FROST ACTION IN GRANULAR MATERIALS

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This thesis presents an experimental study of frost action in granular materials. A highly frost susceptible matrix, consisting of sand and ground chalk was produced. Its freezing behaviour was modified by the addition of selected coarse aggregates - Slag, Basalt and Limestone - which were each sub-divided into two groups of particles - 37.5 to 20mm and 20 to 3.35mm.

The initial experimental work was concerned with assessing the frost susceptibility using the standard TRRL frost heave test. Heaving pressures were measured using equipment, developed during the investigation. It proved to be reliable and permitted an assessment of the effects of the boundary conditions on the heaving pressure.

Both heave and heaving pressure were reduced by the introduction of coarse particles, so such inclusions modified the frost susceptibility of the matrix. These reductions were dependent on both aggregate type and aggregate content, with particle size being less influential, and they have been attributed to changes in pore structure, porosity and thermal characteristics that accompanied the additions of coarse aggregate. Similar behaviour was obtained when the coarse aggregates were added to a natural soil, demonstrating that mechanical stabilisation is effective in controlling frost susceptibility.

A Controlled Heave Unit (CHU) was developed to provide close control of the boundary temperatures during heave tests. It produced reliable heave values, after approximately 100 hours freezing, which were compatible with those obtained from the cold room tests, and so provided a basis for the rapid assessment of frost susceptibility.

Heave tests were performed under different levels of restraint. The results clearly demonstrated the role of surcharge loading in controlling heave. Whilst low surcharges significantly reduced the heave, complete elimination was not achieved even at high surcharges. The reductions in heave were clearly related to the ratio between surcharge loading and heaving pressure.

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Frost heave, heaving pressure, surcharge

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CHAPTER I

INTRODUCTION

When soils are subjected to freezing temperatures there are changes in soil properties and significant increases in soil volume. The increase in volume is due to the volumetric expansion of water already contained in the soil and to the migration of moisture towards the freezing front. If a soil is frost susceptible, the ice accumulation at the freezing front will be substantial and this ice lensing will produce frost heave. In addition, if the heave is restricted by external loads, substantial heaving pressures may be generated. It is, therefore, vital to consider this activity when designing engineering structures and, if neglected, frost action may produce distress in the structure. In North America and Northern Europe this has resulted in uneven road surfaces, tilted retaining walls and differential movements in buildings, (1), (2).

In the United Kingdom the winters are relatively mild compared with those experienced in other temperate countries and, whilst extensive frost damage is not common on a nationwide scale, it has been reported (3),(4) during the severe winters that can be expected once every 10 or 12 years. The problem is generally confined to pavement structures. For pavement design, such a severe winter has been considered as one with 40 consecutive or near consecutive days of frost (5). However, freezing periods longer than 10 days have been reported (6) more frequently and such conditions are sufficient for zero isotherm to penetrate to a depth of about 350mm (6). Depths of frost penetration as great as 525mm were recorded in 1963 under a concrete slab (5). Such conditions, when confined with access to free water, could result in significant damage to the pavement structures built on frost susceptible material and so frost damage cannot be completely ignored in the U.K. The current requirements for major road works (7) require that material used within 450mm of the surface of the road should not be frost susceptible. The frost susceptibility is determined by subjecting the material to the Transport and Road Research Laboratory frost heave test (5), (8). The material is regarded as frost susceptible if the heave is greater than 13mm for contracts in England and Wales or greater than 18mm in Scotland.

Ice accumulation is not usually distributed uniformly through the ground and so frost damage to roads occurs in two ways:

1) frost heaving - the road structure is forced upwards due to the formation of ice lenses and the road surface will be deformed.
2) thaw weakening - ice lenses melt in the spring and the very high moisture contents that are produced will reduce the bearing capacity of the material. This loss of bearing capacity when combined with heavy traffic loads will produce further cracking and damage in the pavement.

A new problem with frost damage became apparent when it was proposed to construct a chilled gas pipeline through the permafrost zone in North America (9). As the permafrost is not continuous throughout the length of the pipeline, at some points the buried pipeline would cross a considerable zone of unfrozen ground, which would be frozen by the chilled pipeline, and so the pipeline may be subjected to considerable distress. Such ice lensing would continue throughout the life of pipeline and so it has become important to estimate how much heave could occur throughout the design life. This analysis must also consider any differential movements developed as the pipeline passes from frozen to unfrozen ground and the magnitude of the stresses induced in the pipe when the heave is restrained.

Cold storage plants, storage facilities for LNG and ice rinks may also experience frost damage. In these cases the frost heave would be restricted by considerable surcharges due to the weight of the structure. It is, therefore, possible that substantial stresses could occur during the life of the structure and cases of structural damage have been reported (10), (11).

The following conditions are necessary for significant ice lensing:

1) subfreezing temperatures penetrating into the soil,
2) frost susceptible material within this penetration distance,
3) a source of free moisture available to feed growing ice lenses.

In addition the extent of frost heaving will be influenced by any external pressures/loadings that may be placed on the soil in its field location.

Many methods have been proposed (1), (2), to prevent or control the extent of frost damage and these can be outlined as follows:

1) removal of frost susceptible soil down to the required depth of frost penetration,
2) mechanical stabilisation whereby the composition of the material is changed by mixing it with other materials to alter the grain/pore structure to produce a non-frost susceptible material,
3) chemical or physical stabilisation which achieve benefits by bonding particles together and/or by waterproofing the matrix,
4) introduction of insulating materials to prevent frost penetration to subgrade or frost susceptible material,
5) installation of drainage to lower the water table and so

limit the availability of water to the growing ice lenses and, secondly, to provide an exit path for the rapid removal of water during thawing,

6) application of external load for reduction of frost heave, although this will probably not be possible in road pavement.
7) banning and/or restriction of traffic to control the pore pressure induced during the spring thaw.

For buildings, it is commonly accepted that the footings should be located below the depth of frost penetration and this has proven to be a very reliable solution (1), (2). However, for highways, such a solution would entail the complete substitution of the frost susceptible soil by a non-frost susceptible soil to a sufficient thickness to prevent frost penetration of the subgrade. This would involve considerable costs and delays in construction. In addition, the supplies of suitable replacement materials are decreasing.

Mechanical stabilisation is one of the simplest methods of improving a soil, or compound material. Although it has been extensively used to improve the strength of soils, it has not been widely studied as a technique for controlling frost action. The stabilising agent is usually a coarse, granular material that is mixed with the particular soil, or unbound matrix, to modify the particle size distribution and pore structure. Indeed, it has been noted elsewhere (12) that, although such materials have been widely used, they have not been extensively studied. As a result, there is insufficient data on which to predict the amount and type of coarse aggregate suitable for reducing frost susceptibility.

The present study included the effects of both aggregate type and particle grain size. The experimental investigation included measurement of both frost heave and heaving pressure since both parameters will affect the behaviour of the freezing soil towards adjacent structures. In this connection, a study was also made of the effects of external pressures on frost heave. It is intended that this research programme should provide information to encourage the wider use of mechanical stabilisation.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

When a soil containing water is frozen the observed expansion may be greater than that due to the volume increase of the in-situ water contained in the pore structure of the soil. This expansion is usually referred to as frost heave. For a frost susceptible soil such expansion will include the 9 percent volume change, as the pore water is transformed to ice, together with additional heave attributed to ice lensing. This phenomenon involves the movement of water from the unfrozen soil to the growing ice lens, and it is generally considered (13) that frost susceptibility is directly related to the amount of heave produced by ice lensing.

The soil will normally exhibit heave in the direction of heat flow and the ice lenses, formed at the freezing front, will accumulate perpendicular to the direction of heat flow. The following conditions are generally considered to be necessary for significant frost heave:-

1) A subzero temperature must be applied to the soil surface which will lead to ice nucleation in the soil.
2) A supply of water must be available to feed the ice lenses.
3) The soil must be frost susceptible in terms of grain or pore size.

The temperature to which the freezing soil is exposed has a great influence on the water movement, heave and texture of the frozen soil. For each soil there are temperature conditions which will produce a maximum rate of ice lensing under given conditions of moisture availability.

When water freezes the latent heat of fusion is liberated. If the heat made available by the supply of water and the phase change transformation into ice is equal to the rate of heat removal from the freezing plane, the growth of ice lenses will continue at the stationary freezing front. When the heat removal rate exceeds the heat produced by the influx of water, the temperature at the ice-water interface drops and the ice front moves into a new position where a new accumulation of ice lenses will commence. In frost susceptible soil alternative layers of soil and ice are observed.

The movement of water towards the freezing front has been described (2) by equation:

$$\dot{i}_{mig} = -K_{grad}F \qquad (2.1)$$

where

$\dot{i}_{mig}$ = migration of water flux

K = a proportionality coefficient, characterizing the specific resistance offered by the soil to motion of water

F = generalized motive force.

The frost susceptibility of a soil also depends on its permeability and capillarity. Permeability of a soil reflects its resistance to the passage of water, while capillarity is a measure of the extent to which water can rise through the soil structure. As fine grained soils (clays) have more complicated systems of channels, than coarse grained soils (sands, gravels), the permeability will decrease with increasing amount of fines (14). However, the capillary rise will also increase with an increase in the amount of fines. In the fine grained soils the low permeability will make transport of water towards the freezing front very difficult. In the case of coarse grained soils, although highly permeable, the low capillary rise will limit the water transport. Therefore both very fine and coarse grained soils are non-frost susceptible. Soils where permeability and capillarity are moderate, will tend to be frost susceptible, providing that all other boundary conditions remain favourable.

2.2 Fundamental characteristics of frost action

The first serious attempt to explain the phenomenon of frost heaving was presented in 1929 by Taber (15). He attributed the heaving process to the formation of ice lenses at the freezing front and he emphasised the likely existence of thin films of unfrozen water at the freezing front. He considered the soil grains to be separated from the ice by such a thin film which permitted water to move through the soil to feed the ice lenses being formed above the individual grains. Indeed Taber (15) also demonstrated that only part of the soil water freezes at $0^{o}C$ so that unfrozen water could be associated with ice in the frozen soil. It was suggested that the quantity of unfrozen water depended on both the temperature (15) and the soil (16).

