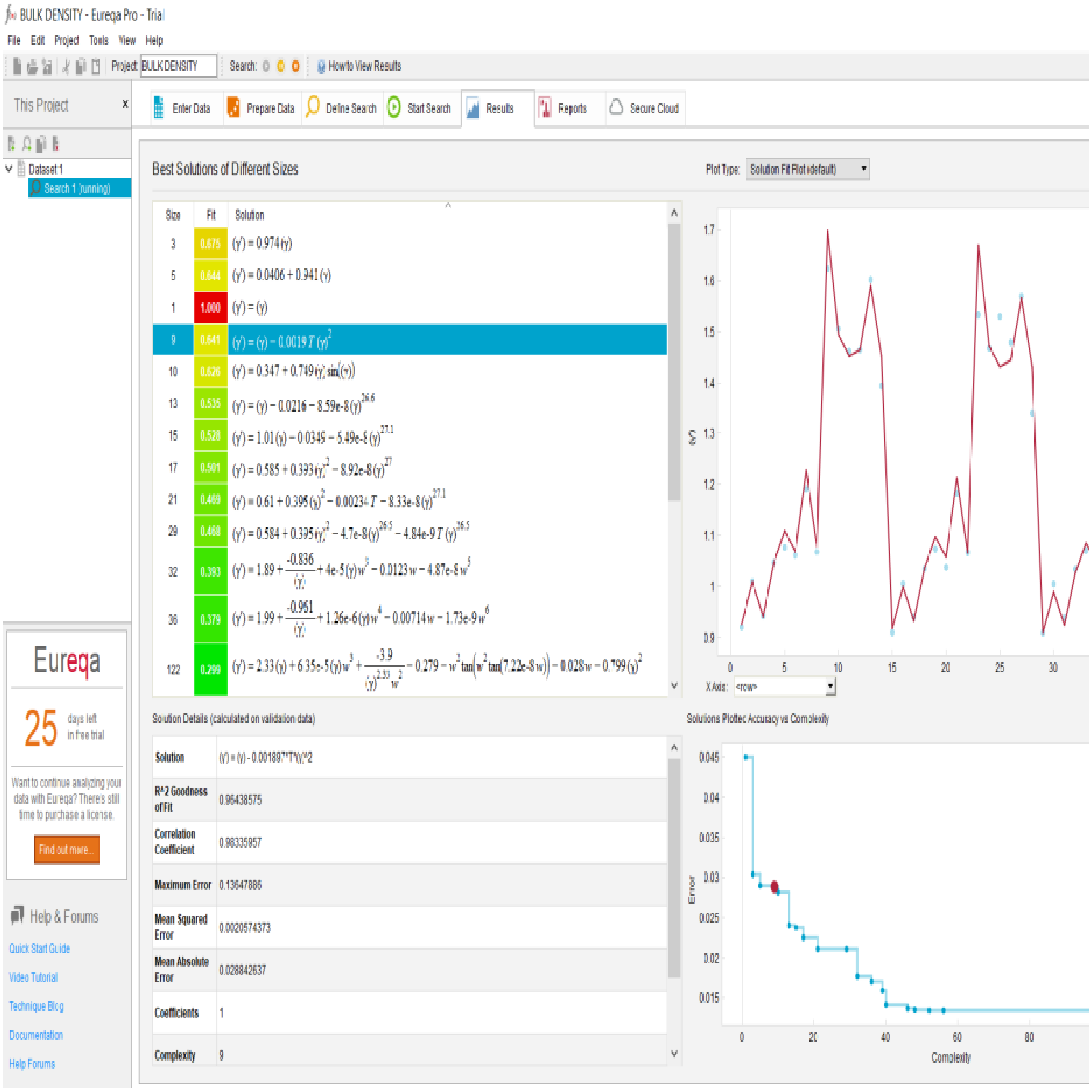


Figure 4.18: Results for weight function in eureqa software.

The relationship found is:

$$\gamma_t' = \gamma_t - 0.0019(-T)\gamma_t^2 \qquad \text{……..(9A)}$$

4.1.4 Degree Of Freezing

Analogous to degree of saturation (S), degree of freezing (F) would tell the degree up to which the soil is frozen. For example, a soil is fully saturated i.e., all the pores are completely filled with water. At -2 degree Celsius, a fraction of water will get crystallized but at -20 degree Celsius, all the water will get frozen. Therefore, degree of freezing will give an idea about the degree up to which the water in pores of soil is frozen. The data obtained from laboratory shown in table 4.5 leads to the following result in eureqa software.

$$S= (w*G_s)/e \quad \text{……..(10)}$$

The relationship is given by,

$$F= f(w,e',T) \quad \text{……..(11)}$$

where F is the degree of freezing computed as,

$$F= V_I/V_v \quad \text{……..(11A)}$$

Table 4.5 Degree of freezing.

Final void ratio	Temprature (°C)	Water content (%)	Specific gravity of soil	Degree of Freezing
e'	T	w	G_s	F
1.95	-5	6	2.803	8.362
1.688	-5	6	2.803	9.732
1.985	-5	10	2.803	13.681
1.688	-5	10	2.803	16.215
1.708	-5	14	2.803	22.420
1.748	-5	14	2.803	22.033
1.532	-5	18	2.803	32.279
1.829	-5	18	2.803	27.230
0.923	-5	22	2.803	66.053
1.074	-5	22	2.803	56.728
1.205	-5	26	2.803	59.717
1.200	-5	26	2.803	59.879
1.074	-5	30	2.803	77.101
1.386	-5	30	2.803	59.953
1.980	-10	6	2.803	8.085
1.698	-10	6	2.803	9.544
1.990	-10	10	2.803	13.512
1.718	-10	10	2.803	15.782
1.713	-10	14	2.803	22.172
1.809	-10	14	2.803	21.135
1.547	-10	18	2.803	31.741

1.829	-10	18	2.803	27.056
1.034	-10	22	2.803	58.578
1.124	-10	22	2.803	53.742
1.104	-10	26	2.803	64.740
1.175	-10	26	2.803	60.606
1.114	-10	30	2.803	73.948
1.477	-10	30	2.803	55.902
1.98	-15	6	2.803	7.9760
1.698	-15	6	2.803	9.437
1.99	-15	10	2.803	13.283
1.718	-15	10	2.803	15.629
1.718	-15	14	2.803	21.929
1.814	-15	14	2.803	21.002
1.567	-15	18	2.803	31.133
1.834	-15	18	2.803	26.897
1.034	-15	22	2.803	58.157
1.124	-15	22	2.803	53.435
1.114	-15	26	2.803	63.889
1.18	-15	26	2.803	59.841
1.114	-15	30	2.803	73.829
1.482	-15	30	2.803	55.422

Steps to run search on software:

