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ASSESSMENT OF PARAMETERS AFFECTING COMPRESSIVE BEHAVIOR OF MINERAL WOOL INSULATIONS

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ABSTRACT

For load-bearing mineral wool insulations, compressive stress at 10% deformation is an important property which is studied as a function of density. The determination of compressive behavior of insulations is not a simple and fast test procedure. However, it can be estimated with indirect test method of determination of density which is simple and fast. For indirect test of σ_{10}, it is necessary to find the relations of σ_{10} and ρ for estimation of mechanical behavior of mineral wool insulations without testing or testing them once in a while. Here, the wool structure, organic content, aging effects on compressive stress for glass wool, rock wool and slag wool are investigated.

Keywords: Mineral wools, thermal insulation, compressive properties, density

1. INTRODUCTION

Mineral wool has a unique range of properties combining high thermal resistance with long-term stability. It is made from molten glass, stone or slag that is spun into a fiber-like structure which creates a combination of properties.

Mineral fiber insulating products are utilized widely for building envelope and industrial process applications [1]. Knowledge of the properties of insulations is necessary for selection of the proper insulation for specific uses. Many times, in a given insulation, a certain property may be of little importance, whereas that same property may be of utmost importance in a different application.

The compressive stress at 10% deformation of mineral wool insulations is a very important property for load-bearing application. σ_{10} of mineral wool insulations increases with an increase in density. It is recognized that different types of these materials exhibit significantly different behavior under compressive load.

The compressive stress at 10% deformation (σ_{10}) of mineral wool insulations is a very important property for load-bearing application. It increases with an increase in density. It is recognized that different types of these materials exhibit significantly different behavior

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under compressive load.

EN13162 presented some classes for σ_{10} of mineral wool thermal insulations [2]. It is important that the product does not deform more than a limited value under specified load and σ_{10} should be high enough for load-bearing applications.

Different types of thermal insulations may exhibit significantly different behavior under compressive load. Data must usually be obtained from a complete load-deformation curve, and the useful working range normally corresponds to only a portion of the curve [3].

Fricke et al investigated on the thermal conductivity and the elasto-mechanical behavior of a fibrous glass paper insulation and a fibrous alumina fleece as a function of external pressure load [4].

Experimentally determined stress-strain diagrams differ considerably for different materials. Even for the same material, they differ depending on the temperature at which the test was conducted, the speed of the test, and several other variables [5].

Mineral wool insulations due to their resilient properties deform without any yield point when the compressive force exerted. However, in practice when it is to load on the insulation, it is very important to know load-bearing capacity of the materials. Solving this problem, compressive stress at 10% relative deformation is defined that is ratio of the compressive force or F_{10}, at 10% relative deformation (ε_{10}) to the initial surface area of the cross section of the test specimen.

Load-deformation curves provide useful data for research and development. All load-deformation data should be reviewed carefully for applicability prior to acceptance for use in engineering designs differing widely in load application rate, and material dimensions involved.

If the thickness of the mineral wool decreases under the load, the thermal resistance (R) will decrease (Eq. 1). This shows the importance of the compressive strength of the mineral wool insulation in load-bearing applications.

$$R = \frac{X}{\lambda} \tag{1}$$

The compressive behavior of fibrous mineral wool insulations, including glass wool, rock wool and slag wool, has been investigated as a function of their apparent density (ρ). The determination of compressive stress at 10% relative deformation, σ_{10}, is not a simple and fast procedure. However, it is simple to determine the density of the sample. Then finding relations of these properties is very important to estimate mechanical behavior of these materials using density results. Using the results, σ_{10} can be predicted using density for each mineral wool with a given fiber diameter range and binder.

In this paper the parameters which are affecting σ_{10} of mineral wools are studied. The experiments have been performed in Building and Housing Research Center (*BHRC*) on a great number of samples. It is intended to present needed information to serve as a general guide for prediction of compressive behavior of the various mineral wool insulations commonly used.

2. APPARATUS AND MATERIALS

The apparatus used in the current investigation for compressive strength tests was the universal testing machine, Tinius Olsen, H5KS. It was equipped with a ball joint connected to one of the plates. The test specimen compressed with the movable plate at a constant speed of displacement of $d_0/10$ per minute. The preload was a pressure of 50 *Pa*. The density of each specimen was measured and then the compressive stress at 10% relative deformation was determined.