Free, unbound water has a freezing point of $0^{o}C$ at standard atmospheric pressure. However, it has been recognised (17) for almost a hundred years that only part of the pore water froze in clay soils at such a temperature. Thus, lower temperatures were necessary to freeze the remaining water in the small pores within such soils. The temperature below $0^{o}C$ at which ice crystals begin to enlarge within the pore space is described as the freezing point depression, ΔT.

In 1921 Bouyoucos (18) reported the freezing points for different soils and he classified the soil water on the basis of freezing point as:-

a) free, capillary water which freezes at $-1.4^{o}C$

b) adsorbed or combined water which remains unfrozen down to $-7.8^{o}C$.

He suggested (19) that pore water moved from the finer capillaries and the adsorbed films to the ice crystals developing in the larger capillaries. This movement by film transference with the stimulus deriving from the force of crystallisation. The pure water diluted the solute concentration on the larger pores so that the original freezing point depression was reduced.

Thus, freezing could be divided into two separate mechanisms:

a) freezing of free water in the large pores, which is the initial process and occurs at temperatures close to $0^{o}C$.

b) freezing of the pore water bound or adsorbed to the particles. This is influenced by soil properties such as grain size, salt concentration in soil moisture and external factors such as the applied load.

The proportion of unfrozen water decreases as the temperature is lowered. However, significant quantities may be present in the frozen soil for it has been reported (20) that as much as half the water may be unfrozen at temperatures close to $-1^{o}C$. In coarse grained soils, with large pores, nearly all the water freezes at temperatures close to $0^{o}C$ so that freezing front closely follows the zero isotherm (21). However, in fine grained soils a significant fraction of the soil water is in the adsorbed films so that freezing point depression is large which can produce a freezing front some distance behind the zero isotherm.

During the past twenty years, several theories have been employed to describe the mechanism of frost action and ice lens formation in soils. The three major theories are:

1) Capillary theory.

2) Secondary heaving theory.

3) Adsorption force theory.

They all accept that the agent causing frost heave is the film water that separates the ice lenses from the soil grains, and some of which remains unfrozen at temperatures below $0^{o}C$.

2.2.1 Capillary theory

In this theory it is only the capillary suction, present at a curved ice/water interface, that causes water to move to a growing ice lens and this model has been applied to lens formation in soils (13),(22). The pressure difference across this curved interface is given (23) by:-

$$p_i - p_w = \frac{2\sigma_{iw}}{r_p} \tag{2.2}$$

where

p_i = ice pressure

p_w = liquid pressure (the negative value of the suction)

σ_{iw} = interfacial tension of the ice/water interface

r_p = effective pore radius of the soil

This derivation is based on the growth of an ice crystal in a regular pore system formed with spherical grains. This expression gives the pressure difference across the ice/water interface which is necessary for the ice to penetrate the neck between two grains as illustrated in Figure 2.1. These changes in pressure also influence the freezing point and the ice lens temperature may be determined from the Clausius-Clapyron equation:-

$$\Delta TL = -(V_i \Delta P_i - V_w \Delta P_w)/T_o \tag{2.3}$$

where ΔT is drop in temperature below T_o, the equilibrium temperature of bulk ice and water, V is the specific volume, L is the latent heat of the phase change and i and w are the initial subscripts for ice and water.

Equations (2.2) and (2.3) may be combined for $\Delta P_i = P_i = 0$, implying $\Delta P_w = P_w$ so that

$$\Delta T = \frac{2\sigma_{iw} T_o V_w}{r_p L} \tag{2.4}$$

This derivation is based on the following assumptions:

a) the angle of contact for ice/water is zero

b) the pores are cylindrical

c) osmotic and adsorption effects can be neglected

d) the pores are air free

e) the ice pressure remains constant during freezing.

Thus in a granular soil with a critical pore radius of r_c, an ice lens will grow at the freezing front whilst:-

$$P_i - P_w < \frac{2\sigma_{iw}}{r_c} \tag{2.5}$$

In order that the frost line may penetrate downwards, it is necessary that the ice-water interface passes through the neck of the pore. The necessary pressure difference is given by equation (2.2) and, by substitution into equation (2.4), the necessary freezing point depression can be established.

However, if the ice-water interface is not small enough to pass through the necks of the underlying pores then the growth of the ice lens will be supported by the migration of water from the unfrozen soil below the freezing front. The moisture flow arises from the suction pressures developed in the films of water at the freezing front, as can be deduced from equation (2.2). The rate of heave will be dependant on the mass transference of water to the freezing front, and this will be directly influenced by three factors:-

1) suction induced at the freezing front

2) availability of water in the unfrozen soil

3) hydraulic conductivity of the unfrozen soil.

As this water transforms to ice at the freezing front, a considerable quantity of latent heat is released. For the growth of a stationary lens it is vital that the rate of heat extraction does not exceed the heat flux released at the freezing front. Whilst the local steady state is maintained, a stationary freezing front will be created.

At some distance back from the ice front the heat flow is in a non-steady state and, consequently, there is a strong tendency for the temperature at the freezing front to be lowered. This change in the local temperature will alter the radius of the ice-water surface. This will permit it to pass through the neck of the pore, and a new lens will develop at a lower elevation, so that a series of lens will be produced by the penetrating freezing front. The rate of heave will, therefore, also be influenced by the rate of heat extraction (24). The application of an overburden pressure will increase the value of P_i in equation (2.2) which will modify the suction so as to limit flow to the freezing front with a consequent effect on the rate of heave.

For compressible soils such as clays, the rate of heave also depends of the compressibility of the unfrozen soil. The accumulation of ice lenses will produce an increase in the effective stress beneath the ice lenses, which will lead to a decrease in the pore size of the unfrozen soil. The hydraulic conductivity will be influenced by these changes in pore size which will further limit the movement of water to the growing lenses. The validity of the capillary model when applied to frost action in such colloidal soils has been questioned (25), particularly as the role of the freezing temperatures has been studied (26).

With granular soils, the capillary model has gained considerable support (20),(22),(23). In such soils the model does predict:-

a) the presence of frozen water in the smaller pores whilst the water in the larger ones is frozen.

b) the freezing point depression of pore water

c) the establishment of a maximum $2\sigma_{IW}/r_c$ during freezing resulting in an increase in suction as the pore size is reduced.

However, when consideration is given to long term freezing and to the development of heaving pressures, it has been suggested (25),(27) that the capillary model may not be appropriate for frost action, even in non-colloidal soils. It has been suggested (25) that the capillary model should be referred to as a "primary heave model". A more general theory has recently been developed by Miller (28) in which he refers to both primary heave and secondary heave.

2.2.2 Secondary heaving model

During the past ten years, it has become evident that the capillary model significantly underestimates the maximum heaving pressure in non-colloidal soils (25),(27). Experimental evidence has also been published (29),(30) which demonstrated that an ice lens could grow behind the freezing front, with moisture migration to this lens taking place through the unfrozen soil and through part of the frozen soil. Miller considered these aspects of soil freezing and produced his theory of secondary heaving (25),(28). He considered two components of frost action - primary heaving and secondary heaving. These two phenomena are shown schematically in Figure 2.2.

With primary heaving, it is considered that an ice lens will grow at the freezing front, where its development is sustained by the inability of the ice/water interface to pass through the neck of a pore of radius r_c. In contrast, secondary heaving involves the growth of the ice phase into some of the pores formed by stationary particles below the ice lens proper. This zone, where the ice penetrates beyond the ice lens, is called a frozen fringe. Secondary heaving involves the mass movement of water through the frozen zone (or fringe) via the liquid films between the pore ice and the mineral pore walls. The movement of water through a frozen soil has clearly been demonstrated (31),(32) with values reported (33), for the apparent hydraulic conductivity of the frozen soil. However, the mass movement is enhanced and dominated by the movement of solid ice in the direction of decreasing temperature.

The sum of two interacting models of mass transport involving moving ice and water has been termed "series-parallel transport".

The ice phase moves as a continuous rigid body with the uniform linear velocity equal to the observed rate of heave. The movement of pore ice is viewed as a (self induced) regelation process involving the continuous liquid phase that lies between the pore ice and the mineral particles which bound the pores. Pore ice movement may be accompanied by a simultaneous net flux of liquid water through films and ice free pores. Regelation involves continuous phase changes, locally circulating liquid flow and an associated circulation of latent heat being liberated and resorbed by these changes. Thus, the microscopic pattern of heat and mass transport is much more complex than the macroscopic pattern, and has the effect of coupling the movement of heat and water in a manner dependent on the rate of ice movement i.e. rate of heave (34). Miller suggests (28) that the rigid pore ice phase and the incompressible mineral phase interact via an intervening phase.

The overburden or load is partially supported by the reaction of the mineral framework (effective stress, σ_e) and partially by the reaction of the pore content (neutral stress, σ_n). In terms (35) of the Terzaghi equation:-

$$P = \sigma_e + \sigma_n \tag{2.6}$$

Miller has further suggested (28) that the neutral stress is distributed between the pore ice and pore water using a suitable stress portion factor, X:-

$$\sigma_n = XP_w + (1-X)P_i \tag{2.7}$$

Through these stress variables, Miller (28) has been able to determine where a new ice lens will start both with respect to changes in the thermal field and to the location of the frost front during frost penetration. The qualitative model presents (28) all the necessary equations although it can only be fully tested when critical data concerning the unfrozen water content, the apparent hydraulic conductivity and the X-factor, as functions of water pressure and temperature, are known. However, it has been used to demonstrate (36) the manner in which this rigid ice model is responsive to thermal and mechanical boundary conditions.