1. After creating a table of inputs and output for degree of freezing function, open eureqa software.

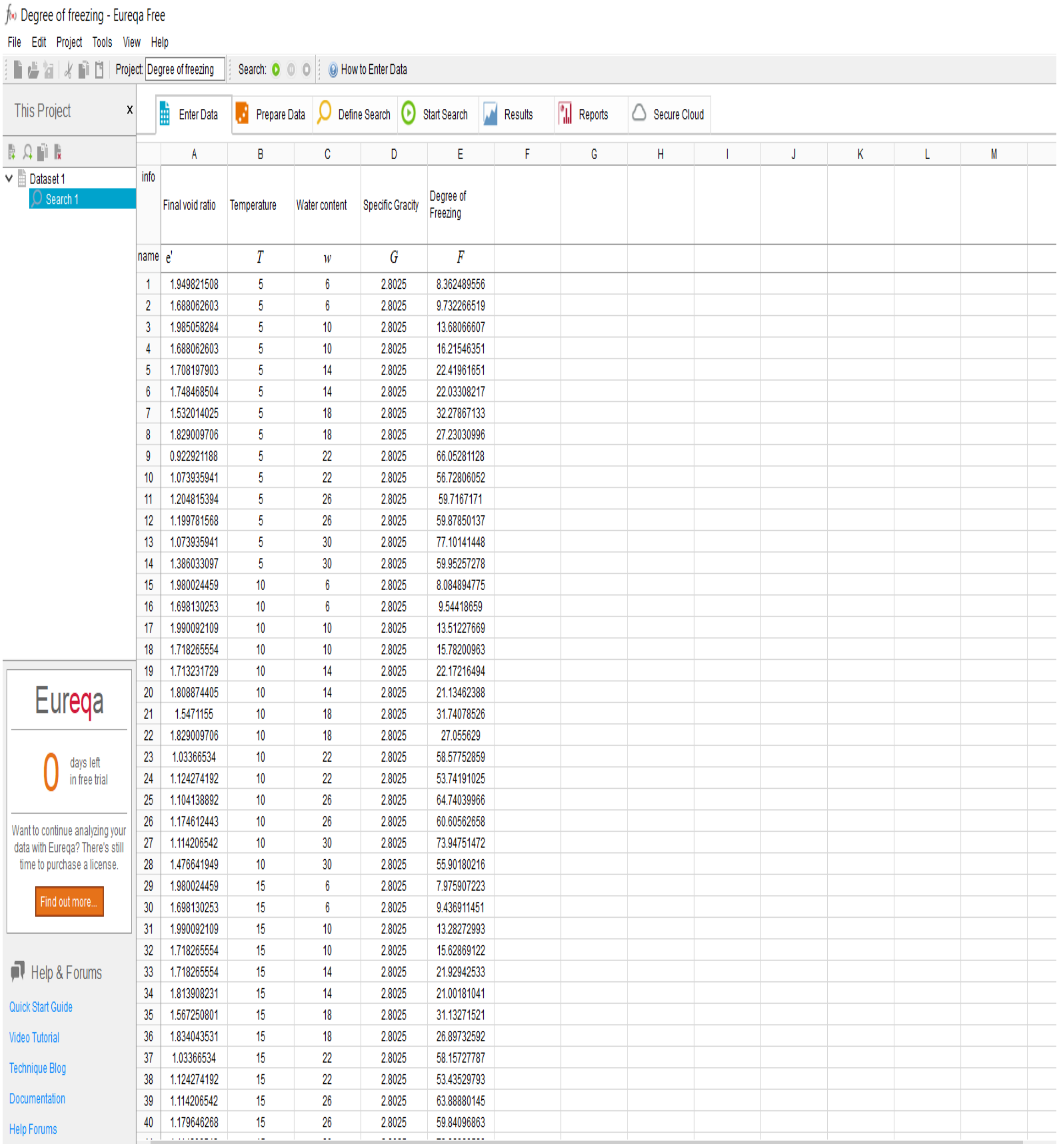
2. An excel sheet will gets open, enter the data in different columns like void ratio of frozen soil (e') in column 1, temperature (T) in column 2, water content (w) in column 3, specific gravity (G) of soil at room temperature in column 4 and output i.e., degree of freezing (F) in column 5 as shown in figure 4.19.

3. Now, click on "prepare data" tab to smoothen the data points if necessary as shown in figure 4.20.

4. Now, click on "Define data" tab to define the relationship between input and output data. For example, F= f(e', w, T,G). Also, select the operators you want to use in your functions like add, subtract, divide, multiply, exponent, etc. as shown in figure 4.21.

5. Now click on "start search" tab and click on "Run" to start the search as shown in figure 4.22.

6. Now, click on “Results” tab to see the formulae so obtained in the search with their amount of errors as shown in figure 4.23.



	A	B	C	D	E
info	Final void ratio	Temperature	Water content	Specific Gracity	Degree of Freezing
name	e'	T	w	G	F
1	1.949821508	5	6	2.8025	8.362489556
2	1.688062603	5	6	2.8025	9.732266519
3	1.985058284	5	10	2.8025	13.68066607
4	1.688062603	5	10	2.8025	16.21546351
5	1.708197903	5	14	2.8025	22.41961651
6	1.748468504	5	14	2.8025	22.03308217
7	1.532014025	5	18	2.8025	32.27867133
8	1.829009706	5	18	2.8025	27.23030996
9	0.922921188	5	22	2.8025	66.05281128
10	1.073935941	5	22	2.8025	56.72806052
11	1.204815394	5	26	2.8025	59.7167171
12	1.199781568	5	26	2.8025	59.87850137
13	1.073935941	5	30	2.8025	77.10141448
14	1.386033097	5	30	2.8025	59.95257278
15	1.980024459	10	6	2.8025	8.084894775
16	1.698130253	10	6	2.8025	9.54418659
17	1.990092109	10	10	2.8025	13.51227669
18	1.718265554	10	10	2.8025	15.78200963
19	1.713231729	10	14	2.8025	22.17216494
20	1.808874405	10	14	2.8025	21.13462388
21	1.5471155	10	18	2.8025	31.74078526
22	1.829009706	10	18	2.8025	27.055629
23	1.03366534	10	22	2.8025	58.57752859
24	1.124274192	10	22	2.8025	53.74191025
25	1.104138892	10	26	2.8025	64.74039966
26	1.174612443	10	26	2.8025	60.60562658
27	1.114206542	10	30	2.8025	73.94751472
28	1.476641949	10	30	2.8025	55.90180216
29	1.980024459	15	6	2.8025	7.975907223
30	1.698130253	15	6	2.8025	9.436911451
31	1.990092109	15	10	2.8025	13.28272993
32	1.718265554	15	10	2.8025	15.62869122
33	1.718265554	15	14	2.8025	21.92942533
34	1.813908231	15	14	2.8025	21.00181041
35	1.567250801	15	18	2.8025	31.13271521
36	1.834043531	15	18	2.8025	26.89732592
37	1.03366534	15	22	2.8025	58.15727787
38	1.124274192	15	22	2.8025	53.43529793
39	1.114206542	15	26	2.8025	63.88880145
40	1.179646268	15	26	2.8025	59.84096863

Figure 4.19: Data entering in eureqa software for degree of freezing function.

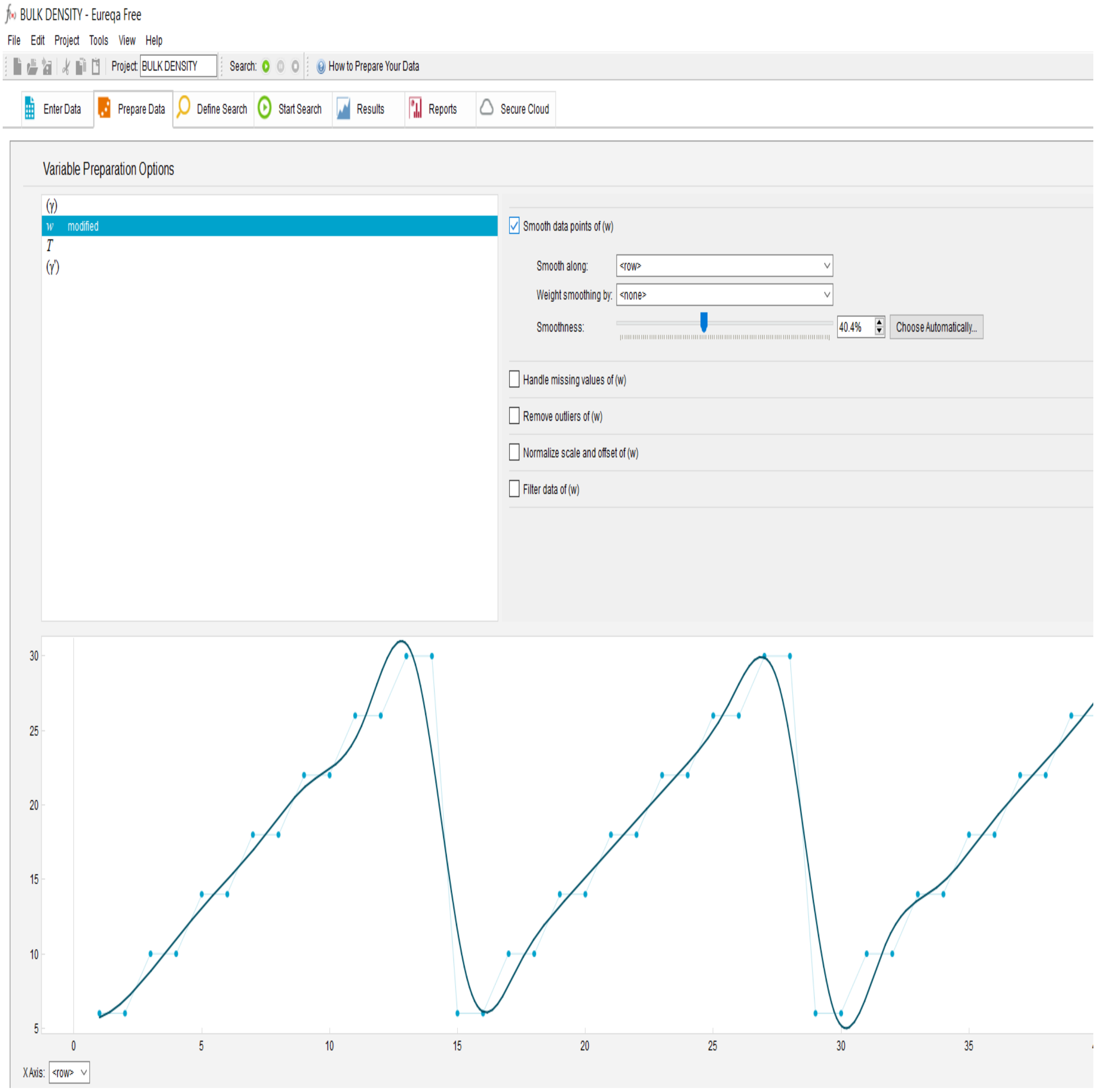


Figure 4.20: Preparing data in eureqa software for degree of freezing function.