For determining the density, ρ, the lengths and widths of the specimens have been measured using digital caliper. The thickness of the specimens measured, according to EN12085, perpendicularly to the length and width plane between a hard flat reference surface on which the test specimen rests and a pressure plate exert a pressure of 50 *Pa*, resting freely on the top surface of the specimen. A special apparatus was designed for thickness determination. The weights of the specimens were measured by balance (Sartorius LP 1200S) to an accuracy of 1 mg.

Stereo microscope, Zeiss Stemi 2000C, and Scanning Electron Microscope (*SEM*), Oxford CamsScan MV2300, were used for structural investigations.

The test specimens were cut from original product so that the direction of loading was the same as that on the insulation in service. They were stored for 24 *h* at (23±2) ^{o}C and (50±5)% relative humidity.

Glass wool from Pashmeshishe Iran company, rock wool from Pashmesange Iran company and slag wool from Pasa company were utilized in this investigation.

3. WOOL FIBER STRUCTURE EFFECTS

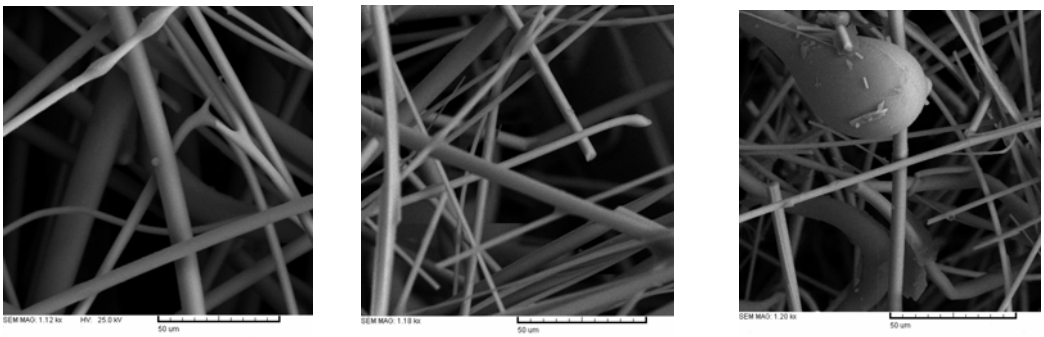
The structure of the wool fibers has a great effect on compressive properties of the insulation. The structure of high density mineral wools ensures higher rigidity and higher compressive resistance.

The orientation of fibers in a mineral wool thermal insulation may be design for optimization of heat transfer or structural properties, or it may be the result of the process employed to manufacture the material. The resulting structure is a matrix of bonded fibers that are largely randomly oriented in space [6]. The spatially random fiber orientation is evident from the small difference between the measured transmittance for the in-plane and transverse directions [7].

For structure investigations, stereo microscope and scanning electron microscope (*SEM*) were utilized. Stereo microscopy observations showed that the most of the fibers lie in parallel to the larger faces of the product (Figure 1), which are perpendicular to the direction of heat flow. The other fibers are randomly oriented. The same result has been obtained by SEM, Figure 2. This study showed that the parallel orientation of the fibers decreases the σ_{10} though this orientation causes greater resistance to the heat flow.

(a) **(b)** **(c)**

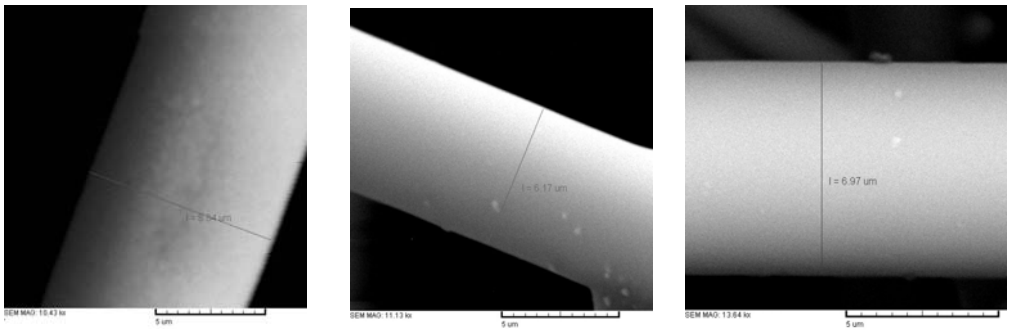
Figure 1. Stereo micrographs (a): glass wool, (b): rock wool and, (c): slag wool