When ice penetrates the pore system beyond the base of the nominal lens, the nominal ice lens may continue to grow and the ice in the frozen fringe will move with it, whilst the particles remain stationary. The immobility of the particles has been attributed to a pressure gradient in the ice coupled with a gradient of film pressure produced by a temperature gradient (37). When the ice pressure is less than the overburden pressure, part of the load would be borne by the particles which will therefore remain stationary as the ice penetrates downwards. Whilst the particles remain stationary, it is envisaged that segregated ice will be formed at the top of the frozen fringe (27) and results in an increased ice pressure compared with that predicted from the capillary model.

The significant result is the conclusion that the maximum heaving pressure that can be developed during secondary heaving depends only on the temperature ΔT_o at the base of the nominal ice lens (the upper limit of the continuous films) and the pore water pressure, (P_w):-

$$(P_i)_{max} = \rho_i[(P_w)_o/\rho_w + \Delta H_f \Delta T_o/T] \tag{2.8}$$

where

ρ = density of ice (i) and water (w)

ΔH_f = heat of phase transition

T = absolute temperature (^oK)

$(P_w)_o$ = pore water pressure at elevation of the nominal ice lens.

The ultimate heaving pressure could turn out to be a constant that corresponds to the temperature at which the unfrozen films disappear, and it seems unlikely that such values will be established experimentally in a reasonable length of time (25).

The rate of secondary heaving will largely be controlled by the rate of water flow through the frozen fringe. An increase in the temperature gradient will reduce the width of the fringe and its impedance to moisture flow. Thus, Miller suggests (25) that the rate of secondary heaving would be inversely proportional to thickness of the fringe or directly proportional to the temperature gradient in the fringe. In contrast, the rate of primary heaving should be directly proportional to the net rate of heat extraction at the frost line (25).

The theory of secondary heaving was associated (38) with the fine grained soils, whereas the capillary model has been related (20),(22) to granular soils. However, it is difficult to visualise natural materials that will be ideal granular soils, completely free of fines. In such mixed materials, it may be more appropriate to consider frost action in terms of secondary heaving rather than solely basing all the observations on the capillary model.

2.2.3 Adsorption force theory

Takagi (39),(40) has offered another explanation of the heaving process in soils. This is related to Corte's experiments (41) which demonstrated that soil particles may be carried by growing ice. This behaviour was attributed to the existence of a thin layer of unfrozen water between the lens and the adjacent soil particle, the thickness of this layer being maintained during heaving by the influx of water from the adjacent reservoir(s). Thus, the freezing film water, which is trying to retrieve the loss of in thickness as water changes to ice, generates a suction pressure that draws water from the surrounding reservoir(s). This suction is attributed (39) to the molecular forces created in the active or adsorbed film as water molecules become attached to the base of the ice lens. He considers that this film has an equilibrium thickness which is determined by the adsorption forces exerted by the particles and the ice. According to this explanation of soil freezing, it is considered that the ice lens grows on the soil particle.

Takagi refers (39),(40) to the freezing of the film water that generates suction as segregation freezing. In contrast, the freezing of the homogeneous free pore water is called in-situ freezing. This latter freezing mechanism does not generate suction.

The adsorption force theory treats the film water as a solid and attributes the primary cause of heaving to the solid-like stress in the unfrozen film formed between the ice and soil surfaces. The theoretical explanation of this solid-like structure is still formative although its existence has been demonstrated by Corte's experiments (41). Takagi has used continuum mechanics to produce a mathematical structure (39) for the adsorption force theory, although this solution will ultimately require the incorporation of molecular forces, since these are considered to produce suction in the film water.

The creation of the solid-like stress depresses the freezing point of the film water and this is referred to as the segregation freezing temperature. The average segregation freezing temperature T_s, has been formulated (39) by an extended use of classical thermodynamics:-

$$T_s = T_I[1 - (w + \rho_i gh)/(\rho_i L)] \tag{2.9}$$

where

T_I = temperature of in-situ freezing

$(w + \rho_i gh)$ = increase in ice pressure

w = surcharge overlying the ice lens

ρ_i = density of ice

g = acceleration due to gravity

h = thickness

L = latent heat of fusion.

The average segregation freezing temperature is lower, by an amount proportional to the frost heaving pressure, than the freezing point of the pore water which is referred to as the in-situ freezing temperature.

The distribution of the solid-like stress determines the intrinsic distribution of the segregation freezing temperature in the film water layer, which interacts with the actual temperature distribution in a complicated fashion and creates a partially frozen zone. This zone is referred to as the zone of diffused freezing which is known (29) to exist in clayey soils but has not been clearly demonstrated in sandy soils. At the lower boundary of the zone in-situ freezing occurs and, although it does not contribute to the frost heave, it governs the supply of water to the freezing zone. Ice lenses grow at the upper boundary of the zone of diffused freezing, where segregation freezing takes place.

The solid-like stress in a film water layer takes the highest value at the point of closest contact with the overlying particle, and becomes negligible in the region near the free pore space. The frost heaving pressure is equal to the average of the vertical components of the solid like stress over a space covering a sufficient number of film water layers and pores. Anderson and Tice (42) have indicated that the surface area is the "decisive factor" for determining the freezing point depression and, by incorporating this observation in segregation freezing it may be inferred that the frost heaving pressure must be small in sandy soils and large in clayey soils. A mathematical derivation of the heaving pressure has recently been proposed (39) involving equations of both heat-flow and moisture-flow although they have yet to be solved for real soils, they do, however, indicate that the heaving pressure is dependent on the soil data, initial and boundary conditions, the heat and water-flow equations and the degree of saturation of the soil.

As in the other two theories, the rate of heave depends on the rate of heat extraction, the rate of water flow towards the zone of diffused freezing and the composition of the soil, particularly in terms of its pore size.

2.3 Freezing phenomena to be investigated

In the previous section the various theories of frost action in soils have been described. It is clear that frost action is a very complex process which has yet to be completely explained. The experimental work reported in this thesis has been concerned with selected aspects and these are outlined in the following paragraphs. Detailed reviews of these aspects are given in the appropriate chapters.

2.3.1 Heaving pressure

An important feature of frost action in soils is the heaving pressure that is generated when the heaving surface is either fully, or partially, restrained from moving. Heaving pressures originate at the boundary between the frozen and unfrozen soil (29) - the freezing front. The heaving pressures may be determined from the ice lens temperature using the Clausius - Clapeyron equation:

$$\Delta TL = -(V_i \Delta P_i - V_w \Delta P_w)/T_o \qquad (2.10)$$

Assuming no change in the water pressure during the freezing process, the heaving pressure can be expressed:-

$$\Delta P = \frac{L \Delta T}{T_o V_i} \qquad (2.11)$$

Thus, the heaving pressure is related to the freezing point depression. The difficulty that arises is how to determine in advance where the ice lens will develop in the temperature gradient field, and further, what characteristics of the soil are helpful in determining this position. However, the freezing point depression is related to the soil texture, in particular pore size, and so the heaving pressure is itself related to pore size.

Other expressions for the heaving pressure have been developed (43),(44) and although they involve different assumptions regarding the ice and water pressures, they indicate that the pressure is a function of the freezing point depression.

2.3.2 Overburden stress or surcharge

It has been recognised (15),(16) for a considerable time that an increase in the applied stress acting on a freezing soil will produce a decrease in the rate of heave. More recently it has been suggested (45) that there is a critical "shut-off pressure" at which moisture transfer to the freezing zone ceases so that subsequent heave may be controlled. However, it has been demonstrated (46) that no "shut-off pressure" exists for soils although marked reductions in heave rate are produced when an external load is applied. Under such conditions, frost heave will coexist with the developed heaving pressures.

The reduction in heave, for a given external load will depend on the soil type and properties such as pore size. The interaction of frost heave, heaving pressure and overburden stress has been examined in some detail and a more extensive review is given in Chapter IX.

2.3.3 Particle/pore size effects

Particle size is the most basic property of an engineering soil and so is one of the major factors that has been considered when studying freezing behaviour. As early as 1929 Taber (15) described the effect of grain size on frost action. He came to the conclusion that in soils with less than 30% clay, no segregated ice could be observed. Casagrande (47) in 1931 determined the frost susceptibility of soils in terms of grain size and this classification is still used today. Indeed, it forms the basis of many standards used in the U.S.A., the most widely known is probably that of the U.S. Army Corps of Engineers (48).

Whilst Taber and Casagrande were investigating frost action in the United States, Beskow was involved on parallel studies in Norway. He studied the frost heaving behaviour of numerous natural soils and divided them into two groups: sediments and moraine materials. For the sediments he concluded (16) that the soils coarser than the limit of 30% finer than 0.062mm/6mm or 55% finer 0.125mm/6mm are not frost susceptible. But he found that it was difficult to distinguish between frost heaving and non-frost heaving moraine soils.

Linell and Kaplar (49) underlined that not only grain size, but material type was important for frost heaving. They stated that the increase of fines above a certain minimum could result in a decrease of frost heave rate of plastic clays (montmorilonite). The reduction in heaving was attributed to a reduction in the permeability of the soil, but presence of such fines in a small amount could have the opposite effect on frost heave. Brandl studied this behaviour in considerable depth and produced guidelines (50) to freezing behaviour based both on particle size and mineralogy.

Penner (51) suggested that particle size graduation was the single most important characteristic of a soil for determining its frost susceptibility. He came to the conclusion that particle size has a significant influence on the ice segregation. The effect of particle size has been attributed (52) to its influence on water flow to the ice front. Jessberger (53) following a major review of frost susceptibility criteria, also suggested that particle size was an important factor in frost action.

Many of the recent developments in the study of frost action have been concerned with the formulation of mathematical models (28),(40),(54). These have permitted study of many of the basic phenomena of frost action and have also been developed to predict the extent of frost heaving. As a result of such work, it has become clear that the key soil parameter involved in frost action is the pore size (55),(56),(57). Virtually all the factors associated with soil freezing, such as capillarity, suction characteristics, permeability and freezing point depression, are closely related to pore size. Thus, criteria based on pore size characteristics are likely to be more reliable than those based on grain size.