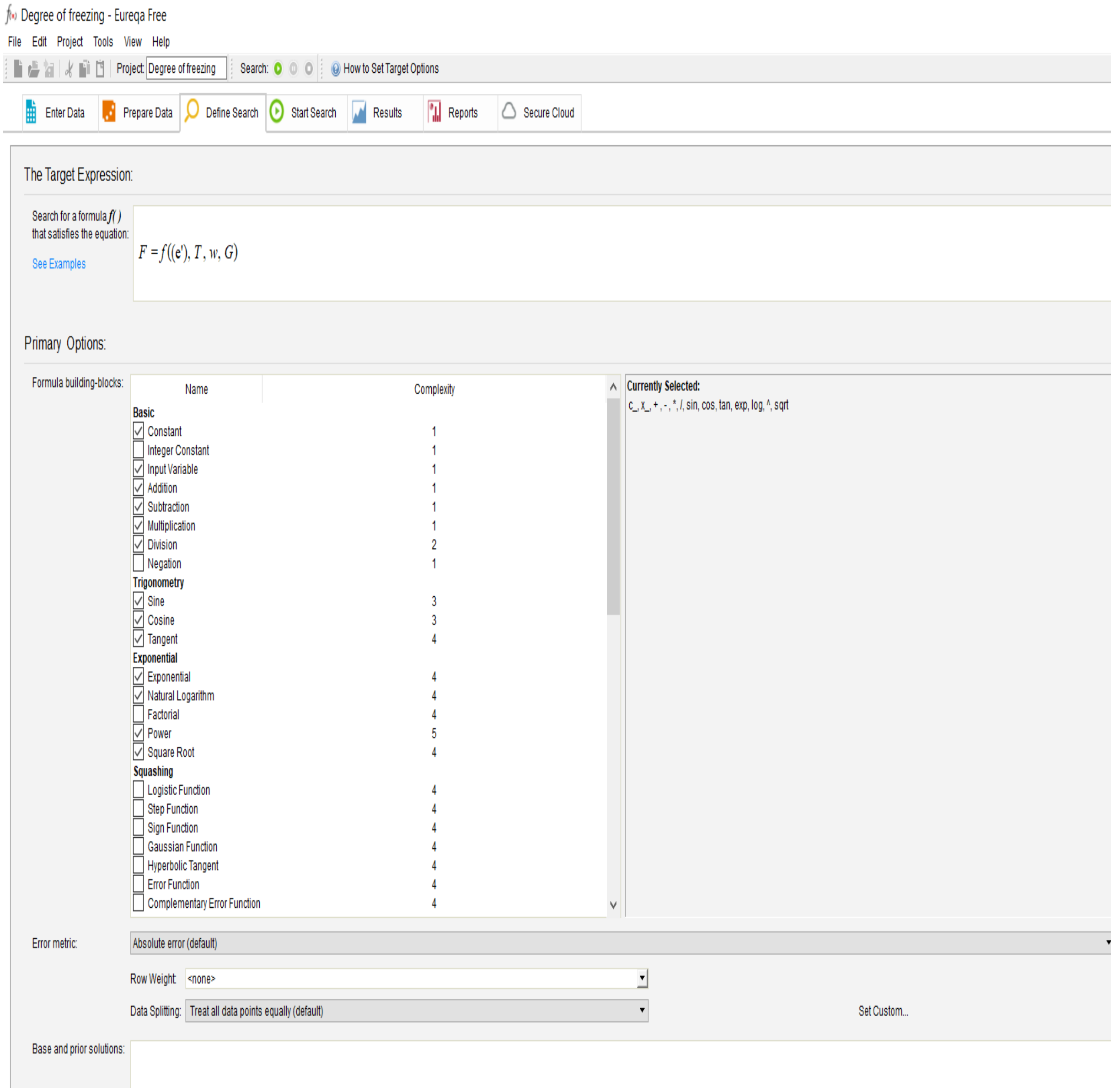


Figure 4.21: Defining search in eureqa software for degree of freezing function.

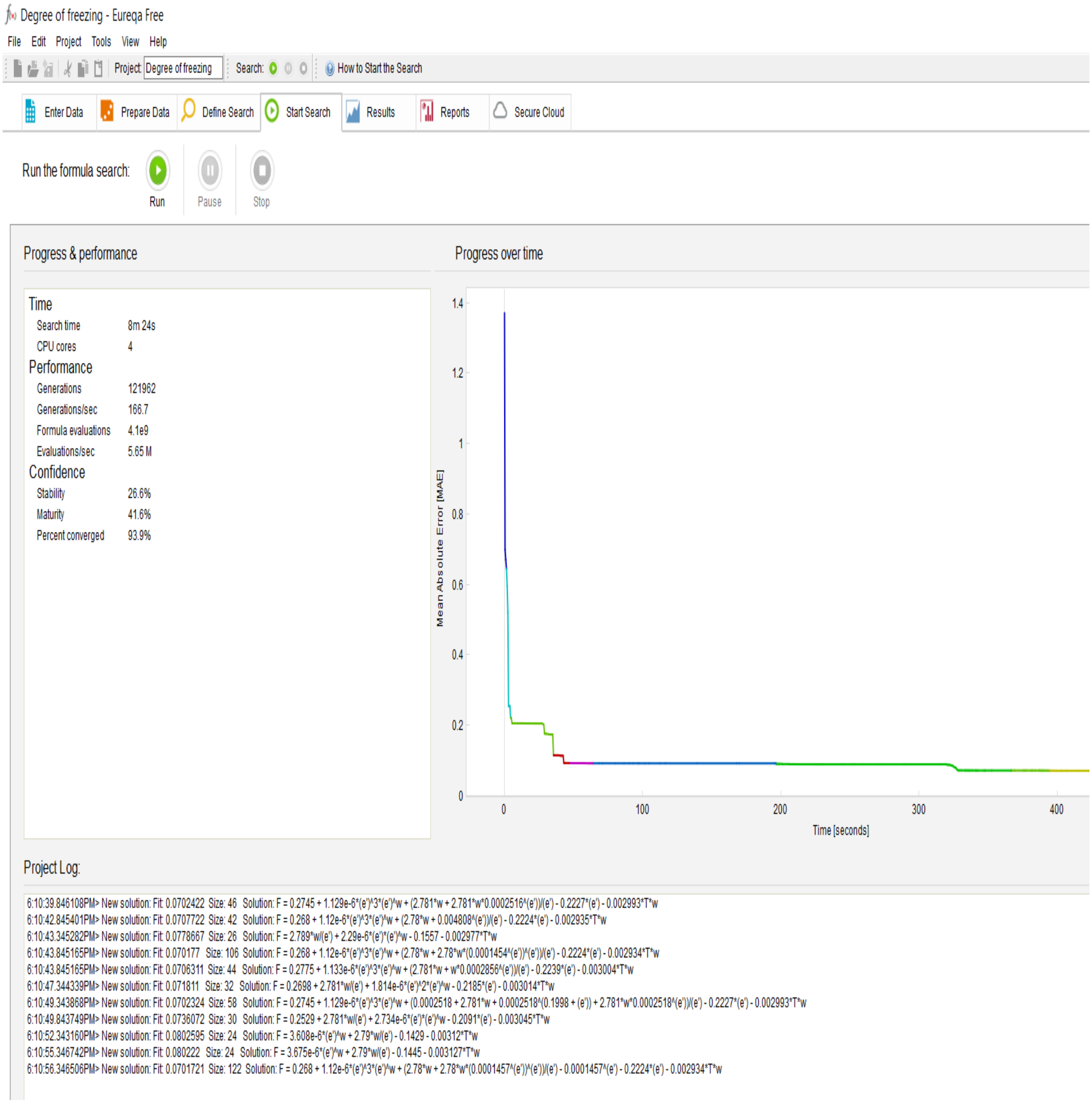


Figure 4.22: Starting search in eureqa software for degree of freezing function.

