

# Experimental Studies on Frozen Soil

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## Research Article

**Keywords:** Frozen Soil, Soil Experimentation, Frozen Soil Parameters. Frozen Soil Tests

**Posted Date:** August 12th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-803641/v1>

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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. For constructions at normal room temperature, there are plenty of experimentation and research data on soil is available. But lack of research data 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 iced condition to get a better idea about the behaviour of frozen soils. There are few research on construction and mechanical behaviour of frozen soil but no study on the very basic parameters of like void ratio, bulk density, porosity, and the degree of freezing and 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 between 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 negative temperature (-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 relation that exist in the soil parameters.

## 1 Introduction

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 like 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 [9]. 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. [4]. 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 [3]. 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. The author will 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[18] 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 Eureka 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.

The purpose of this research is to study the behaviour of glacial soils or frozen soil and establish relationships between different characteristics of soil, which was observed by Smith et al. [2]. Andersland and Ladanyi [6], performed certain tests and observed that the surface area, expandable clay lattice and the activity ratio, was deviated to what assumed. Viklander [5] conducted triaxial drainage shearing 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. Janoo and Shoop [1], grouped undisturbed fine-grained soil and remoulded them into saturated remolded 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 [12], 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 [13]. Tulaczyk et al. [20], inferred those studies on the behaviour of glacial sediments are limited, and those studies are concentrated only on investigating ultimate strength of frozen soil and mechanical behaviour. An elaborative model considering the particle breakage and its plastic shear mechanisms is established by Chang et al. [24]. The shear strength and elastic modulus of frozen soil as studied by Khoroshilov et al. [25], 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. [15]. 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 [11]. The mechanical properties of frozen soil, the stress-strains are discussed deeply in Qi et al. [19] and Shen et al. [17]. The books on the chemical and biological properties, Edwards and Cresser [12], Merzlyakov [23] and the creep in frozen soil, Fish [7], Eranti and Lee [14] and Andersland and Ladanyi [16]. Further, various research has been done on flow throw partially frozen soil. For example, hydraulic conductivity calculated by Azmatch et al. [8] and Burt and Williams [10] in partially frozen soil. Research work is also done on fully frozen soils. For example, strength and deformation characteristics of fully frozen soil by Xu et al. [22] and the thermal effects and strain rates by Zhu et al. [21]. 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 Methodology

The soil is mixed with certain amount of water(i.e., known water content) and then filled in 100ml cylindrical beakers with different bulk densities. Sample represents soil condition in open ground of colder regions. The sample is placed in a freezer to replicate the temperature conditions of colder regions. In this study, the working temperatures are 20, -5, -10, -15, -20 degree Celsius which is 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 eureka software.

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 degrees 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.
- B. Take out samples from this soil bag. Sieve the soil for classification. For this research, locally available soil is used and sieve analysis is done on that.
- C. Let the dry weight of soil sample=  $W_s$

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

$$w = (W_w/W_s) \quad \dots\dots(1)$$

- D. Separately, determine specific gravity( $G_s$ ) of soil solids using pycnometer test.

And relate it with equation (2) to get value of  $\gamma_s$ . As per **IS-2720-PART-3-1980**.

$$G_s = (\gamma_s/\gamma_w) \quad \dots\dots(2)$$

Once,  $\gamma_s$  is calculated volume of soil solids will be further calculated by

$$\gamma_s = (W_s/V_s) \quad \dots\dots(3)$$

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

$$e = (V_v/V_s) \quad \dots\dots(4)$$

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

$$V_v = (V_t - V_s) \quad \dots\dots(5)$$

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

H. After 24 hours, take the sample out and weigh it. Also measure 5 heights from different sides should be measured of the sample and the average is taken. Do this step as soon as possible to avoid error due to temperature change.

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

$$w' = (W_i / W_s) \quad \dots\dots(6)$$

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.

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

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 **Fig 2.1**.

### 3 Observations And Results

In this study, the author has studied the following soil parameters and their relationship at various temperature. The study is performed on locally available soil and the soil gradation curve after sieve analysis suggest that the soil is well graded sand. The  $C_u$  and  $C_c$  of the soil found is 8.33 and 1.09 respectively. The gradation curve for the soil is shown in **figure 3.1**.

After performing the experimental studies on frozen soil, following relationship between parameters of frozen and unfrozen soil at varying temperatures are found.

### 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, Eureka software gives the following relationships (**Fig. 3.2**) The weight function would be:

$$W' = f(W, w, T) \quad \dots\dots(7)$$

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

$W$  is the weight of soil at room temperature

$T$  is the temperature of frozen soil.