Pore size has been used to predict (58),(59) the maximum heaving pressures, although the freezing temperature must also be considered. In addition to the pore size effects some studies (57) have also been concerned with the effects of porosity on heat flow, moisture transfer and related phenomena.

From the previous discussion of the various theories of frost action, it is clear that pore size is a major determinant in the behaviour. Particle size factors have been widely adopted (13) as they are relatively easy to assess. However, the use (55) of pore size characteristics not only reflect the grain size dimensions and interactions, but also take into account the compaction variables of moisture and density. Although particle size and pore size are closely connected and both influence the extent of frost heaving, no successful attempts have been reported to connect these two parameters. Thus, the effects of soil texture have been assessed either in terms of pore size or particle size.

Considerable research effort has been directed towards assessing the role of the finer grains and pores in frost action. However, very little work has been undertaken to assess the influence of the coarse particles in frost action. It has been suggested (60) that the coarse particles, lying across the freezing plane, will offer frictional and displacement resistance to the heave forces located in the plane of freezing and so will reduce the heave. Frost heave tests performed on mixed materials containing porous particles have indicated (61),(62),(62a) that the internal pore structure can influence the recorded heave. It is, therefore, clear that comprehensive criteria for predicting frost susceptibility should encompass both fractions in such mixed materials.

2.4 Assesment of frost susceptibility

There are two basic approaches that may be followed to assess frost susceptibility of soils. The first approach involves the measurement of soil properties such as grading, permeability, suction characteristics etc. and relating them to the values for materials whose frost susceptibility has been established, usually by field experience. This is an empirical approach since it does not involve freezing the test materials. The second approach consists of freezing specimens of soil in the laboratory, under a chosen regime, and measuring their response either in terms of heave or heaving pressure. These values are judged against field performance so that laboratory performance criteria can be established for predicting the frost susceptibility of other materials. This is a simulation approach.

Both approaches have recently been considered in some depth by Chamberlain (13). He cited over one hundred entries and has presented a major review of the current criteria for assessing frost susceptibility. Only the major conclusions are discussed in the subsequent sections in view of the definitive presentation (13) by Chamberlain.

2.4.1 Empirical assessment

Most of these methods are based on particle size characteristics. Criteria based on particle size are the most popular since they rarely require little or no more testing than is normally done for roads and other heavy construction projects. Particle size methods are often successful because they address the problem of frost susceptibility on a basic level, but they are often unsuccessful because few address the effects of minerology, moisture, density, structure, boundary conditions, overburden etc.

With development of the various models of frost action, interest has also been directed towards other criteria for predicting frost susceptibility. These have involved pore size and soil-water interaction tests and, although they are closer to the problem of frost heave, none have proven to be the universal solution for predicting frost susceptibility.

Particle size characteristics have gained widespread use in North America. The initial consideration dates from Taber's work (15), which drew attention to the effects of soil texture on frost action. Probably the most widely used criteria were proposed in 1931 by Casagrande (47). Soils are designated either as uniform or non-uniform on the basis of their coefficient of uniformity and their subsequent frost susceptibility is related to the amount of materials finer than 0.02mm. Casagrande stated (47),

> "... one should expect considerable ice segregation in non-uniform soil containing more than 3% of grains smaller than 0.02mm, and in very uniform soils containing more than 10% smaller than 0.02mm. No ice segregation was observed in soils containing less than 1% smaller than 0.02mm ..."

It is considered that Casagrande's criteria are conservative (63), but safe. Even though there has been almost continuous research on frost heave since then, there has been little success in developing comprehensive criteria that more successfully predict the frost susceptibility than does the Casagrande's criteria. This has occurred in spite of the probability that Casagrande never intended his grain size criteria to be applied universally. More recent criteria, such as those of Linell and Kaplar (49) on the U.S. Army Corps of Engineers (48), involve particle size and the Atterburg Limits but only give the same reliability as the Casagrande criteria (63).

In Europe, criteria based on particle size have been proposed and are still widely used (64) in Norway, Switzerland and West Germany. Based on data obtained during the severe winter of 1946/47, Croney (3) established a grading envelope for frost susceptible soils in Great Britain. However, it is rarely used as frost susceptibility is usually based on simulation testing.

2.4.2 <u>Simulation assessment</u>

Frost heave tests are, perhaps, the most direct laboratory method of assessing the frost susceptibility of soils. The frost susceptibility is assessed either in terms of the total heave or the rate of heave. The two most widely reported tests are the U.S. Army Corps of Engineers frost susceptibility test (65) and the Transport and Road Research Laboratory frost heave test (5),(8).

The main difference between the tests relates to the temperature regime above the specimens. In the British test the temperature is maintained at -17°C, but in the American test it is gradually lowered so that the 0°C isotherm passes slowly through the specimen at a specified rate of 6.7mm/day. These tests are of long duration and recent interest has been directed towards the development of a quick-index test.

In Britain, recommendations have been presented (66) which will reduce the freezing period from 250 hours to 100 hours. These recommendations follow from the findings of several users, who have demonstrated the correlation between the 100 hour and 250 hour heave values (61),(67). In the U.S.A. Zoller (14) and his associates have developed a rapid freeze test in which the frost susceptibility is related to the average rate of heave observed during the freezing period of 12 hours.

In addition to heave tests, alternative freezing techniques have been considered as quick index tests. Penner (22) and Hoekstra (29) have both suggested that measurement of the heaving pressures developed when heaving is restrained could lead to some simplification of the test procedures. Martin and Wissa (52) presented tentative recommendations for predicting frost susceptibility from heaving pressure data. In an extension of this study (68) they also suggested that the changes in pore water suction below the freezing front could also be used to assess frost susceptibility.

One further aspect of frost action, which is outside the scope of this investigation, relates to thaw weakening - the loss of bearing capacity when a frozen soil thaws in the spring. However, it has been an almost universal tendency to define frost susceptibility on the sole basis of heaving. However, soils such as fat clays can exhibit significant losses in bearing capacity although the heave may not be excessive. It is, therefore, clear that in future studies this behaviour will have to be catered for in developing frost susceptibility criteria. Currently, this aspect is only examined (13) in Germany and Switzerland, where CBR tests are usually performed after thawing.

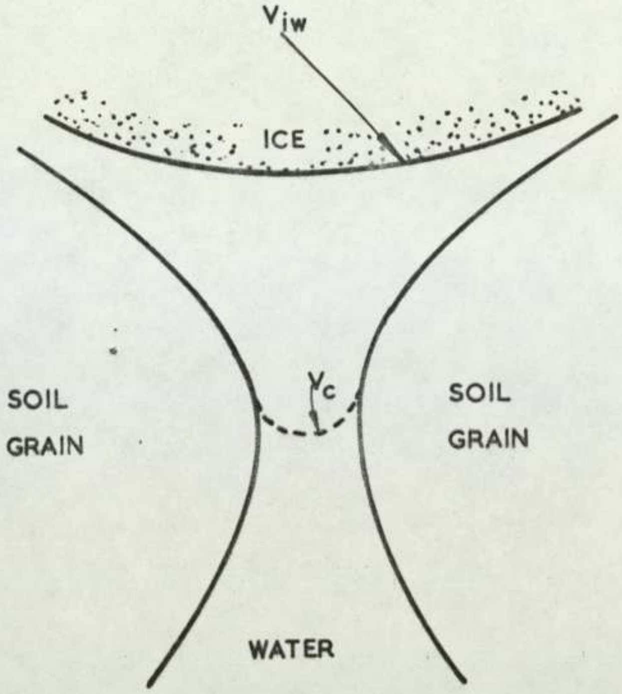


Fig. 2·1. Capillary model of frost heaving.

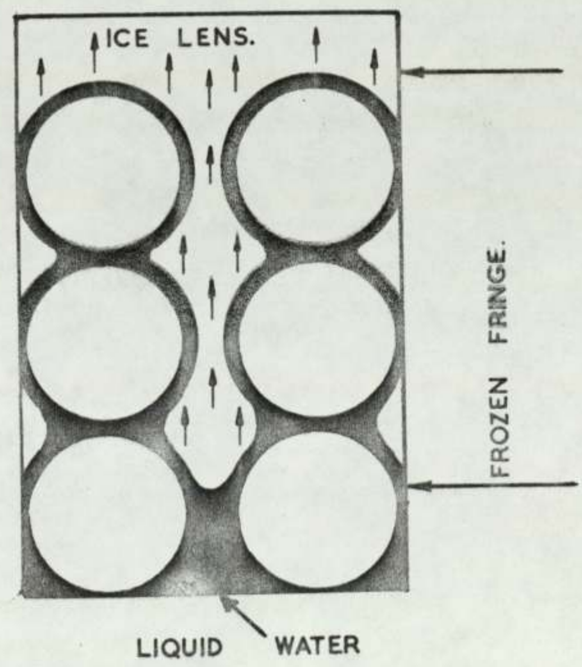


Fig. 2·2. Secondary heaving.

CHAPTER III

SCOPE OF INVESTIGATION

3.1 General Outline

The work reported in this thesis is concerned with frost action in granular mixtures. Particular interest was centred on modifying frost susceptibility through the addition of various coarse aggregates to a frost susceptible matrix. In addition to studying the effect of aggregate content, both particle size and aggregate type were investigated. The frost susceptibility was determined by subjecting specimens to the Transport and Road Research Laboratory frost heave test (5),(8). Controlled freezing tests, restrained heaving tests and heaving pressure tests were performed in order to understand the mechanisms involved in modifying frost susceptibility.

The basic matrix consisted of a single size (600 - 300μm) sand and a propriety ground chalk (snowcal) mixed in the ratio of 4:1 by weight. Three coarse aggregates, sub-divided into either 3.35 - 20mm particles or 20 - 37.5mm particles, were blended into the matrix to cover a range of aggregate contents between 10 - 50 percent. Thus, 31 different mixed materials were studied during the investigation.

3.2 Study of material properties

Measurements were made of selected properties of both the mixed materials and the coarse particles, so that they could be classified. These properties were:

1) Particle size distribution.
2) Pore size of the matrix and individual aggregate.
3) Specific gravity.
4) Water absorption.
5) Compaction characteristics.