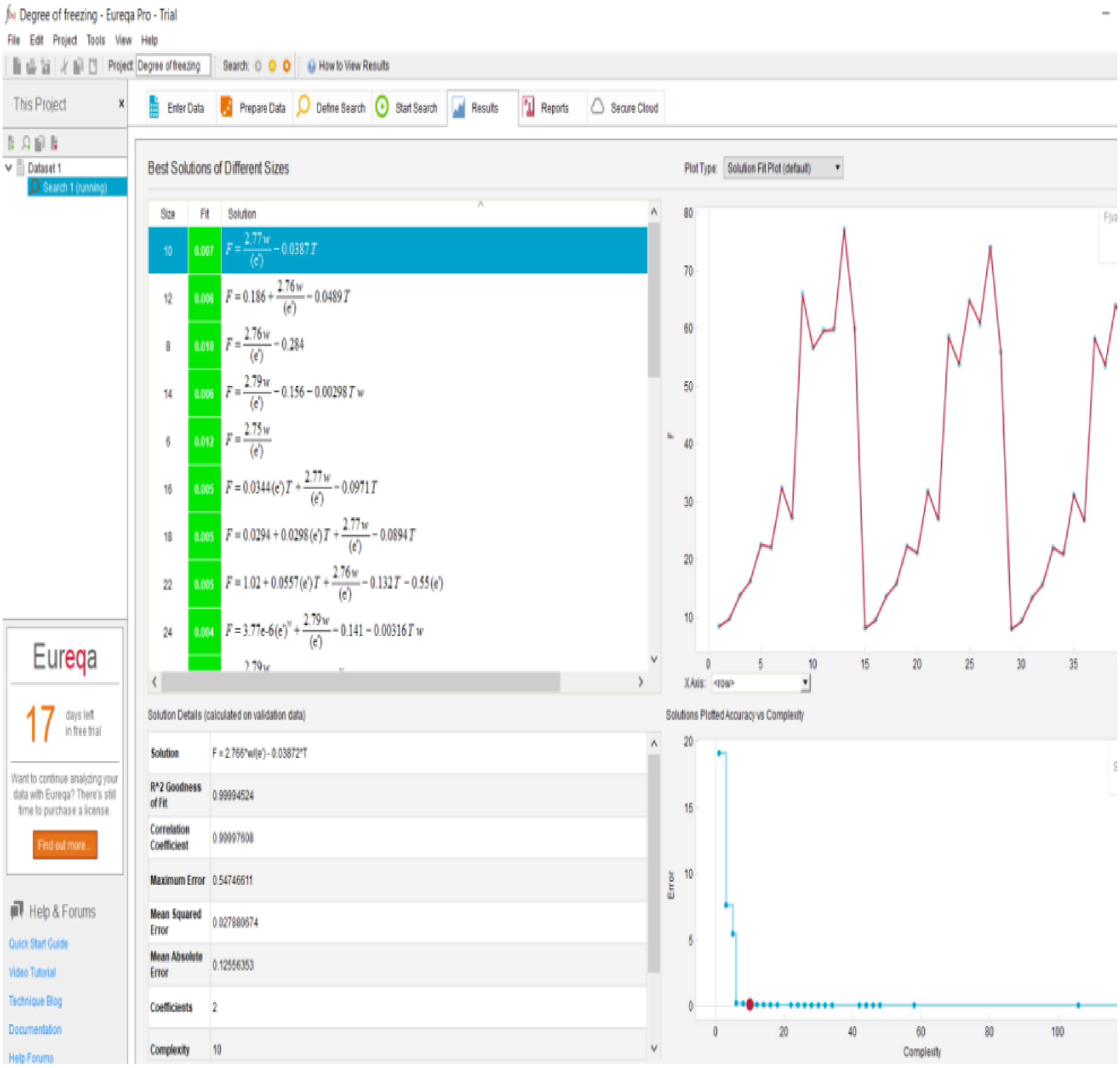


Figure 4.23: Results for degree of freezing in eureqa software.

The relationship found is:

$$F = (2.77\ w/e') - 0.0387(T) \qquad \text{……..(11B)}$$

4.1.5 Porosity

Porosity of soil is a function of temperature. When temperature becomes negative, the water present in the pores converts into ice which expands in volume. The increased volume of ice at first try to occupy all the void space. Once occupied, on further increase in water content, more water turns into ice which expands more than the void space. This thereby increases the volume of voids. When volume of voids increases, the porosity will also increase. By entering data obtained from laboratory shown in table 4.6 in the Eureqa software, relationship can be obtained. The function of porosity with temperature can be given by;

$$n' = f(n,w,T) \quad \ldots\ldots..(12)$$

Table 4.6 Porosity at normal (n) and frozen temperature (n')

Unfrozen soil porosty	Water content (%)	Temperature (°C)	Frozen soil porosity	% change in porosity
n	w	T	n′	z
0.656	6	-5	0.661	0.66
0.625	6	-5	0.628	0.63
0.663	10	-5	0.665	0.67
0.625	10	-5	0.628	0.63
0.616	14	-5	0.631	0.63
0.631	14	-5	0.636	0.64
0.589	18	-5	0.605	0.61
0.640	18	-5	0.647	0.65
0.448	22	-5	0.480	0.48
0.515	22	-5	0.518	0.52
0.544	26	-5	0.546	0.55
0.540	26	-5	0.545	0.55
0.515	30	-5	0.518	0.52
0.558	30	-5	0.581	0.58
0.656	6	-10	0.664	0.66
0.625	6	-10	0.629	0.63
0.663	10	-10	0.666	0.67
0.625	10	-10	0.632	0.63
0.616	14	-10	0.631	0.63
0.631	14	-10	0.644	0.64
0.589	18	-10	0.607	0.61
0.640	18	-10	0.647	0.65
0.448	22	-10	0.508	0.51
0.515	22	-10	0.529	0.53
0.544	26	-10	0.525	0.53
0.540	26	-10	0.540	0.54
0.515	30	-10	0.527	0.53
0.558	30	-10	0.596	0.60
0.656	6	-15	0.664	0.66
0.625	6	-15	0.629	0.63
0.663	10	-15	0.666	0.67
0.625	10	-15	0.632	0.63
0.616	14	-15	0.632	0.63
0.630	14	-15	0.645	0.65
0.589	18	-15	0.610	0.61
0.640	18	-15	0.647	0.65
0.448	22	-15	0.508	0.51

0.515	22	-15	0.529	0.53
0.544	26	-15	0.527	0.53
0.54	26	-15	0.541	0.54
0.515	30	-15	0.527	0.53
0.559	30	-15	0.597	0.60

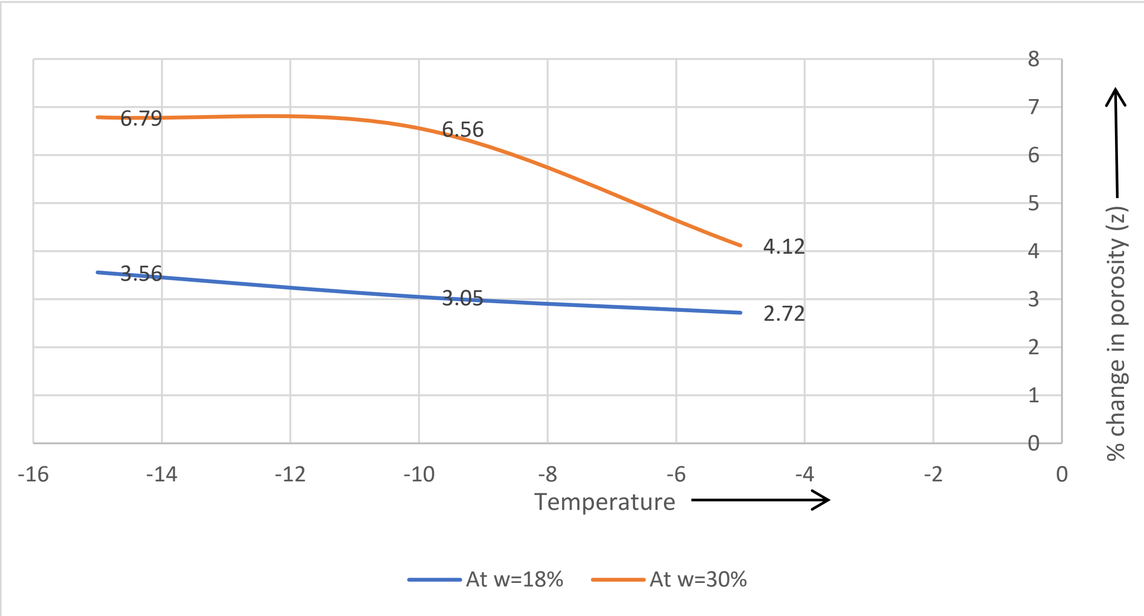


Fig. 4.24 Graph of % change in Porosity (z) vs Temperature.