The relationship found is:

$$W' = W + 0.992w - 0.000208 W(-T) \quad \dots\dots(7A)$$

This relationship has the maximum error of 0.18.

## Void Ratio

The void ratio of soil will change with temperature as the volume of water gets increased when 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, the following relationship is obtained by the eureka Software (**Fig. 3.3**).

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

$$e' = e + 0.00503(-T) \quad \dots\dots(8A)$$

Where  $T$  is in Degree Celsius.

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 3.4. This is because more water will convert into ice and volume of voids will increase sharply in case of higher water content.

## 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, the following relationship is obtained by eureka software(**Fig. 3.5**)

The function is

$$Y_t' = f(Y_t, w, T) \quad \dots\dots(9)$$

$$Y_t' = Y_t - 0.0019(-T)Y_t^2 \quad \dots\dots(9A)$$

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.

## 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 leads to the following result in eureka software (**Fig. 3.7**)

$$S = (w \cdot G_s) / e \quad \dots\dots(10)$$

The relationship is given by,

$$F = f(w, e', T) \quad \dots\dots(11)$$

$$F = (2.77 w / e') - 0.0387(T) \quad \dots\dots(11A)$$

where F is the degree of freezing computed as,

$$F = V_i / V_v \quad \dots\dots(11B)$$

## 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 in the Eureka software, the following relationship is obtained (**Fig. 3.8**). The function of porosity with temperature can be given by;

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

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

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.

In **figure 3.9**, 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.

After performing the soil parameters analysis on eureka software above, the author come across various results as follows:

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 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.  $F = (2.77 w/e') - 0.0387(T)$

Using this formula, one can calculate the degree of freezing which will indicate 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.

$\gamma'_t$  = Bulk unit weight of frozen soil.

$\gamma_t$  = 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 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 paper 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 20 degrees 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 degree Celsius. To calculate this, one needs not to measure void ratio of frozen soil if he have a handy formula with him.

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

And,

$$F = (2.77 w/e') - 0.0387(T) \dots\dots(\text{from } 11A)$$

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.

## 5 Conclusion

- The main objective of this paper i.e., to find relationships between properties of soil at frozen state to that of at room temperature is achieved. Different formulae are obtained using eureka software in which the author entered the data obtained by him in the laboratory of Delhi Technological University, Delhi, India.
- 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.
- This study can play a vital role in determining the parameters of frozen soil and can also prove helpful in further studies of frozen soils.
- This research inculcate all the references and thorough reviewing of the literature reviews related to the field of frozen soil.

## Declarations

**Acknowledgments.** The authors would like to thank all the teachers and laboratory assistants in Delhi Technological University for helping and providing all necessary types of equipment required in the successful completion of this study.

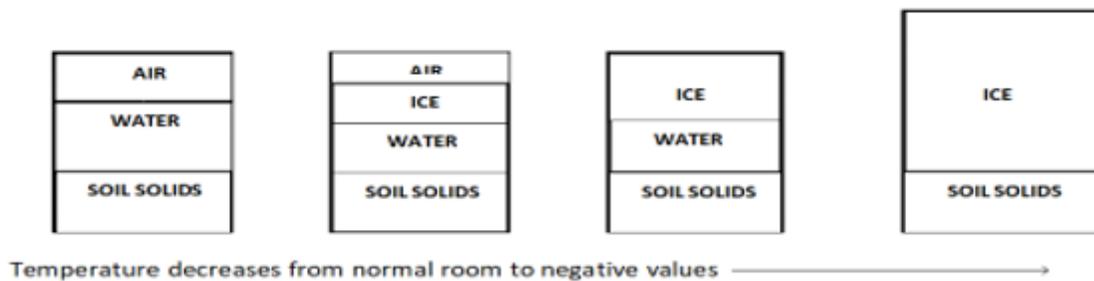
**Conflict of Interest.** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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## Figures