In addition, selected properties of materials were examined for possible correlation with frost susceptibility.

3.3 Study of permeability

It is generally considered that the mass movement of water to the freezing front takes place under condition of unsaturated flow. The measurement of such flows is difficult to achieve and was not attempted in the present study. However, saturated permeability was measured since this would be useful in assessing the effects of the coarse aggregates on the behaviour of the matrix. The permeability was studied using drained triaxial equipment and the tests were performed on similar specimens to those used for the frost heave test.

3.4 Preliminary freezing tests

Prior to the main investigation, it was decided to study the repeatability of the frost heave test and the influence of the boundary conditions on the recorded heave. This included such factors as water bath temperature, water level, specimen conditioning prior to freezing, specimen size and location of the trolley in the cold room.

3.5 Frost heave

Frost susceptibility was determined using the standard TRRL frost heave test (5),(8). Tests were performed on the matrix material and on mixtures containing up to 50 percent of selected coarse aggregate. The standard test is performed on specimens of 102mm diameter, but a larger mould was also employed to produce specimens of 145mm diameter so as to study the influence of large particles of up to 40mm.

3.6 Development of controlled heave test

As the standard heave test involves a test period of at least 12 days, it was decided to examine other testing techniques and so a controlled heave unit (CHU) was developed. This unit allowed precise control over the boundary conditions together with constant recording of frost heave.

3.7 Heaving pressure

In considering alternative test methods, the literature review also drew attention to the merit of measuring heaving pressures developed when heaving is restrained. Equipment used in earlier investigations (58),(61) was further developed and modified. A multi-ring system was introduced to eliminate the effects of adfreeze and friction. Tests were performed on the same materials as were tested in the frost heave test, so that relationships between these two major parameters could be established. This study was performed with two sizes of specimen, 120mm and 145mm diameter.

3.8 Frost heave under restraint

The literature review also produced considerable evidence as to the role of surcharges and overburden pressures in reducing heave. In order to quantify these effects, a study was undertaken of the relationship between frost heave and surcharge. Several levels of surcharge were used. Initially, these tests were undertaken in the standard frost heave facilities using dead loads to produce the required surcharge. However, with this system the maximum load was restricted and so, for higher surcharges, a Bellofram diaphragm air cylinder was linked with the controlled heave unit (CHU) to produce the required boundary conditions.

CHAPTER IV

ENGINEERING PROPERTIES

4.1 Introduction

The major theme of this study was the examination of the role of coarse particles in frost action in granular soils. This was to be achieved through the addition of controlled portions of selected coarse aggregates to a highly frost susceptible matrix material. It was, therefore, essential to select an appropriate matrix that contained only a low percentage of clay-sized particles.

In studies (69,(70) involving the frost heave test reference materials, consisting of mixtures of sand and limestone dust, have been used and so a similar mixture was adopted as the matrix material in this investigation. This consisted of a mixture of single-sized Leighton Buzzard sand (No. 14 -Arnold Bros. Ltd.) and a proprietry ground chalk, Snowcal 2ml, mixed by weight in the proportions of 4:1. Similar mixtures used elsewhere (69),(70), had proved to be highly frost susceptible and, as shown by the data in Chapter V, this mixture was also highly frost susceptible. It was, therefore, considered to be an ideal matrix with which to assess the role of the coarse particles.

Three types of coarse aggregate were selected for incorporation in the matrix and these were:-

a) Blastfurnace Slag - a by-product from the reduction of iron ores and consisting basically of fused compounds of calcium and silica, dark grey in colour.

b) Rowley Basalt - a dark grey, fine grained igneous rock composed of calcic plagioclase and iron ores.

c) Caldon Low Limestone - a bedded limestone consisting mainly of calcium carbonate, a light grey, fine textured rock.

It was considered that these would cover a range of possible rock types, each having distinctive physical characteristics.

Three particle types were supplied direct from source by Tarmac Roadstone Ltd. The materials were generally supplied as 40 - 3.35mm particles although some were sub-divided at source on a 20mm mesh. However, for the main programme it was decided to sub-divide all the particles into two groups:-

a) 37.5 - 20mm particles

b) 20 - 3.35mm particles.

This permitted the subsequent investigation to cover the effects of particle type, size and content on the frost susceptibility of the matrix.

4.2 Particle size distribution

The standard (71) wet sieving method was used for the sand and aggregates. The dry sieving method (71) was also compared with wet sieving and the results obtained were very similar. It was, therefore, decided to use dry sieving method later in the programme for additional checks on grading. The particle size distribution of Snowcal was determined using the hydrometer method (71). The results obtained are summarised in Tables 4.1 and 4.2. Typical results are plotted in Figure 4.1 and all the reported values represent the mean of at least three determinations.

The gradings of the mixed materials were calculated from the proportions of aggregate, sand and snowcal required for the particular composition of the material. These values are collected in Tables 4.3 and 4.4 for slag-matrix mixtures. In view of the similarity in particle distributions, the values for the mixtures containing limestone or basalt are similar to those given for the slag. Typical plots for slag mixtures containing 10, 30 and 50 percent of 20 -

AGGREGATE	PERCENTAGES FINER THAN MM							
	37.5	28.0	20.0	14.0	10.0	6.3	5.0	3.35
SLAG	100	85	0	-	-	-	-	-
SLAG	-	-	100	76	40	18	9	0
ROWLEY BASALT	100	80	0	-	-	-	-	-
ROWLEY BASALT	-	-	100	72	45	20	13	0
CALDON LOW LIMESTONE	100	79	0	-	-	-	-	-
CALDON LOW LIMESTONE	-	-	100	79	48	20	12	0

TABLE 4.1 PARTICLE SIZE DISTRIBUTION

MATERIAL	PERCENTAGE FINER THAN								
	MM	MICRON							
	1.18	600	300	212	150	63	20	6	2
SAND 14	100	99	9	4	0	-	-	-	-
SNOWCAL GROUND CHALK 2ML	-	-	100	99	93	81	56	47	22
80% SAND + 20% CHALK	100	99	27	23	19	16	11	9.4	4.4

TABLE 4.2 PARTICLE SIZE DISTRIBUTION

MATRIX PLUS	PERCENTAGE FINER THAN										
	MM				MICRON						
	20.0	10.0	5.0	3.35	600	300	150	63	20	6	2
10% SLAG	100	94	91	90.0	89	24	17	14	10	8.5	4.0
20% SLAG	100	88	82	80.0	79	22	15	13	8.8	7.5	3.5
30% SLAG	100	82	73	70.0	69	19	13	11	7.7	6.6	3.1
40% SLAG	100	76	64	60.0	59	16	11	9.6	6.6	5.6	2.6
50% SLAG	100	70	54	50.0	49	13	9.5	8	5.5	4.7	2.2

TABLE 4.3 PARTICLE SIZE DISTRIBUTION

MATRIX PLUS	PERCENTAGE FINER THAN										
	MM			MICRON							
	37.5	28.0	20.0	600	300	212	150	63	20	6	2
10% SLAG	100	98	90	89	24	21	17	14	10	8.5	4.0
20% SLAG	100	97	80	79	22	18	15	13	8.8	7.5	3.5
30% SLAG	100	95	70	69	19	16	13	11	7.7	6.6	3.1
40% SLAG	100	94	60	59	16	14	11	9.6	6.6	5.6	2.6
50% SLAG	100	92	50	49	13	11	9.5	8	5.5	4.7	2.2

TABLE 4.4 PARTICLE SIZE DISTRIBUTION

3.35mm particles are shown in Figure 4.2.

4.3 Compaction characteristics

The compaction tests were carried out using the 2.5kg rammer method (71). When the programme was commenced, this test was recommended (5) for use with the frost heave test, and so it was the appropriate test to adopt. Each compaction test was repeated five times for the sand/snowcal matrix whilst at least two separate test runs were performed for each aggregate mixture. For the mixed materials, the tests were only performed with 20 - 3.35mm particles. It was assumed that, for a given aggregate content, the same compaction parameters would apply to mixtures containing either size of aggregate particles. It is permissible (71) to use values obtained from 2.5kg hammer compaction test for soils with up to 50% of coarse aggregate if they contain fine particles.

The results of the tests are summarised in Table 4.5 and provided the compaction parameters for the subsequent preparation of frost heave specimens.

4.4 Specific gravity

The specific gravity was determined for all materials using both of the standard methods (71). The gas jar method was used for samples of 400g mass, the maximum particle size being 20mm. It was assumed that the 37.5 - 20mm particles would have similar values to those for the corresponding 20 - 3.35mm particles. The density bottle was used for tests on 10g powdered samples of all the materials. For each material, three determinations were carried out using each technique and the results are summarised in Table 4.6.

MATRIX PLUS		DRY DENSITY Mg/m^3	MOISTURE CONTENT (%)
0%		2.02	9.5
SLAG	10%	1.99	9.0
	20%	2.08	7.0
	30%	2.12	7.0
	40%	2.17	6.6
	50%	2.16	6.0
ROWLEY BASALT	10%	2.03	7.5
	20%	2.06	8.0
	30%	2.13	7.0
	40%	2.20	7.0
	50%	2.24	6.0
CALDON LOW LIMESTONE	10%	2.00	9.0
	20%	2.07	8.0
	30%	2.10	7.0
	40%	2.18	7.0
	50%	2.24	6.5

TABLE 4.5 SUMMARY OF COMPACTION TESTS (2.5kg hammer)

MATERIAL	SPECIFIC GRAVITY		
	GAS JAR	PYKNOMETER	MEAN
SLAG	2.850	2.890	2.87 ± 0.03
ROWLEY BASALT	2.876	2.884	2.88 ± 0.005
CALDON LOW	2.695	2.710	2.70 ± 0.01
SAND	N/A	2.690	2.69 ± 0.005
SNOWCAL	N/A	2.750	2.75 ± 0.005

TABLE 4.6 SPECIFIC GRAVITY VALUES

AGGREGATE	Water absorption	
	Standard	With Vacuum
SLAG	1.42%	2.29%
ROWLEY BASALT	1.34%	1.40%
CALDON LOW LIMESTONE	0.72%	0.78%

TABLE 4.7 WATER ABSORPTION VALUES
FOR THE AGGREGATES

4.5 Water absorption of aggregates

Water absorption of aggregate was expressed (72) as the increase in weight of the saturated surface of dry aggregate following soaking for 24 hours in distilled water. The major difficulty in the method (72) is the removal of surface water without the additional removal of some of the internal absorbed water. Four tests were carried out on each aggregate and mean values are shown in Table 4.7.