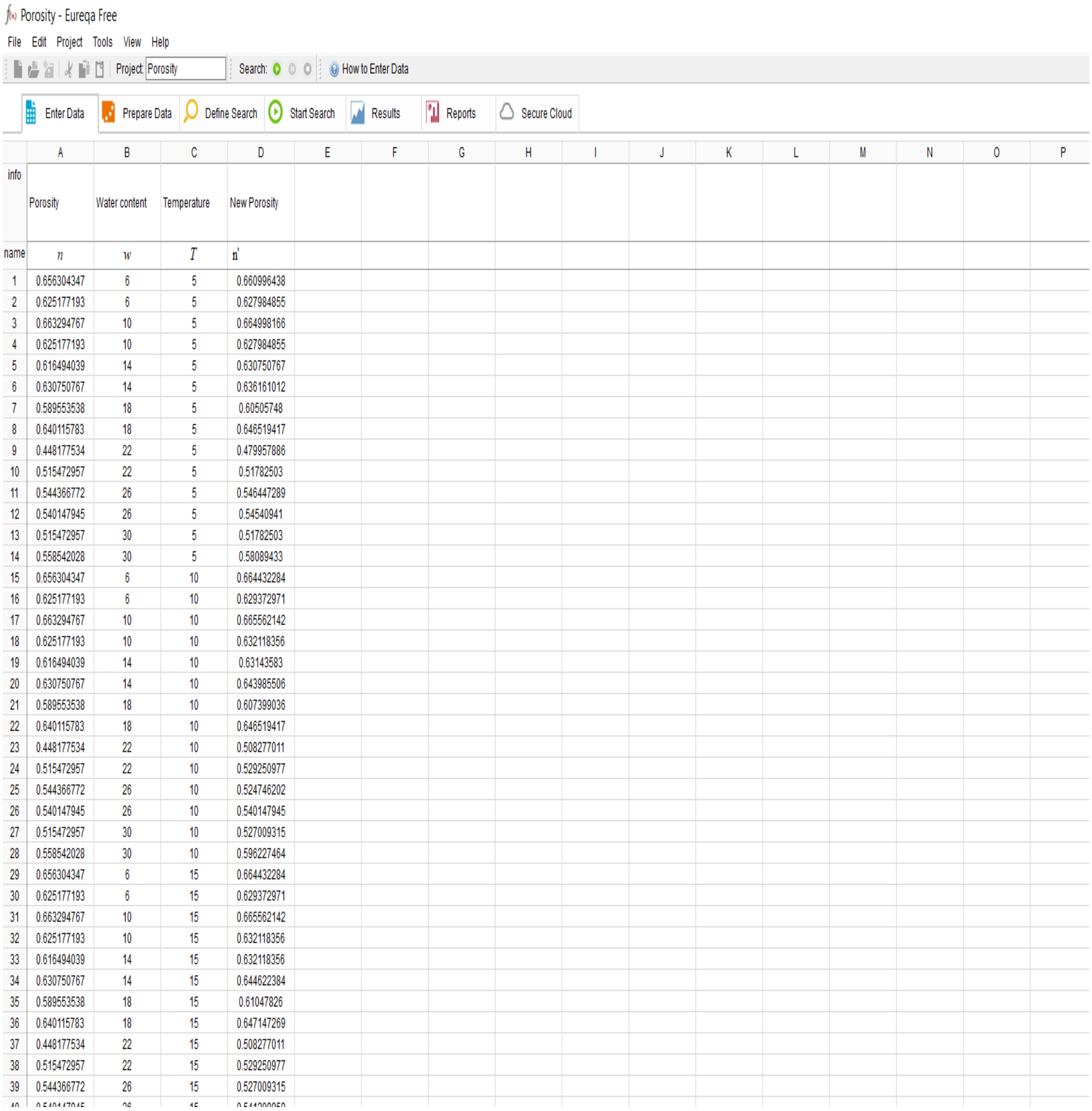
In figure 4.24, a graph between percentage of change in porosity vs temperature is plotted. The trend of the curve suggest that at more water content, the change is more visible marked with a steep slope. This is because more water will convert into ice and volume of voids will increase sharply in case of higher water content.

Steps to run search on software:

1. After creating a table of inputs and output for porosity function, open eureqa software.
2. An excel sheet will gets open, enter the data in different columns like porosity of soil (n) at normal room temperature in column 1, water content (w) in column 2, temperature (T) in column 3, porosity of frozen soil (n’) in column 4 as shown in figure 4.25.
3. Now, click on “prepare data” tab to smoothen the data points if necessary as shown in figure 4.26.
4. Now, click on “Define data” tab to define the relationship between input and output data. For example, n’= f(n, w, T). Also, select the operators you want to use in your functions like add, subtract, divide, multiply, exponent, etc. as shown in figure 4.27.

5. Now click on “start search” tab and click on “Run” to start the search as shown in figure 4.28.

6. Now, click on “Results” tab to see the formulae so obtained in the search with their amount of errors as shown in figure 4.29.



	A	B	C	D
info	Porosity	Water content	Temperature	New Porosity
name	n	w	T	n'
1	0.656304347	6	5	0.660996438
2	0.625177193	6	5	0.627984855
3	0.663294767	10	5	0.664998166
4	0.625177193	10	5	0.627984855
5	0.616494039	14	5	0.630750767
6	0.630750767	14	5	0.636161012
7	0.589553538	18	5	0.60505748
8	0.640115783	18	5	0.646519417
9	0.448177534	22	5	0.479957886
10	0.515472957	22	5	0.51782503
11	0.544366772	26	5	0.546447289
12	0.540147945	26	5	0.54540941
13	0.515472957	30	5	0.51782503
14	0.558542028	30	5	0.58089433
15	0.656304347	6	10	0.664432284
16	0.625177193	6	10	0.629372971
17	0.663294767	10	10	0.665562142
18	0.625177193	10	10	0.632118356
19	0.616494039	14	10	0.63143583
20	0.630750767	14	10	0.643985506
21	0.589553538	18	10	0.607399036
22	0.640115783	18	10	0.646519417
23	0.448177534	22	10	0.508277011
24	0.515472957	22	10	0.529250977
25	0.544366772	26	10	0.524746202
26	0.540147945	26	10	0.540147945
27	0.515472957	30	10	0.527009315
28	0.558542028	30	10	0.596227464
29	0.656304347	6	15	0.664432284
30	0.625177193	6	15	0.629372971
31	0.663294767	10	15	0.665562142
32	0.625177193	10	15	0.632118356
33	0.616494039	14	15	0.632118356
34	0.630750767	14	15	0.644622384
35	0.589553538	18	15	0.61047826
36	0.640115783	18	15	0.647147269
37	0.448177534	22	15	0.508277011
38	0.515472957	22	15	0.529250977
39	0.544366772	26	15	0.527009315

Figure 4.25: Data entering in eureqa software for porosity function.