**Figure 1**

4-Phase diagram of soil

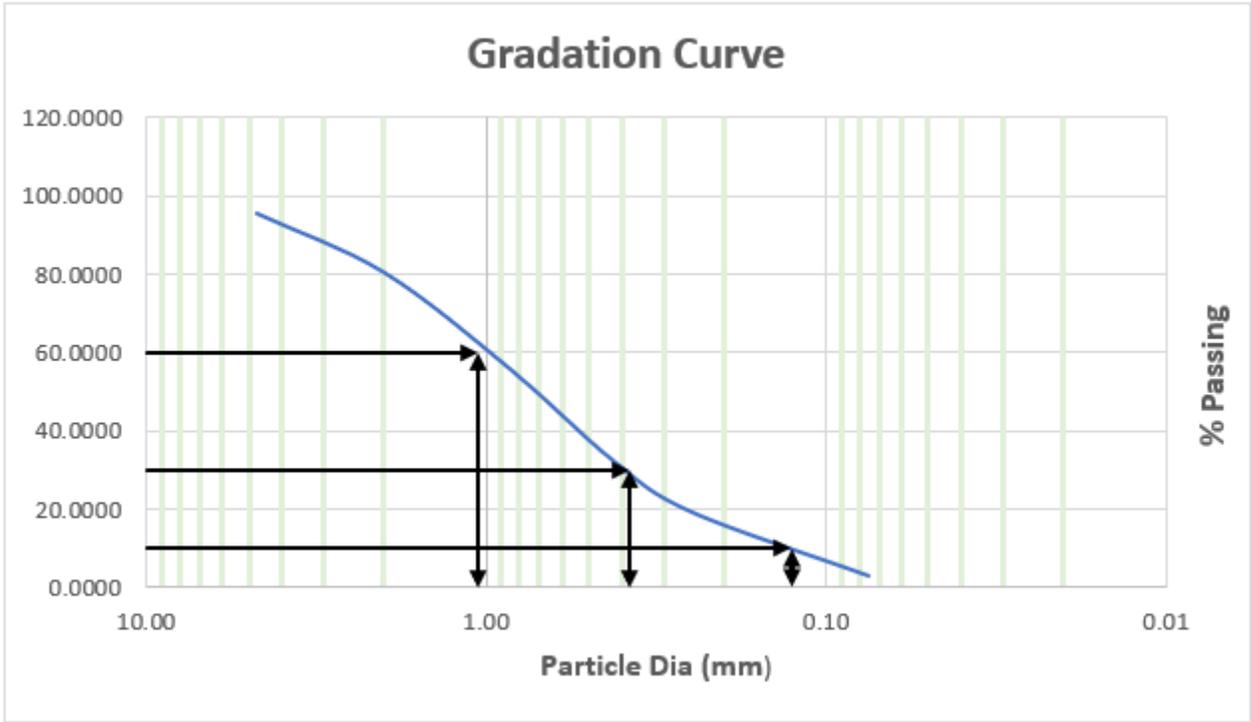


Figure 2

Gradation curve for the soil.