(a) **(b)** **(c)**

Figure 2. Scanning electron photomicrographs (a): glass wool, (b): rock wool and (c): slag wool

The determination of diameter of the fibers with *SEM* showed that the mean diameter (D_{mean}) of glass wool, rock wool and slag wool fibers are 8.1 μm, 7.2 μm and 6.4 μm, respectively (Figure 3).



(a) **(b)** **(c)**

Figure 3. Determining the diameter of mineral wools using Scanning electron photomicrograph (a): glass wool, (b): rock wool and (c): slag wool

The distribution of the fiber diameter in glass wool is shown in Figure 4. The diameters of these fibers are much less than their length. The compressive behavior of the mineral wools are not affected by little diameter changes.

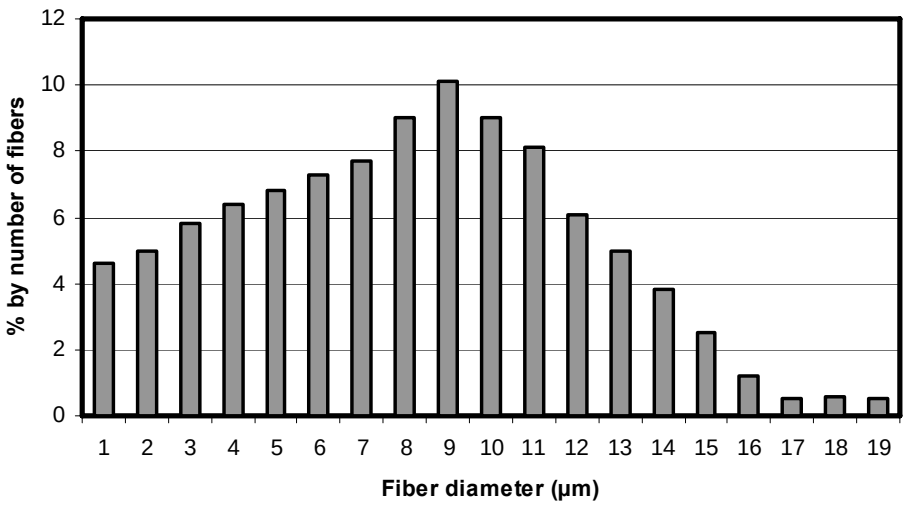


Figure 4. Distribution of fiber diameter in glass wool, D_{mean} = 8.1 μm

4. THICKNESS EFFECTS

One of the important parameters affecting proper compressive behavior of mineral wools is the thickness of the test specimen. The product is designed to have a specific thermal resistance (R) for a design thickness.

The experiments showed that the recovered thickness is usually different from design thickness. Tye, 1999, reported recovered thickness range of 7.2-10.7 *cm* for fiberglass product at design thickness of 8.9 *cm*. These data contains 47 measurements of randomly sampled products of one manufacturer. The results for products of all other manufacturers of similar products showed essentially the same order of 20 percent variability [8]. The products are heterogeneous and are somewhat difficult to manufacture economically in a high reproducible form.

For investigation on thickness effect, in this research a great number of the mineral wool products were tested. Variations in mineral wool thicknesses measured were very high (Figures 5, 6 and 7).