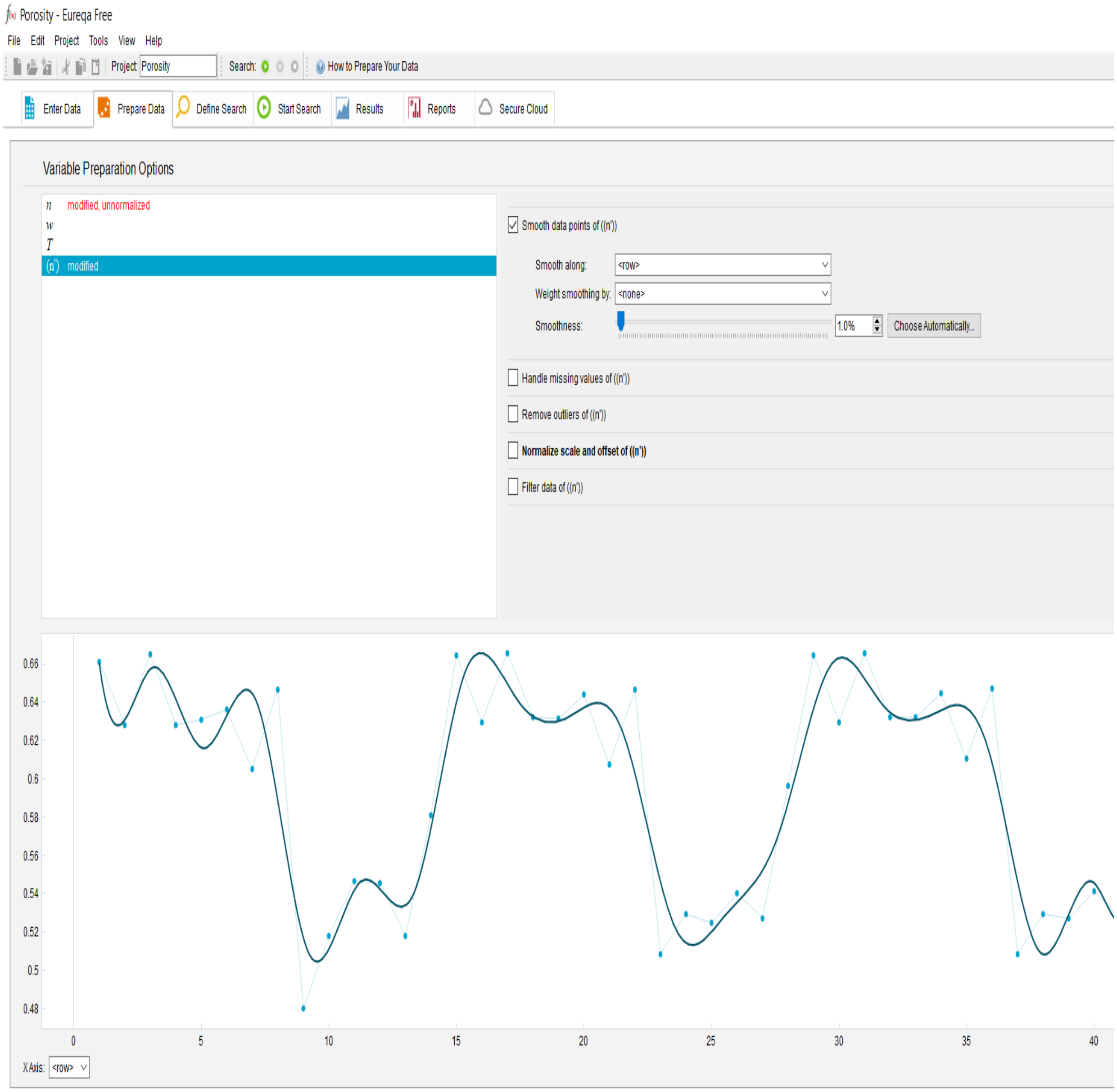


Figure 4.26: Preparing data in eureqa software for porosity function.

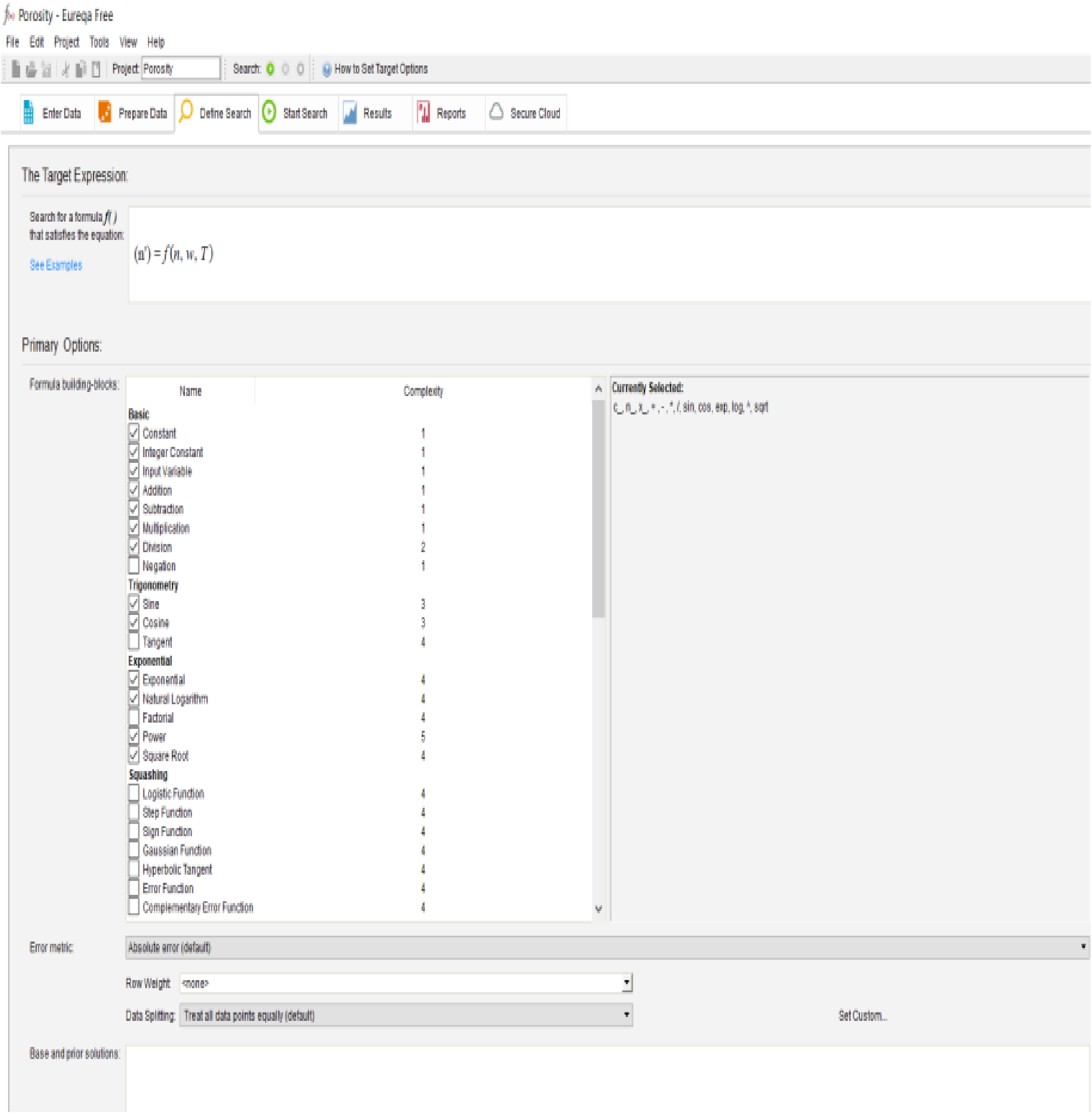


Figure 4.27: Defining search in eureqa software for porosity function.