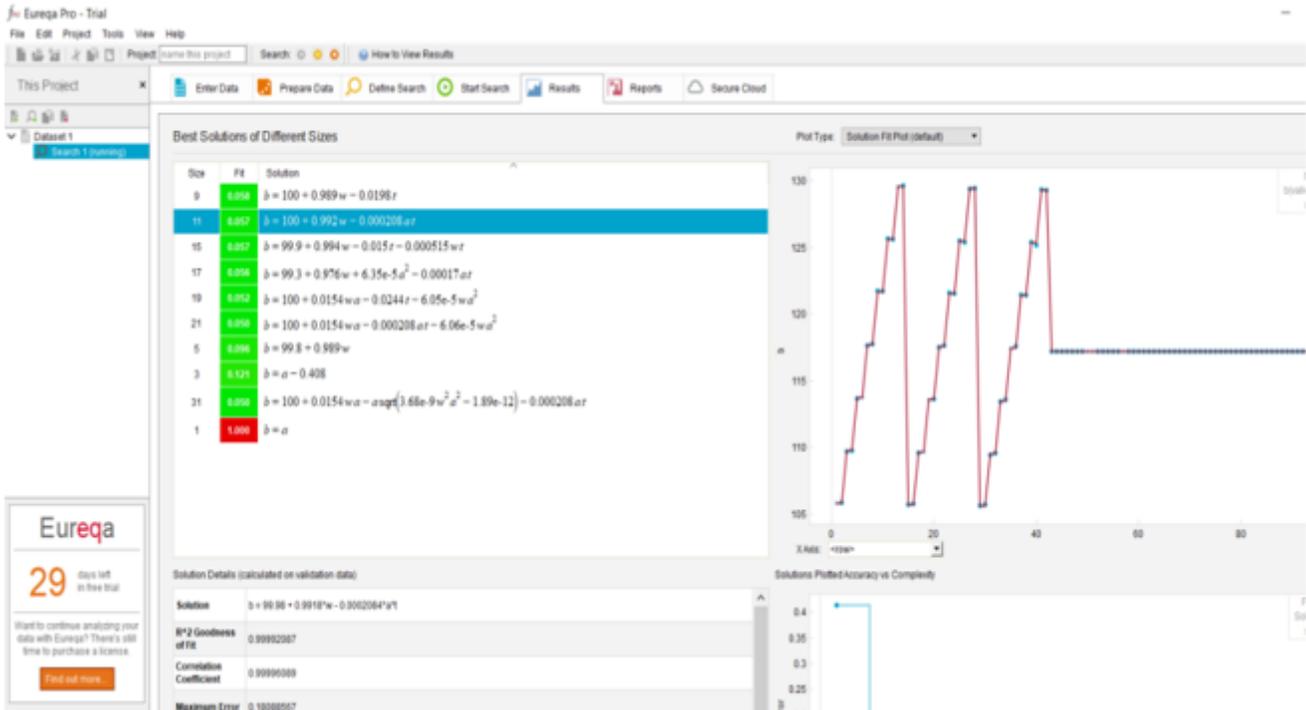


Figure 3

Weight relationship

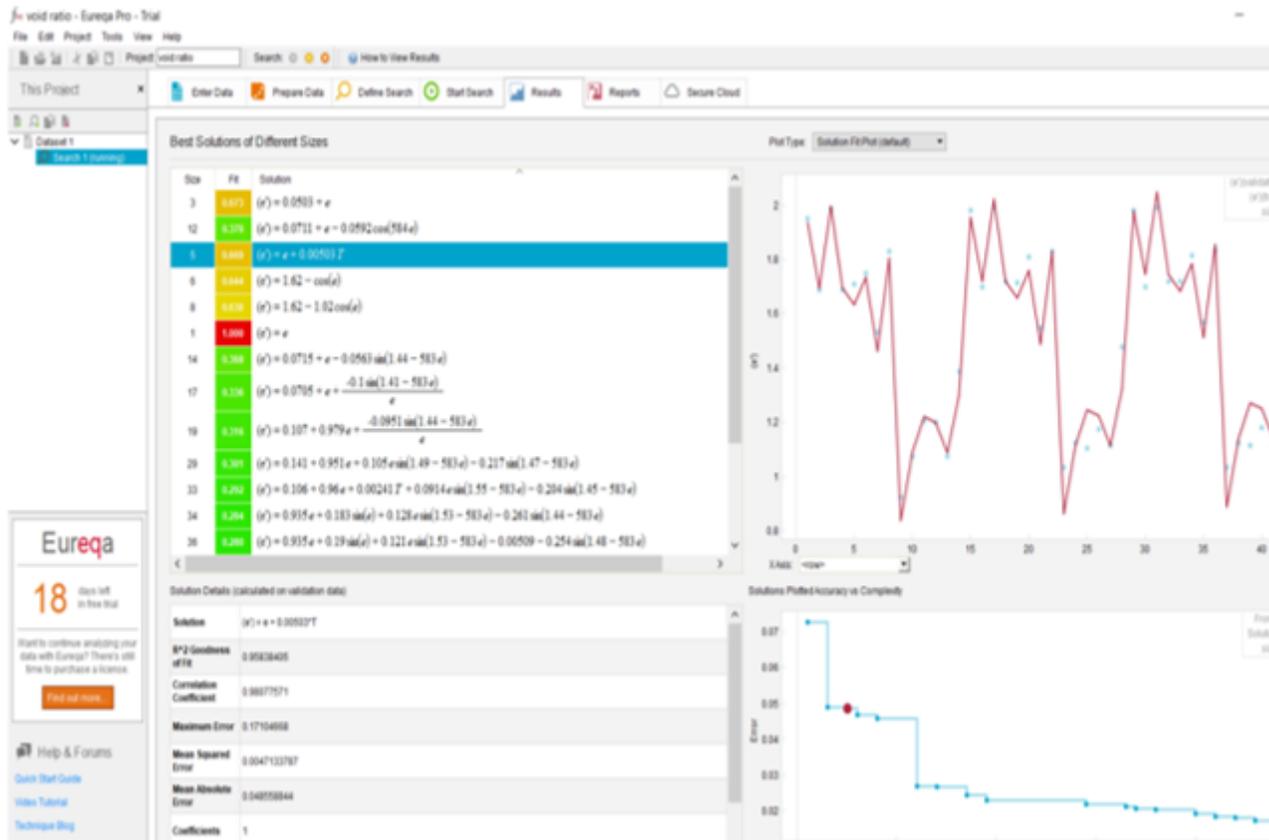


Figure 4

Void ratio relationship.