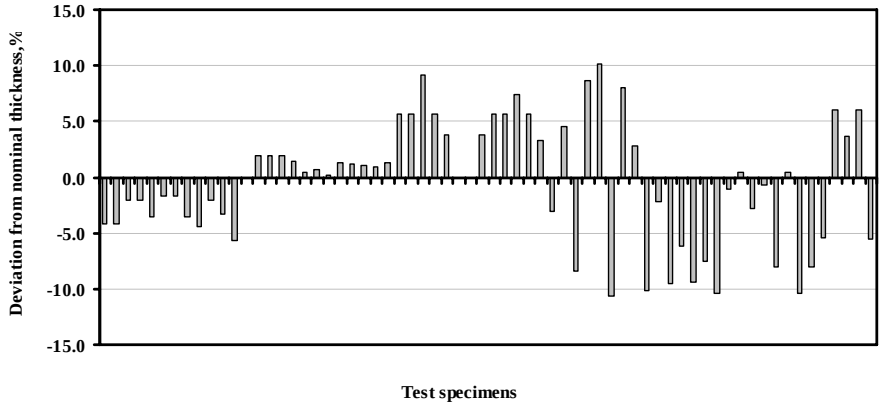


Figure 5. Deviation from nominal thickness of 66 glass wool specimens

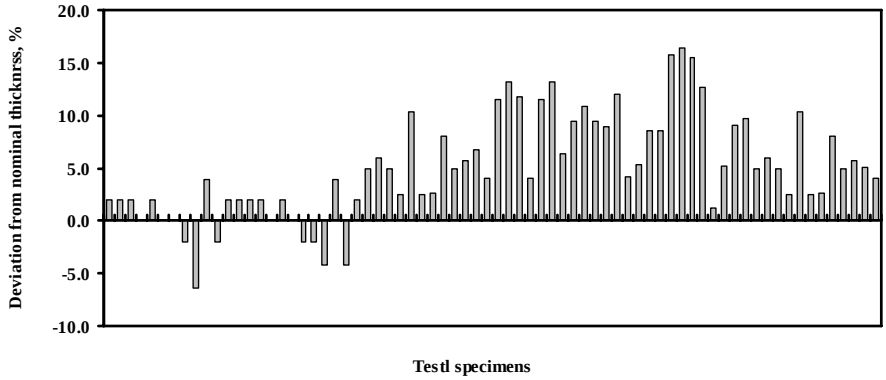


Figure 6. Deviation from nominal thickness of 72 rock wool specimens

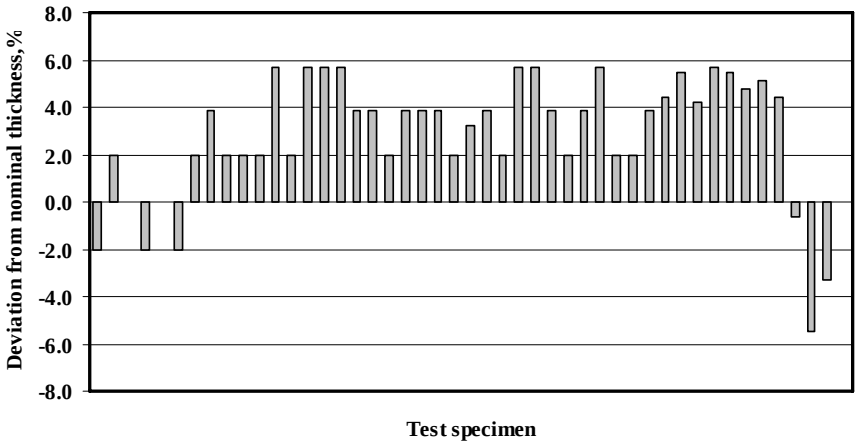


Figure 7. Deviation from nominal thickness of 48 slag wool specimens

5. ORGANIC CONTENT EFFECTS

Mineral wool insulations have been paired with phenol formaldehyde resins and a mineral oil lubricant. Thermosetting resin binds the fiber in the contact points. It cause resilience, handleability and strength to the fiber mass.

The test results showed that the organic content (M_{OC}) range for glass wool, rock wool, and slag wool are 1.61-8.84, 0.6-2.77 and 2.79-5.64 percent respectively. Figure 8 shows the binder content versus apparent density of glass wool. R^2 of the fitted line (Eq. 2) is 0.802.