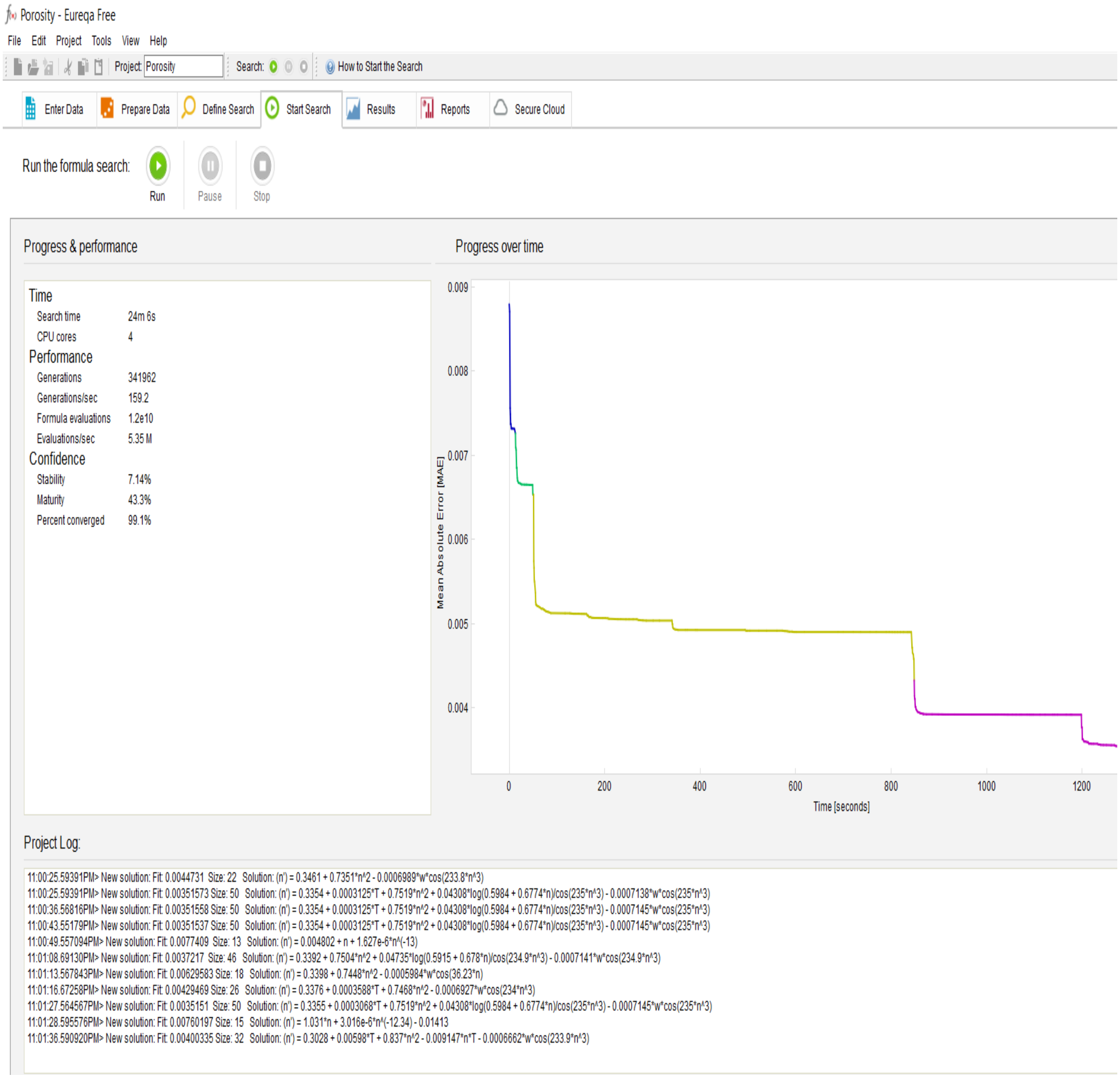


Figure 4.28: Starting search in eureqa software for porosity function.

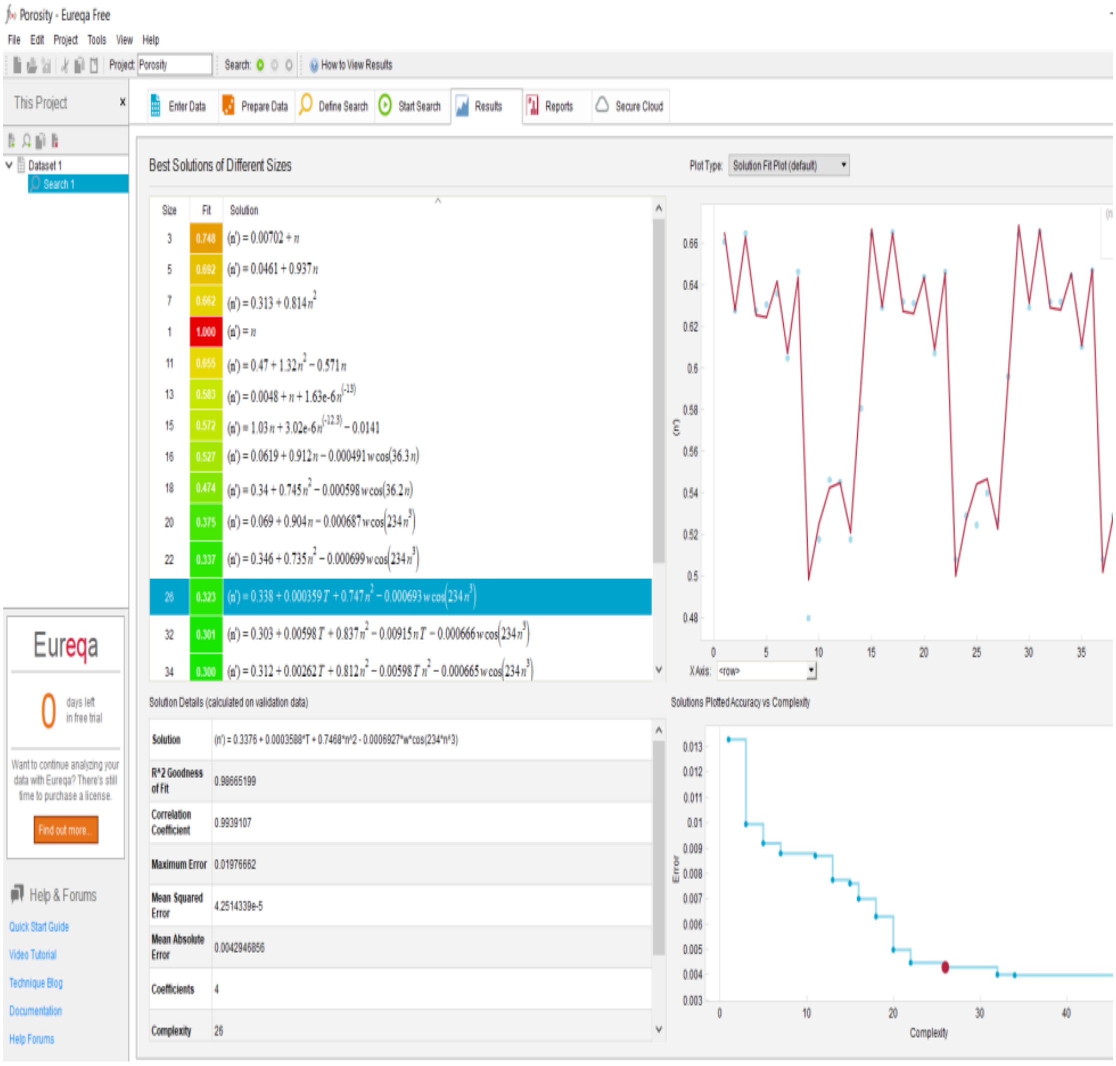


Figure 4.29: Results for porosity function in eureqa software.

$$n' = 0.3376 + 0.0003*T + 0.74*n^2 - 0.00069*w*\cos(234*n^3) \quad \ldots\ldots..(12A)$$

Where,

n’= Porosity of frozen soil

T= Temperature in degree Celsius

n= Porosity at room temperature

The above function has the maximum error of 0.021.

After performing the soil parameters analysis on Eureqa software above, the following relationships are obtained.

a) $W' = W + 0.992w - 0.000208\, W(-T)$

Using this formula, one can obtain the water content of frozen soil if weight of frozen soil, weight of soil at room temperature and Temperature of frozen soil is known. This formula thereby helps in calculating the water content of soil sample theoretically.

b) $e' = e + 0.00503(-T)$

Using this formula, one can obtain the void ratio of frozen soil if the void ratio of same soil sample at room temperature is known and the temperature of frozen soil is also known.

c) $\gamma_t' = \gamma_t - 0.0019(-T)\gamma_t^2$

Using this formula, one can calculate the bulk density of frozen soil sample, if the bulk density of same soil sample under room temperature is known along with the temperature at which frozen bulk density is required.

d) $F = (2.77\, w/e') - 0.0387(T)$

Where, F is the degree of freezing which will give the fraction of water which is converted into ice.Using this formula, one can calculate the degree of freezing can be calculated which will tell the amount of freezing occurred in the frozen sample. This term is analogous to degree of saturation in normal room temperature soil which tells the amount of saturation of soil sample.

e) $n' = 0.3376 + 0.0003*T + 0.74*n^2 - 0.00069*w*\cos(234*n^3)$

Using this formula, one can obtain the porosity of frozen soil if the porosity of same soil sample at room temperature is known and the temperature of frozen soil is also known.

Where,

W'= Weight of Frozen soil.

W = Weight of soil at room temperature.

T = Temperature at which soil is being investigated.

W = Water content of soil.

γ_t' = Bulk unit weight of frozen soil.

γ_t = Bulk unit weight of soil at room temperature.