The water absorption value for the Slag was close to that for the Basalt, but the Slag appeared, visually, to have a more porous surface texture than the Basalt. It was considered possible that not all of the very fine pores had become saturated during the standard soaking period. It was, therefore, decided to repeat the tests but to employ a vacuum so as to ensure that all the available pore space was determined. It was applied for between one and three hours and no air bubbles were observed when it was removed. The absorption values for the Basalt and Caldon Low were close to the previously determined values, but that for the Slag had increased.

4.6 Total porosity

The total porosity was calculated as a ratio of the volume of pores to the total volume of soil.

Total porosity for soil sample was calculated using formula:

$$n = \frac{G_s p_w - p_d}{G_s p_w} \quad \text{, where} \tag{4.1}$$

n = porosity

G_s = specific gravity of soil (was calculted from G_s of materials composing soil)

p_w = density of water

p_d = dry density of soil

and the values are given in Table 4.8.

TYPE OF AGGREGATE	% OF AGGREGATE IN SAND/SNOWCAL MATRIX				
	10%	20%	30%	40%	50%
SLAG	0.27	0.24	0.23	0.22	0.23
ROWLEY BASALT	0.27	0.25	0.23	0.21	0.20
CALDON LOW LIMESTONE	0.26	0.23	0.22	0.19	0.17

TABLE 4.8 POROSITY VALUES

4.7 Examination of materials under microscope

In order to investigate the pore structure of the various materials, it was decided to examine matrix and aggregates with an electron microscope.

The aggregate particles were sliced with a water cooled "diamond wheel" to produce slices of approximately 2mm thick. These were broken into smaller pieces (approximately 10mm diameter) to enable these to be mounted. They were glued onto aluminium stubs and coated with a thin film (300Å) of carbon following oven drying, the matrix material could also be sliced and so a similar mounting procedure was followed for this material. The specimens were examined with a Cambridge SEM 150 Scanning Electron Microscope that is operated in the Department of Metallurgy. Photographs were taken of the matrix and of the three aggregates at several levels of magnification and typical prints are shown in Plates 4.1 to 4.5.

In Plate 4.1 it can be seen that the relatively large sand particles of the matrix are surrounded by the silt-sized particles of ground chalk. The spaces between sand particles are evenly filled with ground chalk and on photo C it can be seen that the very small particles ($< 6\mu m$) tend to adhere to the larger particles.

The higher magnifications in Plate 4.2 show that the pore size distribution of the filler is well graduated with a broad range of pore sizes being evenly distributed, although there are not many pores smaller than $0.5\mu m$.

Plates 4.3 to 4.5 relate to the aggregate particles and Plate 4.3 indicates that the Slag aggregate has very large "crater" like pores. However, these pores are closed or of "ink bottle" shape and, at higher level of magnification in Plate 4.4 and 4.5, it was clearly seen that the Slag aggregate is a quite dense material with little evidence of network of small pores. Thus, the presence of the closed pores is not revealed by the water absorption tests since the water is unable to penetrate through the particle.

The Rowley Basalt is a dense material as well, but Plates 4.4 and 4.5 indicate that it has internal cracks that add to its microstructure. It has smaller pores than Slag aggregate as can be seen from Plate 4.5. In general, it seems to contain only larger pores probably mostly due to cracks and significant amount of small pores located between the large flat grains of dense material.

The Caldon Low Limestone, on the contrary, is a quite porous material. It is clear from Plate 4.3 that it does not have a great number of large pores, but the small pores are very uniformly distributed as can be seen in Plates 4.4 and 4.5. The individual material grains are also small which produces this very fine pore structure, which resembles the structure of the pores in the matrix filler. This can be seen by comparing Plate 4.2 and 4.5.

In order to quantify pore structure of the materials, a further measurement of pore size distribution was undertaken using a Mercury

Penetration Porosimeter.

4.8 Pore size distribution

The mercury intrusion method (73) was used to determine the pore size distribution of the matrix and the aggregate particles. It is based on the concept that a non-wetting liquid, such as mercury with soil materials, will only enter an empty capillary under pressure, with increasing pressure being needed to intrude the smaller pores. The surface tension of the mercury opposes its entry into smaller pores and its resistance must be overcome by the externally applied pressure. If the liquid has a contact angle with a solid of greater than 90^{o}, it will not wet the solid but enter into void spaces or penetrate the pores. Mercury exhibits a greater contact angle with a large number of materials than any other conveniently usable liquid and, so is particularly useful for the evaluation of pore sizes. Contact angles between mercury and a large variety of materials range (74) from about 112^{o} to 142^{o} with 130^{o} being the most frequent value.

If a cylindrical pore shape is assumed, then knowing the contact angle between soil and mercury and the surface tension of mercury, the absolute pressure of intrusion can be used to calculate the pore diameter using the Washburn (75) equation:-

$$d = - \frac{4 \sigma_m \cos \theta}{p}$$

where d = pore diameter (mm)

σ_m = surface tension of mercury (N/mm)

θ = contact angle between mercury on the pore wall

p = absolute pressure (N/mm^2)

Based on the computed pore size diameter and the amount of mercury intruded at the desired pressure, a pore size distribution can then be calculated.

The tests were performed in a Micromeritics Model 900/910 Mercury Penetration Porosimeter and the procedure followed the specified (73) test procedure. All the samples were dried and evacuated to remove adsorbed gases and vapours so as to permit mercury penetration. The sample cell not only confined the sample but also incorporates a portion of the system for measuring the quantity of mercury forced into the sample pores. The cell is connected to an external circuit which is capable of generating and transmitting the pressure to the mercury.

The Porosimeter cell that was available for this study was only able to accomodate small samples of approximately 5g, and so it was impossible to test a representative slice from any of the mixed aggregate-matrix samples. It was, therefore, decided as a pilot study, to determine separately the pore size distributions for the matrix and each of the aggregates. The data are presented in Figures 4.3 and 4.4.

There are two major limitations with mercury intrusion. The major drawback is that it measures the diameter of the channel leading to the pore, rather than the actual pore diameter. This is often referred to as the "ink bottle" effect (74),(76), where mercury does not flow into a large pore with a small opening until the pressure is sufficient to intrude the pore opening. This characteristic is likely to have influenced the data for the Slag aggregate since such a pore structure was indicated by the electron micrographs. However, when related to frost action, this may not be a major problem since the advancing ice front and moisture migration must both pass through, and be restricted by, these pore channels. The second limitation concerns the shape of the pores. The Washburn (75) equation is based on cylindrical pores. However, this assumption may be fairly reasonable (77) since differences due to pore shapes are within an order of magnitude whereas the pore size range normally extends over five orders of magnitude.

4.9 Hydraulic conductivity

The permeability of soil reflects its ability to permit the passage of water through the network of channels formed by the interconnected pores. There are few indications in the literature of direct relationships between the saturated permeability and frost susceptibility of a soil. However, it was considered useful to study the saturated permeability of the materials with regard to changes in soil structure when different amounts of coarse aggregate are introduced to the matrix.

The permeability of the soil at a given temperature is directly related to:-

1) particle size distribution
2) porosity
3) adsorbed cations and mineralogical composition of a soil.

Changes in particle size and, therefore, pore structure of a soil will influence the saturated water flow through the soil. The suction force generated at the freezing front is the major driving force for water migration towards freezing front, and so the resistance of the soil to water movement, in terms of its permeability, might have some effect on frost susceptibility. The saturated permeability of soils was, therefore, studied to assess how changes in particle size can influence permeability and, ultimately, to examine the possible relationships with the frost susceptibility of the materials.

4.9.1 Test procedure - 102mm specimens

The specimens used for the hydraulic conductivity tests were prepared in the same way as those for the frost heave test and this procedure is detailed in Chapter V. The test procedure followed that for a constant head permeameter with the specimen being located in a triaxial cell. The test method was based on the work of Bjerrum and Hoder (78) and later used by Kettle (61) for studies of colliery shale.

A saturated, de-aired porous disc was placed at the bottom of the specimen and the assembly was positioned on the pedestal of the triaxial cell. Two rubber membranes were placed consecutively over the specimen, using a membrane stretcher, to prevent any possibility of membrane puncture and leakage, since the specimens contained sharp, aggregate particles. These membranes were sealed with two rubber "O" rings to the pedestal. A saturated porous disc was placed at the top of the specimen and the end cap fitted. The membranes were stretched slightly to eliminate any trapped air and were then sealed with two "O" rings against the top cap.

The triaxial cell was assembled and filled with de-aired water. The various pressure lines were then connected to mercury dash-pot systems which were used to set out and control the individual pressures. The cell pressure was set at 103kN/m^2 and the back pressure line was opened to water at atmospheric pressure. The sample was left to consolidate for 24 hours.

At the end of the consolidation time the cell pressure was increased slowly to 448kN/m^2. Concurrently the back pressure was increased to 345kN/m^2, so that the effective stress remained at 103kN/m^2. When the cell and back pressures had been stabilised, the head pressure was raised to 400kN/m^2, so that flow was initiated through the sample. The flow of water through the sample was measured using an electronic volume change cell, and the flow and pressure readings were recorded on a data logger. The readings of pressure and volume change were taken every 8 - 10 seconds until a representative result was obtained.