$$M_{OC} = 0.0292\rho + 2.7983 \tag{2}$$

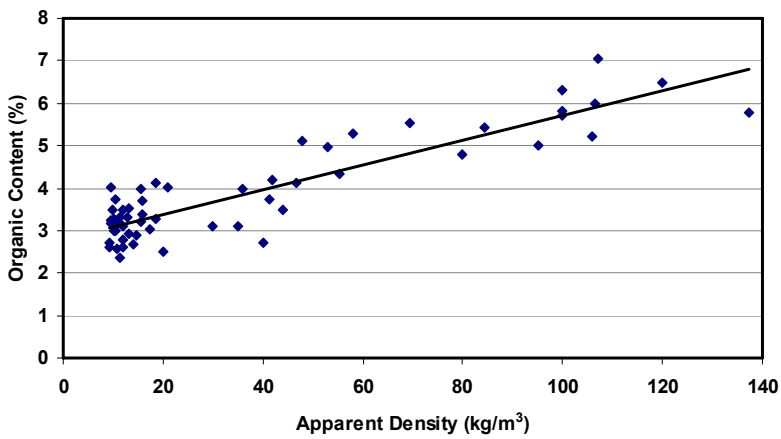


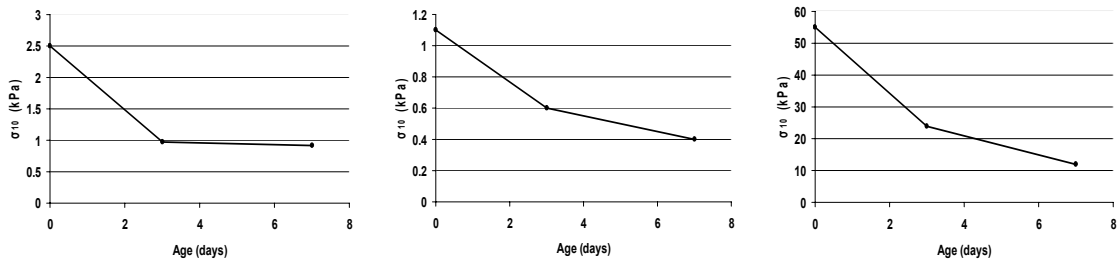
Figure 8. Binder content versus apparent density of glass wool

6. HUMIDITY AND TEMPERATURE EFFECT

Mechanical strength decreases as the temperature increases up to 200 º*C* where the binder burns and have no load-bearing capacity. The decrease is not linear and most significant changes takes place above 75º*C*, which is generally above the normal building environment except for hot, dry desert climates.

The mineral wool insulations were found to exhibit physical disintegration and morphological modifications on the fiber surface when these fibrous products were exposed to environments in which an excessive water medium and heating at temperatures up to 100º*C* were maintained for a period of several months [9].

For investigation on the effect of humidity and temperature (aging), three groups of experiments have been conducted. The first group of samples conditioned at 23º*C* and 50 % relative humidity. The second and third groups were stored in the chamber at 40º*C* and 90% relative humidity. The initial values of σ_{10} were determined for the first group of the samples. The other groups have been determined after 3 and 7 days. The relationship between the σ_{10} and age of glass wool, rock wool, and slag wool are shown in Figures 9(a-c).



(a) (b) (c)

Figure 9. Effect of aging on σ_{10} (a) glass wool: ρ=100 kg/m^3, (b) rock wool ρ=76 kg/m^3, and (c) slag wool ρ=250 kg/m^3

As it can be seen in Figure aged values of σ_{10} decrease, which means mechanical strength was declined due to humidity and temperature effect.

7. DENSITY EFFECTS

Mineral fiber products in density range of 60 to 250 kg/m^3 are the most common type of insulation used in load-bearing applications. For these materials, the change in σ_{10} versus ρ is significant. The compressive stress at 10% relative deformation, σ_{10}, is calculated using Eq. (3):

$$\sigma_{10} = 10^3 \frac{F_{10}}{A_0} \tag{3}$$

Strother et al, 1990, presented some data about physical properties of various thermal insulation including rock wool slab and glass fiber with organic binder-board. The compressive stress at 10% deformation and the density of glass wool and rock wool are shown in Table 1, Ref. [10].

Table 1. Compressive stress at 10% deformation and density of mineral wools, after Strother [10]

Type	**Density** ***(kg/m³)***	σ_{10} **(*kPa*)**
Glass wool	24	0.21
Glass wool	47	4.8
Glass wool	80-112	16.6
Rock wool	112-192	2.4-4.4
Rock wool	128-208	16-35.5
Rock wool	192-400	69-104

The relationship between extension versus force have been obtained for more than 400 samples of mineral wool with different densities. The relationship between X and F of some selected densities of glass wool, rock wool and slag wool are shown in Figures 10-12 respectively. Quadratic equations have an excellent match with these curves (Eq. 4):

$$F = aX^2 + bX + c \tag{4}$$

The estimated coefficients and R^2 for the Eq. (4) for glass wool, rock wool and slag wool for some selected densities are given in Tables 2-4, respectively. Determination coefficient (R^2) is very near to 1 that shows a very good agreement between the equation and experimental results.