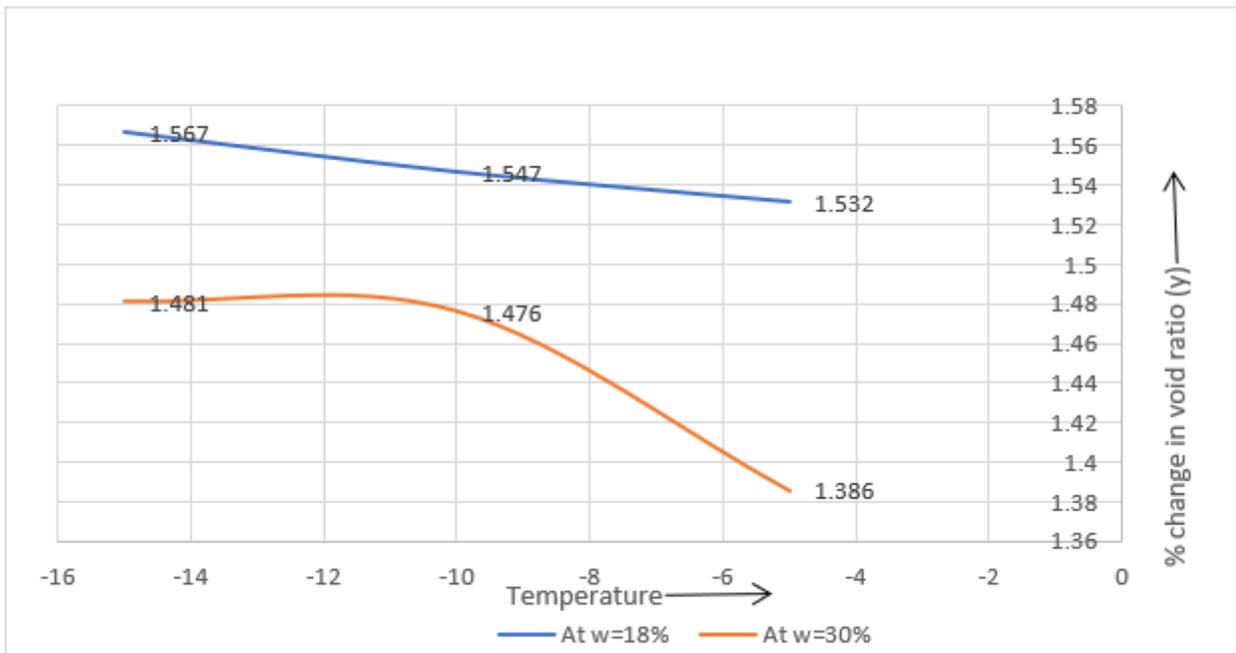


Figure 5

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

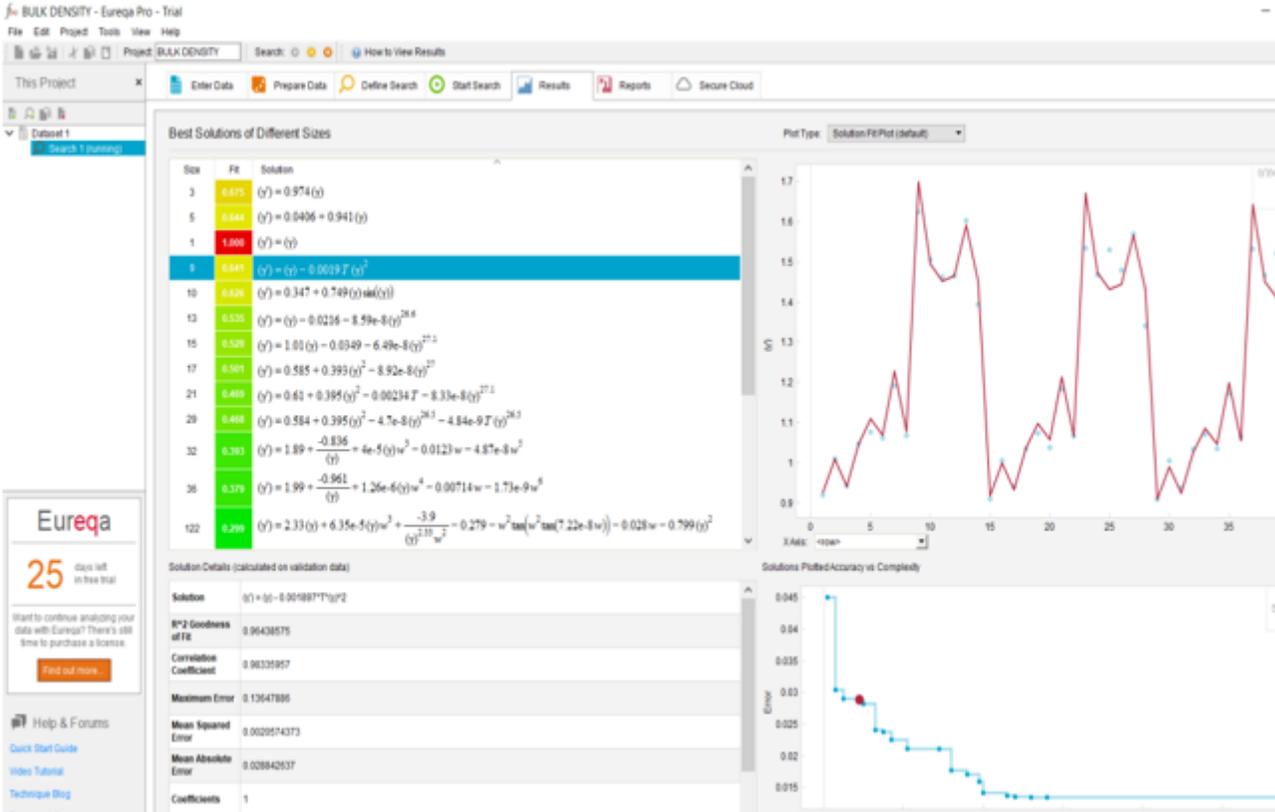


Figure 6

Bulk density relationship.