The hydraulic conductivity was measured at different head pressures to determine the optimum flow conditions. However, it was noticed that as the head pressure was increased the hyraulic conductivity decreased. In addition, the water flowing from the sample became cloudy, which was an indication of the migration of fines (ground chalk) from the sample passing through the porous plate. At the end of the test porous plate was noticeably blocked with fines.

In the sand/snowcal matrix, the relatively large sand grains act as a skeleton with the snowcal as the filler between them. This could be clearly seen on photographs from microscope examination in Plates 4.1 and 4.2. With the introduction of coarse aggregate particles, large pores will appear as a result of the interactions between aggregate particles. In addition, intermediately sized pores will be formed between the coarse particles and the sand grains. The filler would be unable to uniformly fill all these pores, since the increase in coarse aggregate content will proportionally reduce the amount of fines. This is apparent from the particle size data in Tables 4.3 and 4.4. Therefore, some of the fine particles could be easily washed through the large pore channels. Indeed, with an increase in aggregate content, the effect of head pressure on hydraulic conductivity was more noticeable as can be seen in Figure 4.5 where data is presented for both the matrix material and for mixture containing 40% of 20 - 3.35mm limestone particles. It was clear that as the head pressure was raised, the fine particles migrated towards the base of the specimen i.e. the porous plate connected to the back pressure line. This effect was not apparent in the matrix specimens but was observed in those containing large quantities of coarse particles. As is apparent in Figure 4.5 this migration produced a reduction in hydraulic conductivity as the fine particles blocked pore channels at the base of the specimen.

When a soil is freezing in the frost heave test, water moves upwards towards the freezing front. The migration of the fines, therefore, would not be a major influence as in the hydraulic conductivity measurements, but some fine particles might still be lifted. The flow of water towards the freezing front will vary with time and distance from growing ice lenses, so that the suction force applied to water and, possibly lifting the fine particles, will vary considerably. However, within the test procedure, the major effect of this migration was the difficulty of selecting a suitable head pressure for all the samples. It was, therefore, decided to measure the hydraulic conductivity by following a single procedure that did not involve selecting an optimum head pressure for each sample. Due to the large pores in the aggregate-matrix mixtures, it was clear that once the head pressure exceeded $400kN/m^2$, the back pressure would also start to increase. The hydraulic conductivity was, therefore, determined for incremental pressure drops across the specimen ranging from 10 to $55kN/m^2$. The initial difference between the head and back pressures was $-10kN/m^2$ and this was increased by $10kN/m^2$. For each pressure drop, flow readings were monitored constantly and when the readings became steady the hydraulic conductivity was determined. The hydraulic conductivity was then taken as the overall mean of all individual means corresponding to each pressure drop.

The results obtained from two similar samples were checked for significance using "Student t-test" and if the results from the samples were not significant at the 5% level they were accepted. Where the differences were significant, additional samples were prepared and the procedure was repeated until satisfactory results were obtained. The results of all these tests were summarised in Table 4.9.

MATERIAL	NUMBER OF SPECIMENS	COEFFICIENT OF PERMEABILITY (cm/sec)
80% sand + 20% snowcal	8	0.61×10^{-4}
10% Slag	3	1.32×10^{-4}
20% Slag	2	1.60×10^{-4}
30% Slag	4	1.96×10^{-4}
40% Slag	2	2.20×10^{-4}
50% Slag	2	2.59×10^{-4}
10% Rowley Basalt	2	1.96×10^{-4}
20% Rowley Basalt	2	1.64×10^{-4}
30% Rowley Basalt	4	1.51×10^{-4}
40% Rowley Basalt	3	0.71×10^{-4}
50% Rowley Basalt	2	0.65×10^{-4}
10% Caldon Low Limestone	3	2.18×10^{-4}
20% Caldon Low Limestone	3	1.60×10^{-4}
30% Caldon Low Limestone	2	1.46×10^{-4}
40% Caldon Low Limestone	2	1.30×10^{-4}
50% Caldon Low Limestone	2	1.10×10^{-4}

TABLE 4.9 MEAN COEFFICIENT OF PERMEABILITY FOR 20 - 3.35MM AGGREGATES AND MATRIX MIXTURES

4.9.2 Test procedure - 145mm specimens

Some frost heave tests were performed on larger specimens of 145mm diameter and so it was decided to also measure the appropriate hydraulic conductivity values for these specimens. The specimens were prepared as for frost heave test, the procedure being detailed in Chapter V and tested following the procedure used for the 102mm specimens. The only difference was the use of a new triaxial cell with a 150mm diameter pedestal and so which was suitable for testing 145mm specimens.

However, the migration of the fines was clearer than with the 102mm specimens. This was apparent even with the sand/snowcal matrix. The variation in hydraulic conductivity with change in head pressure was considerable and became more marked when coarse particles were introduced into the matrix. This is shown in Figure 4.6, where hydraulic conductivity is plotted against head pressure for specimens of both sand/snowcal and a mixture with 30% of Rowley Basalt. Plate 4.6 shows a specimen with 30% of Rowley Basalt at the completion of the test. It is clear that there is a concentration of fines at the bottom of the specimen with a coarser sand grain texture at the top.

An attempt to quantify this effect was undertaken by determining the pore size distribution at the top and bottom parts of the sand/snowcal specimen. The mercury intrusion method described in Section 4.8 was used and the results are shown in Figure 4.7. By comparing the various curves in Figure 4.7, it is apparent that for pore sizes greater than approximately 12 μm, the bottom is some 5 - 8 percent finer than the top of the 145mm sample. Within the matrix material, approximately 60% of the pores are larger than 12 μm, whereas some 10 percent of the particles are smaller than 10 - 12 μm. These particles are, therefore, able to move through the larger pores. The matrix contains some 4 percent of particles finer than 2 μm and it is apparent that all three samples had a similar pore structure at the fine end of the range. This may well indicate that the small, clay-sized particles are less mobile due to their surface forces that loosely bond them to the larger sand particles as shown in Plate 4.2.

At the other end of the spectrum, the larger particles of coarse silt (+20 μm) in the snowcal are too large to move through the pore structure. However, the intermediately sized particles (10 - 2 μm) are both small enough and sufficiently mobile to move through the available (12μm) pore openings. Thus, the increase in porosity (5 - 8 percent) at the top of the sample may be attributed to the migration of the medium-fine silt particles (10 - 2μm) through the pore system.

Tests were performed on the matrix material and some aggregate/matrix mixtures using 145mm specimens. The results are summarised in Table 4.10, clearly show that higher values were determined using the larger specimens and these differences were significant at the 5 percent level. This may also be attributed to differences in the pore size distribution in these samples. In Figure 4.7 it can be seen that the material in the 102mm specimens has fewer large pores than that in the larger specimens, and this would restrict the passage of water through the 102mm specimens. It is suggested that this behaviour may be attributed to the compaction procedure, and the associated boundary effects, followed during specimen preparation.

Material	Coefficient of permeability (cm/sec)	
	Mean	After 4 - 6 hours of testing
Sand/Snowcal matrix	1.54×10^{-4}	1.04×10^{-4}
10% Slag	3.04×10^{-4}	1.17×10^{-4}
30% Slag	6.59×10^{-4}	1.01×10^{-4}
10% Rowley Basalt	3.12×10^{-4}	0.98×10^{-4}
30% Rowley Basalt	2.68×10^{-4}	0.79×10^{-4}

TABLE 4.10 COEFFICIENT OF PERMEABILITY FOR 37.5 - 20mm AGGREGATES AND MATRIX MIXTURES

A further attempt was made to measure the hydraulic conductivity of aggregate-matrix mixtures, without using a positive back pressure. Following consolidation at a cell pressure of 103kN/m^2, the head pressure was raised to 130kN/m^2 using only water and the flow through the specimen was monitored continuously. The sample consisted of the matrix with 30 percent of 37.5 - 20mm Rowley Basalt particles, and the measured hydraulic conductivity decreased from 10.3×10^{-4} to 0.59×10^{-4} cm/sec over a four hour test period. This was similar to the behaviour observed at higher pressures and, again, the water flowing from the sample became increasingly cloudy. When the cell was dismantled this migration of fines was also evident from the appearance of the specimen. It was, therefore, decided that this washing out of the fine particles was not appropriate to frost action and so further permeability testing, using 145mm specimens, was abandoned.