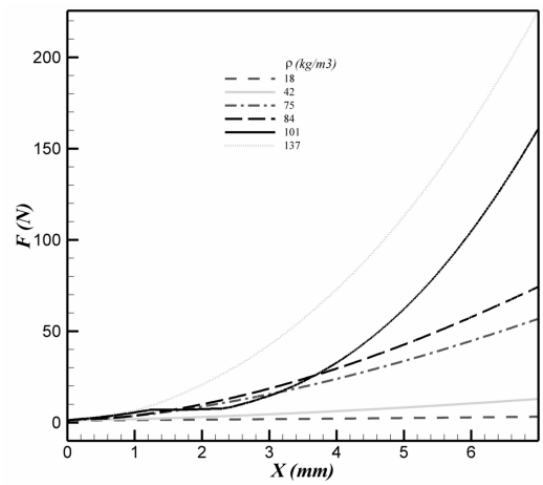


Figure 10. Extension (X) versus Force (F) for glass wool of different densities

Table 2. Estimated coefficients and R^2 for the Eq. (4) for glass wool with different densities

ρ (kg/m^3)	a	b	c	R^2
18	0.0142	0.1952	1.1471	0.9995
42	0.1418	0.7062	1.1195	0.9997
75	0.7670	2.7772	0.3775	0.9997
84	1.1457	2.6613	0.3787	0.9997
101	4.9133	-13.8642	11.6012	0.9949
137	4.6354	-0.9461	2.9857	0.9998

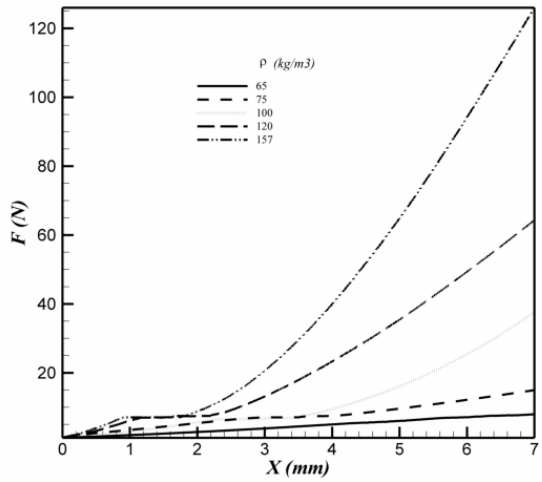


Figure 11. Extension (X) versus Force (F) for rock wool of different density

Table 3. Estimated coefficients and R^2 for the Eq. (4) for rock wool with different densities

ρ (kg/m^3)	a	b	c	R^2
65	0.0123	0.9459	0.9721	0.9979
75	0.0763	1.2011	2.1582	0.9824
100	0.9401	-2.0517	3.8995	0.9837
120	1.0533	1.4097	1.5127	0.9977
157	2.9710	-2.9626	4.1778	0.9986

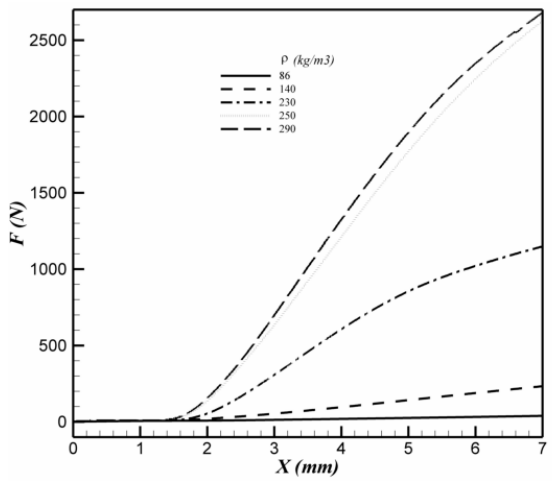


Figure 12. Extension (X) versus Force (F) for slag wool of different densities

Table 4. Estimated coefficients and R^2 for Eq. (4), for slag wool with different densities