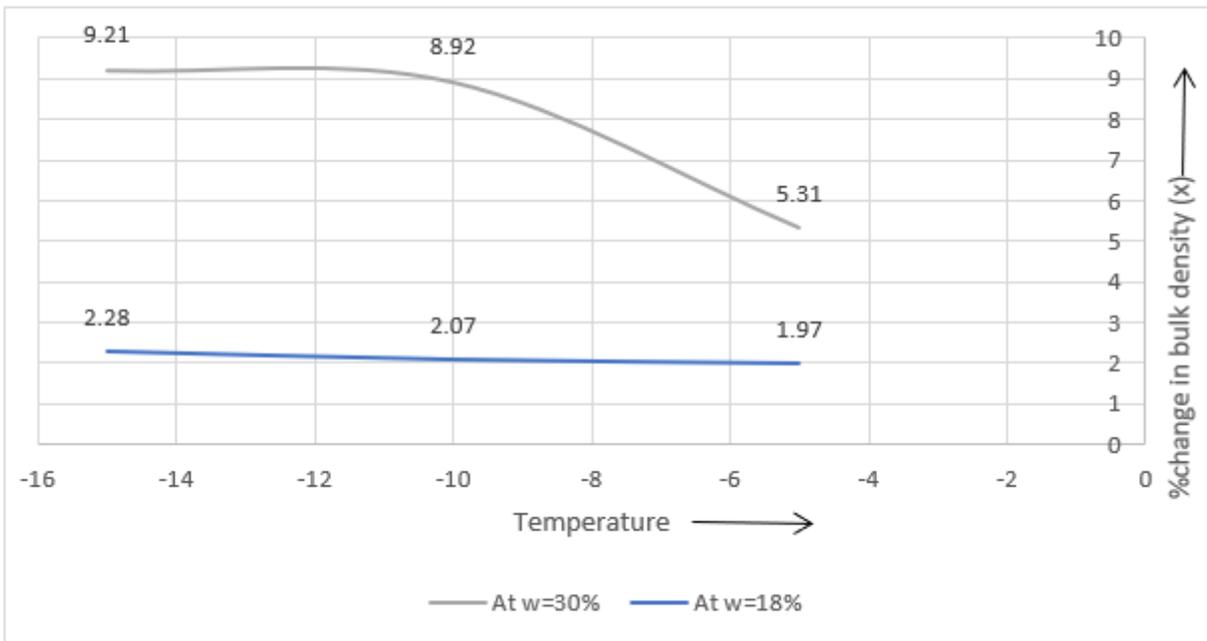


Figure 7

Percentage change in Bulk density Vs Temperature