F = Degree of freezing.

n = Porosity of soil at room temperature.

n' = Porosity of frozen soil.

4.2 Discussion

There are five relationships that have been established between unfrozen and frozen soils. Formulae so obtained are valid up to -20 degree Celsius and are tested on sandy soil. Below this temperature, the soil parameter becomes constant. Therefore at -20 degree Celsius, the soil becomes fully frozen, and the water present in the voids of the soil is fully transformed into ice by going through crystal phase. The leads of this study can help other authors for detail study of frozen soils and to take the results of this research to dig further into the newly studied branch of Frozen Soil mechanics.

The Novelty of this work lies in the methodology of the work performed, as this it includes a new idea of relating the properties of frozen soil with that of unfrozen soil. From these relationships one can found properties of frozen soil if the data of unfrozen soil is available and vice-versa. While all the research that have been done on frozen soil prior to this is about mechanical, physical, biological and chemical properties but the basic idea about relationship between characteristics of soil like its porosity, void ratio, bulk density, etc at different temperature is forming a gap in the studies that needs to be fulfilled to get the knowledge about how these characteristics changes as the temperature drops to negative values.

In various regions of Northern India, the temperature goes as high to 20 degrees Celsius but for a small period of time, while throughout the major period of time it remains negative. For such sites and for other colder regions, if data is obtained for soil at higher temperature (say, 20 degrees Celsius), then when the same soil becomes frozen then the relationships developed in this research would be helpful to determine the characteristics at frozen temperature.

For example, if the value of void ratio is 0.6 at 25° Celsius, its water content is 25% and it is required to calculate void ratio and degree of freezing of same soil at same density at -20° Celsius. To calculate this, one needs not to measure void ratio of frozen soil if he have a handy formula with him.

$$e' = e + 0.00503(-T) \qquad \text{……..(from 8A)}$$

And,

$$F = (2.77\ w/e') - 0.0387(T) \quad \text{……..(from 11B)}$$

Therefore, the value of void ratio at -20 degree Celsius of the given soil sample will be 0.7006 and the degree of freezing will be 99.617% which means at -20 degree Celsius, almost all the water content is converted into ice and the soil tends to be fully frozen.

Likewise, formulae for porosity, weight of soil, bulk density developed in this research will help the site engineers to have reliable formulae to measure these parameters of frozen soil if unfrozen soil data is available. The formulae will also help in determining several other functions that uses these parameters.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

- The formulae obtained will help cover the gaps in the literature review by providing basic information about frozen soil and its parameters.
- This study can be used for practical purpose as the data obtained by the author in the laboratory is true and self-verified. The constructions done in colder regions can use the formulae so obtained to carry out soil investigation and understand the frozen soils in a better way. The results so obtained will help to know any parameter of soil at different freezing temperature if there values at normal room temperature is known or vice-versa.
- The study can play a vital role in determining the parameters of frozen soil and can also prove helpful in further studies on frozen soils.
- The study inculcate all the references and thorough reviewing of the literature reviews related to the field of frozen soil.

5.2 Recommendations for the future work

As this study is for the locally available soil i.e., sand, the work can be further extended to different soil types like clay, silt and gravels. By following same experimental procedure and similar simulation technique, the results for different soil types can be found.

Also, this work opens up a door to different new possibilities. By using these results as to calculate different parameters and then utilizing those parameters to estimate the settlement, bearing capacity and other such properties of soil. For example, void ratio is used in the calculation of soil settlement, therefore, settlements of frozen soil may depend on its void ratio too.

References

1. Altuhafi, F.; Baudet, B.. A hypothesis on the relative roles of crushing and abrasion in the mechanical genesis of a glacial sediment. Engineering Geology. **2011**. 10.1016/j.enggeo.2011.03.002.
2. Andersland, O. B., and Ladanyi, B.; Frozen Ground Engineering. New York: Wiley; **2004**.
3. Andersland, O.B., Ladanyi, B. An introduction to frozen ground engineering. Chapman and Hall, New York. **1984**.
4. Azmatch, T.F., Sego, D.C., Arenson, L.U., and Biggar, K.W. Using soil freezing characteristic curve to estimate the hydraulic conductivity function of partially frozen soils. Cold Reg. Sci. Technol. **2012**. 83–84: 103– 109.
5. Baker, J.M., and Spaans, E.J.A. Mechanics of meltwater above and within frozen soil. In: CRREL Spec. Rep. 79. US Army Corps of Eng., Cold Regions Res. Eng. Lab., Hanover, NH.**1997.** p. 31– 36.
6. Bakulin, F.G. and Zhukov; Deformations of Frozen Dispersed Soils during Thawing; **1955**.
7. Burt, T.P., and Williams, P.J. Hydraulic conductivity in frozen soils. Earth Surf. Processes.**1976.** 9: 411– 416.
8. Chang, Dan; Lai, Yuanming; Gao, Jianqiang. An investigation on the constitutive response of frozen saline coarse sandy soil based on particle breakage and plastic shear mechanisms.Cold Regions Science and Technology. **2018**. 10.1016/j.coldregions.
9. Edwards, A. C., Cresser, M. S.; Freezing and Its effect on Chemical and Biological Properties of Soil; **1992**.
10. Eranti, E., and Lee, G. C.. Cold Region Structural Engineering. USA: McGraw Hill.**2000.**
11. Eureqa Software Created by: Michael Schmidt and Hod Lipson. **2009.**
12. Fish, A.M.: Strength of frozen soil under a combined stress state. In: Proc., 6th Int. Symp. on Ground Freezing, Beijing, China, **1991**. vol. 1, pp. 135–145.
13. Janoo, V.; Shoop, S. Study of shear strength of silty clay under freeze-thaw cycle. Earth Environment Science. **2019.** 330 042009.
14. Khoroshilov, K., Katarov, V.; Gavrilov, Timmo; Kolesnikov, Gennady. Strength and Elastic Modulus of Frozen Sandy Soil as a Material for a Logging Road. Resources and Technology. **2019**. 10.15393/j2.art.2019.4742.
15. Li, D.W., Wang, R.H., Zhao, Y.H., Hu, P. Research on parabolic yield-surface creep constitutive model of artificial frozen soil. Rock Soil Mech. **2007**. 28(9), 1943–1948.

16. Liu, Tiejun; Xu, Xiangtian; Yang, Jie. Experimental study on the effect of freezing-thawing cycles on wind erosion of black soil in Northeast China. Cold Regions Science and Technology. **2017**. 10.1016/j.coldregions.

17. Merzlyakov, V. Physical and Mechanical Conditions for Primary Frost Crack Formation. Soil Mechanics and Foundation Engineering. **2016**. 10.1007/s11204-016-9389-1.

18. Qi, Jilin; State-of-art of research on mechanical properties of frozen soils; Springer Series in Geomechanics and Geoengineering, pp. 129-133, **2010.**

19. Shen, Mingde; Zhou, Zhiwei; Zhang, Shujuan. Effect of stress path on mechanical behaviors of frozen subgrade soil. Road Materials and Pavement Design. **2021**. 10.1080/14680629.2020.1869583.

20. Smith; Chen; Haofeng. Lower and Upper Bound Shakedown Analysis of Structures With Temperature-Dependent Yield Stress. Journal of Pressure Vessel Technology.**2010.** 132. 10.1115/1.4000369.

21. Tulaczyk, Slawek; Kamb, W.; Engelhardt, Hermann. Basal mechanics of Ice Stream B, West Antarctica 1. Till mechanics. Journal of Geophysical Research. **2000**. 10.1029/1999JB900329

22. Viklander, P. Influence of cycles of freezing and thawing on the permeability in soils. Lulea University of Technology.**1995**. SE-971 87.

23. Xu, Xiangtian; Lai, Yuanming; Dong, Yuanhong; Qi, Jilin. Laboratory investigation on strength and deformation characteristics of ice-saturated frozen sandy soil. Cold Regions Science and Technology. **2011**. 10.1016/j.coldregions.2011.07.005.

24. Zhu, Y.L., Carbee, D.L. Creep behavior of frozen silt under constant uni-axial stress In: Proc., 4th Int. Conf. on Permafrost, Fairbanks, Alaska, pp. **1984**. 1507–1512.

25. Zhu, Zhi-Wu; Ma, Yue; Zhang, Hai-Dong; Song, Weidong; Gan, Yuan-Chao. Evaluation of thermal effects and strain-rate sensitivity in frozen soil. Thermal Science. **2014**. 10.2298/TSCI1405631Z.

Appendix

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