ρ (kg/m^3)	*a*	*b*	*c*	R^2
86	0.3914	2.6673	1.9955	0.9974
140	2.0091	20.7936	-17.6824	0.9928
230	-3.1406	213.1848	-214.833	0.9717
250	4.2568	390.2408	-409.35	0.9806
290	29.6084	252.9233	-263.212	0.9793

The compression modulus of elasticity, *E*, is calculated using Eq. (5):

$$E = \sigma_e \frac{d_0}{Xe} \tag{5}$$

The mineral wool insulations become increasingly stiffer as load is increased. As there is no well defined straight portion of the force-displacement curves, it is not possible to determine the compression modulus of elasticity for these materials. The quadratic equations, Eq. (4), were properly fitted to the force-displacement curves thus it is obvious that a linear relationship for a part of *F*-*X* curve can not be found.

Manufacturers not having some means of measuring directly the compressive stress at 10% deformation should relay on measurements of some indirect parameter. In many cases, the density has been found to be the most suitable one for mineral wools.

Relationships between compressive stress at 10% deformation and density of mineral wool insulations have a wide band of measured data, follows some form of median line. Departures from the mean are mainly due to the fact that manufacturing conditions can never be identical. The reason is the difference between methods of manufacture, raw materials, and internal procedures and so on. With these data it is possible to note changes in production processes, raw materials, etc.

If indirect testing is used, the correlation between the directly tested and the indirect property shall be known and the approach shall be calculated on a one sided 90% prediction interval. In this context compressive stress by 10% deformation may be evaluated indirectly using the apparent density and its established mathematical correlation of these properties. For the relationship between σ_{10} and ρ a large amount of data obtained in this research. The power equations were used for the best fit of the data. Using polynomials for the model curve has not resulted in any improvement.

The relationship between compressive stress at 10% relative deformation and the density and predicted σ_{10} of glass wool, rock wool and slag wool are shown in Figures 13-15.

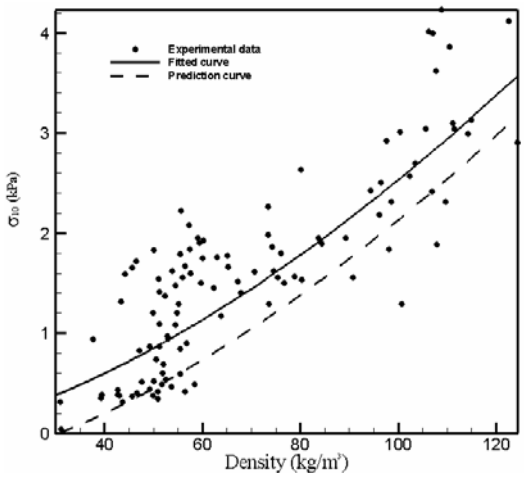


Figure 13. Compressive stress at 10% relative deformation versus density: glass wool

For glass wool the number of experiments is 192. The model definition and prediction curve are as Eq. (6) and (7):

$$\sigma_{10,mean} = 1.8 \times 10^{-3}.\rho^{1.574} \tag{6}$$

$$\sigma_{10,pred} = 1.8 \times 10^{-3}.\rho^{1.574} - 0.4 \tag{7}$$

The coefficient of determination (R^2) of the fitted curve for Eq. (6) is 0.92. The test results showed that, σ_{10} changes from approximately 0.04 to 4.2 *kPa* for a change in density from 8 to 125 kg/m^3.