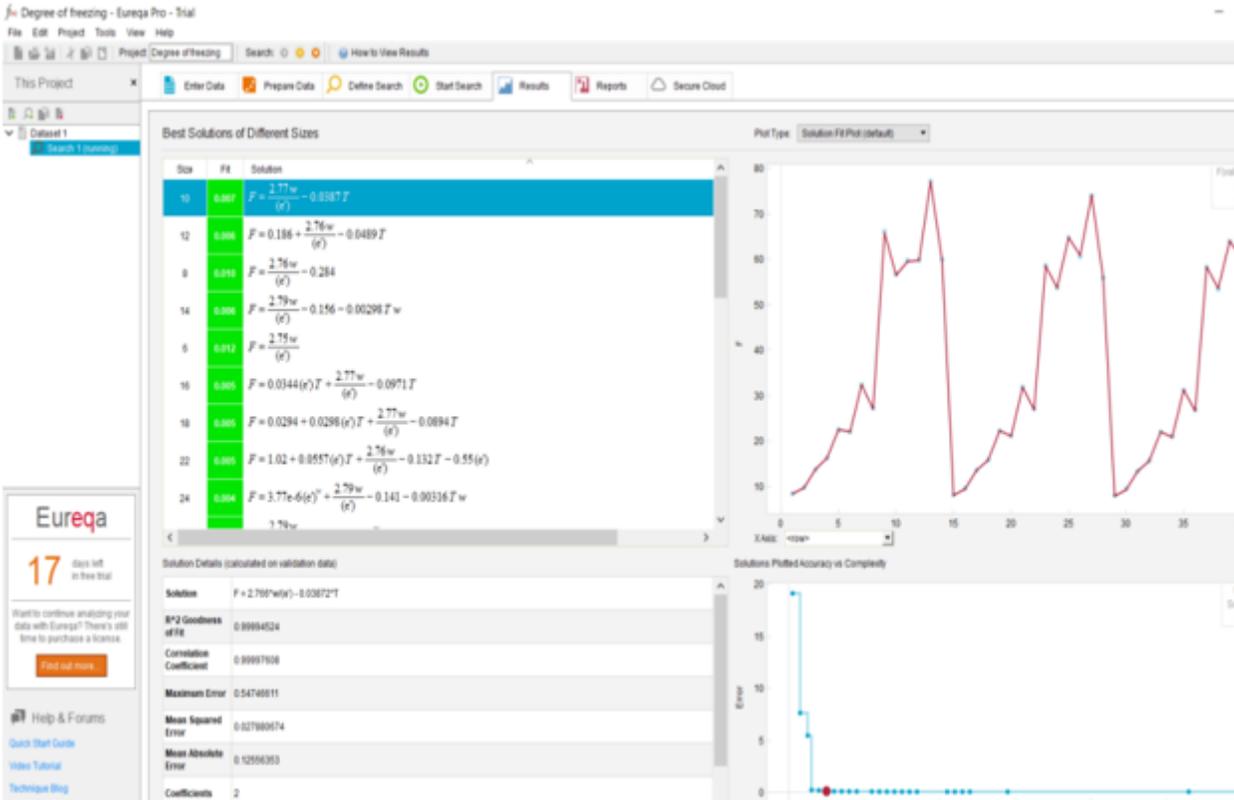
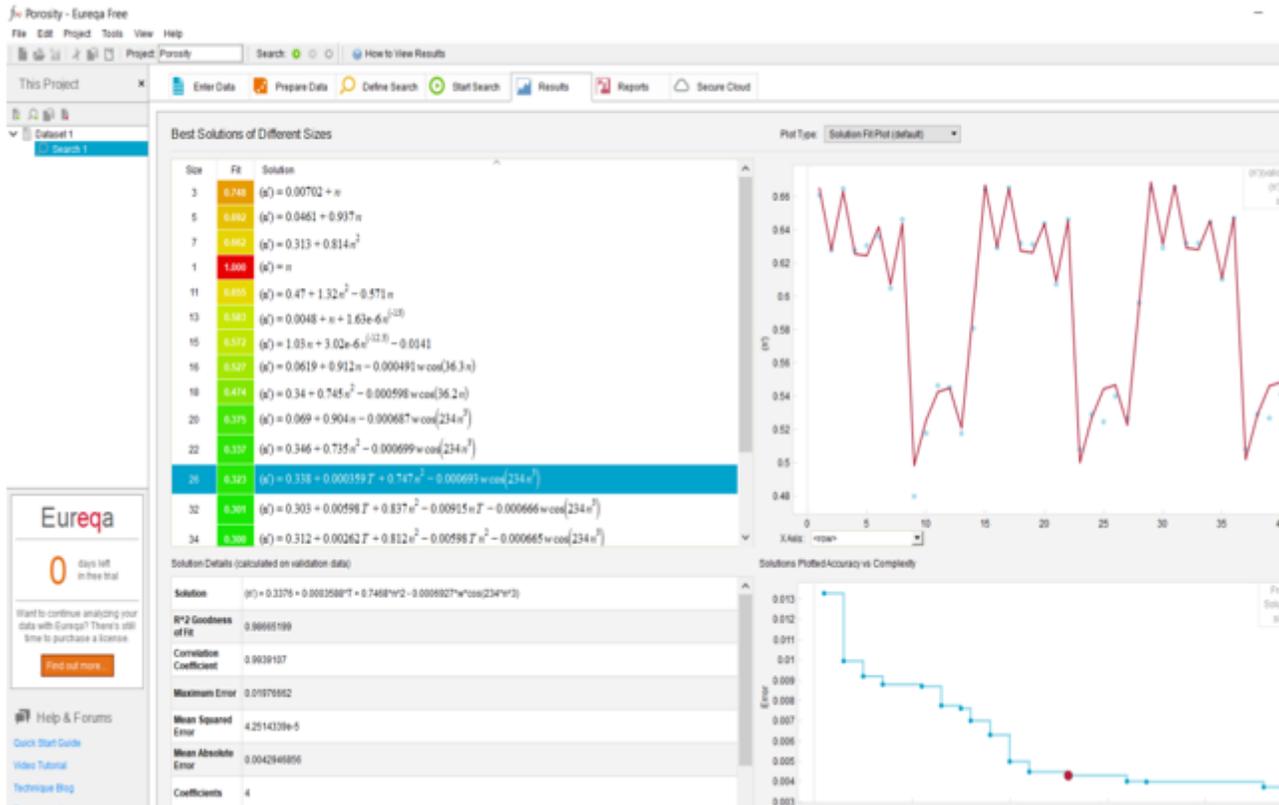