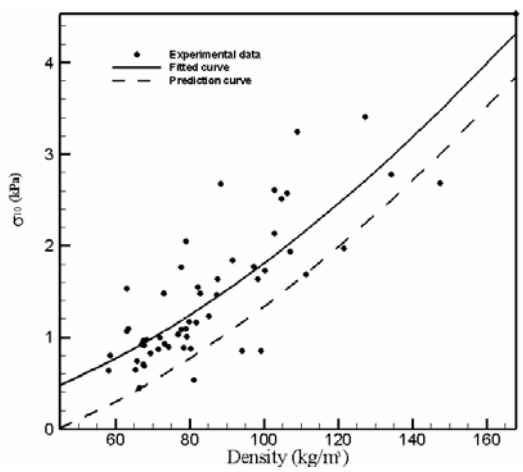


Figure 14. Compressive stress at 10% deformation versus density: rock wool

For rock wool, the model definition and prediction curve are given in Eq. (8) and (9):

$$\sigma_{10,mean} = 7.74 \times 10^{-4}.\rho^{1.68} \tag{8}$$

$$\sigma_{10,pred} = 7.74 \times 10^{-4}.\rho^{1.68} - 0.47 \tag{9}$$

The number of samples is 82. R^2 of the fitted curve for Eq. (8) is 0.79. As it can be seen values of σ_{10} in rock wool spread considerably. The reason may be the difference in manufacturing condition including the degree of compression.

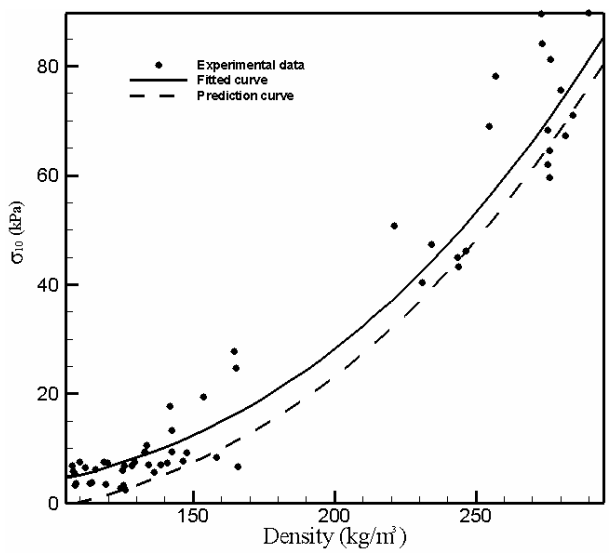


Figure 15. Compressive stress at 10% relative deformation versus density for slag wool

For slag wool the model definition and prediction curve are as Eq. (10) and (11):

$$\sigma_{10,mean} = 7.79 \times 10^{-6}.\rho^{2.85} \tag{10}$$

$$\sigma_{10,pred} = 7.79 \times 10^{-6}.\rho^{2.85} - 5 \tag{11}$$

The experiments were performed on 93 samples. R^2 for Eq. (10) is 0.95.

Using these models, it is possible to investigate the changes of the product properties due to changes in production process. The more consistent the material, the better is conformity and the departure from the mean value will be less. On the other hand, if the mechanical properties of the materials change during manufacture (because of changes in raw materials, process, …) the more imprecise will be the relationship.

8. CONCLUSIONS

The aged values of σ_{10} decrease, which means mechanical strength was declined due to humidity and temperature effect. As the organic content increases the density and as a result σ_{10} of the mineral wools increases. The power equations have the best fit to the relationship between compressive stress at 10% relative deformation and the density of glass wool, rock wool and slag wool. The quadratic equations have an excellent match with force-displacement curves of the materials. As the correlation between the ρ and σ_{10} has been determined, the indirect testing of determination of density can be used for prediction of σ_{10} on a one sided 90% prediction interval. As there is no well defined straight portion of the these curves, it is not possible to determine the compression modulus of elasticity for such materials.

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NOTATIONS

A_0	Initial area of the cross-section of the test specimen, (mm^2)
F	Force, (N)
F_{10}	Force corresponding to a relative deformation of 10%, (N)
d_0	Initial thickness (as measured) of the test specimen, (mm)
σ_{10}	Compressive stress at 10% deformation
$\sigma_{10,\ mean}$	Mean compressive stress at 10% deformation
$\sigma_{10,\ pred}$	Predicted compressive stress at 10% deformation with a prediction interval of 90%
R^2	Determination coefficient
R	Thermal resistance, ($m^2.K/W$)
λ	Thermal conductivity, ($W/m.K$)
ρ	Apparent density, (kg/m^3)
X_e	Displacement at F_e, (mm)
X	Displacement, (mm)
E	Compression modulus of elasticity, (kPa)
M_{OC}	Organic content, (%)