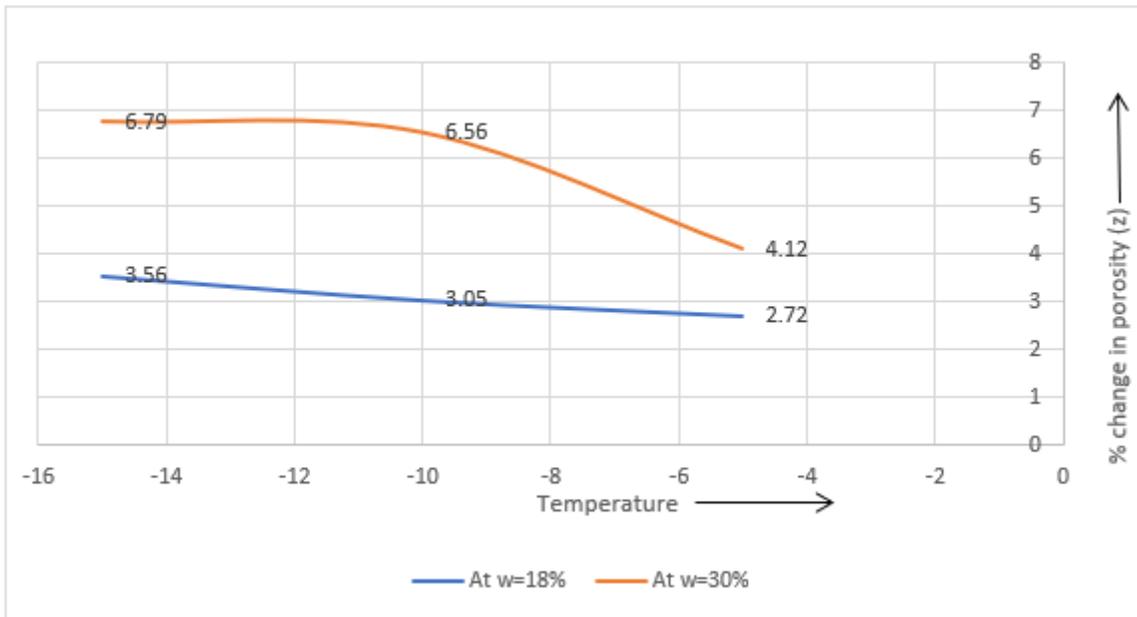
Figure 8

Degree of freezing relationship



**Figure 9**

Porosity relationship.



**Figure 10**

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