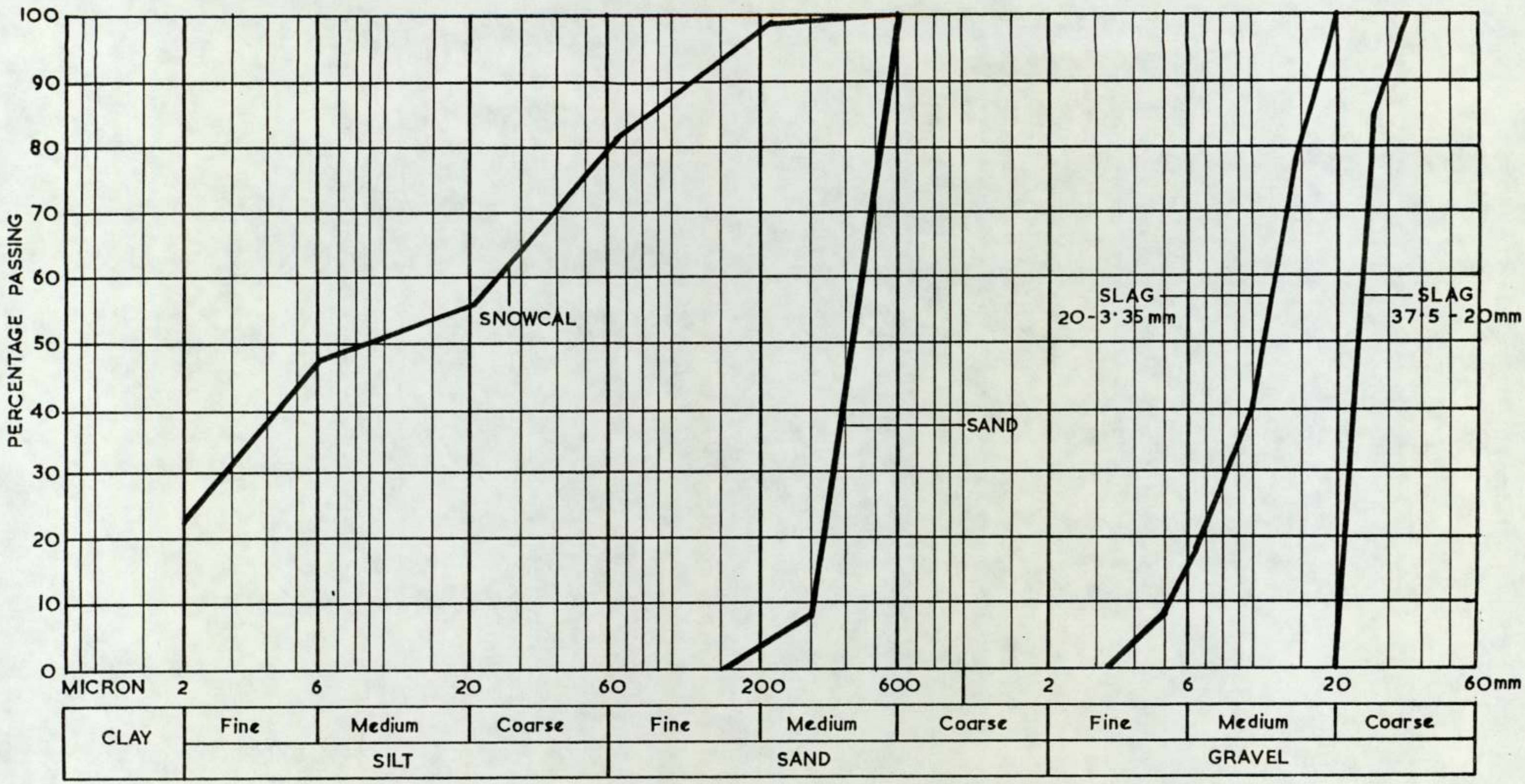


FIG. 4. I. PARTICLE SIZE DISTRIBUTION.

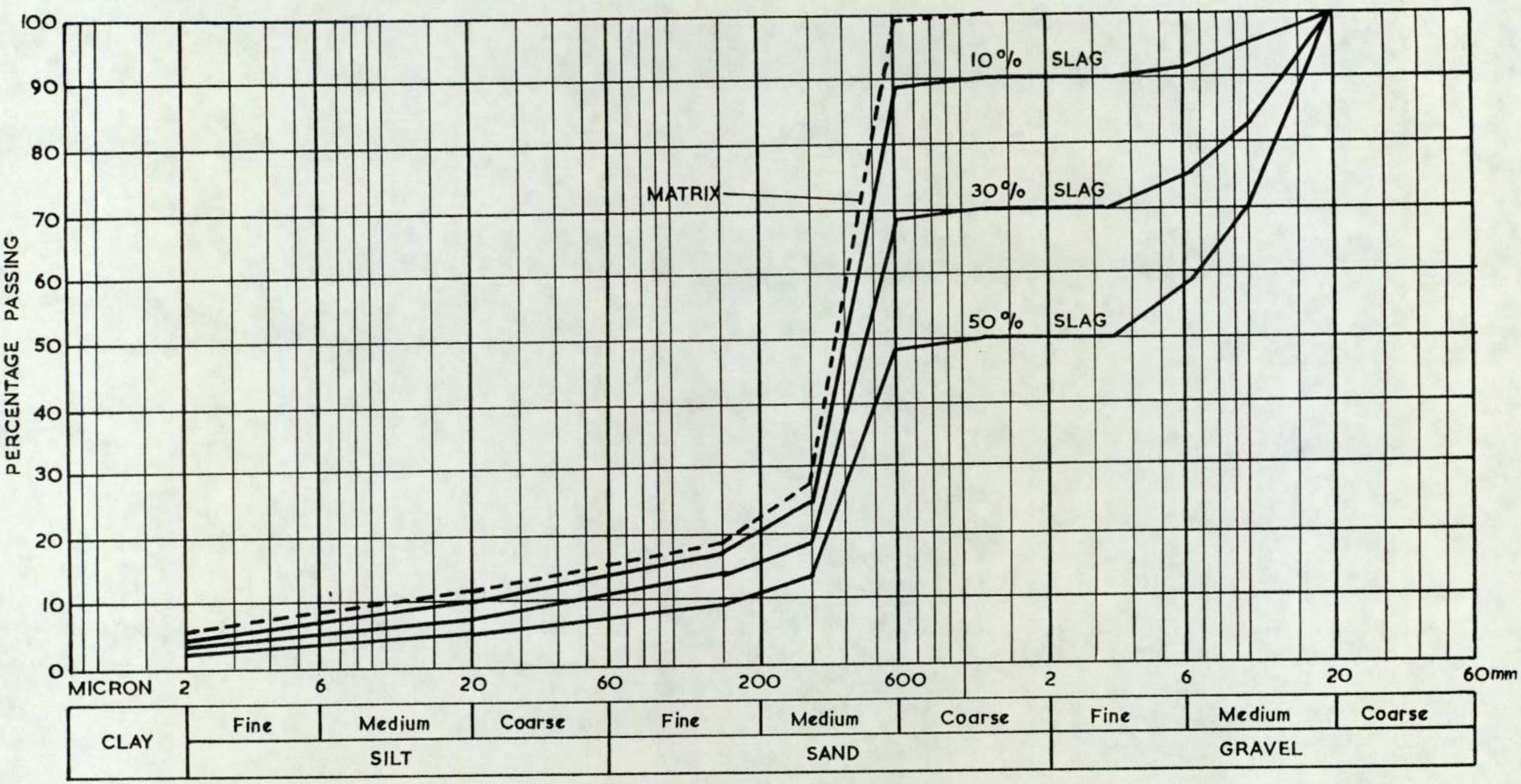


FIG. 4.2. PARTICLE SIZE DISTRIBUTION.

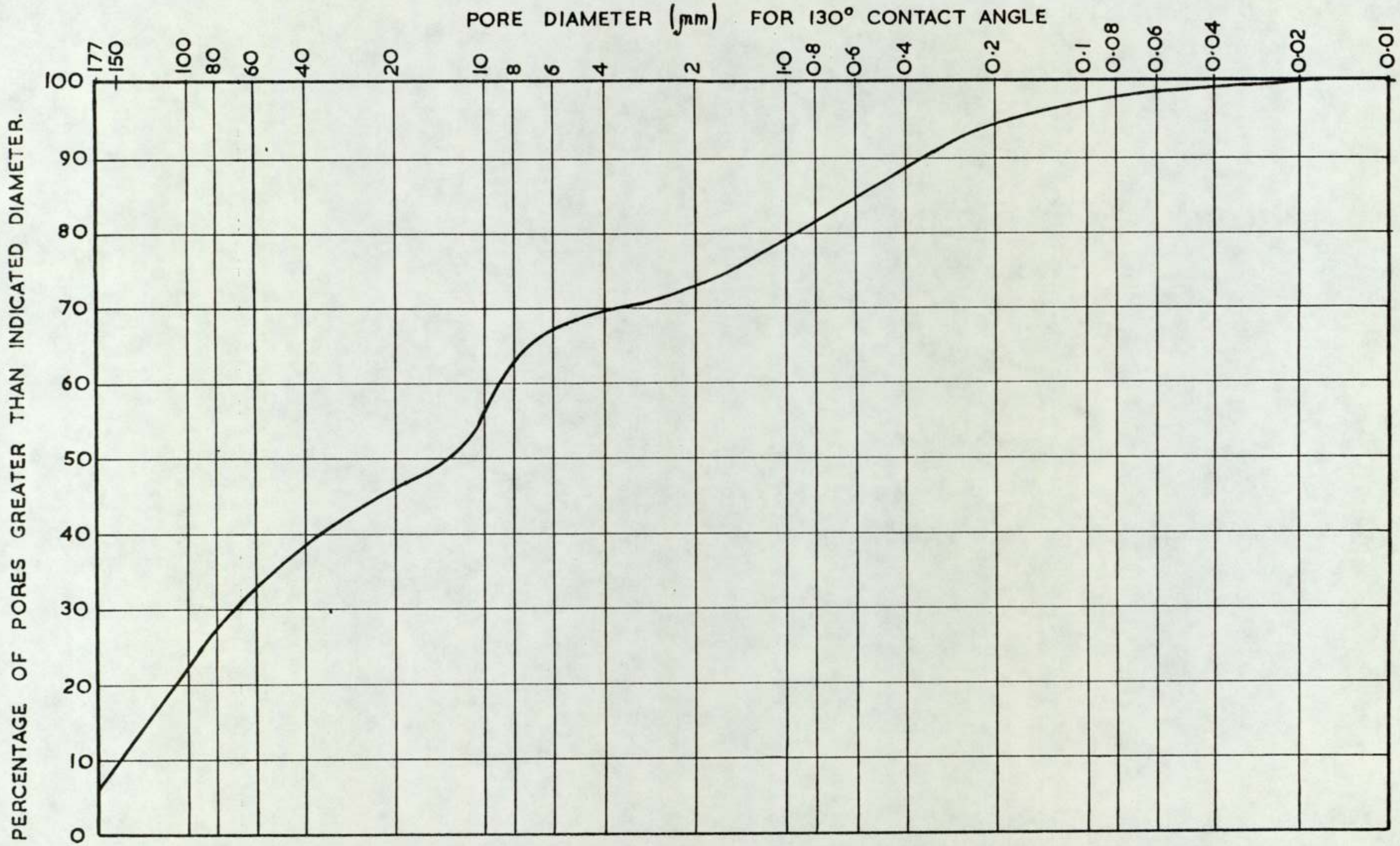


FIG. 4.3. PORE SIZE DISTRIBUTION FOR SAND/SNOWCAL MATRIX.

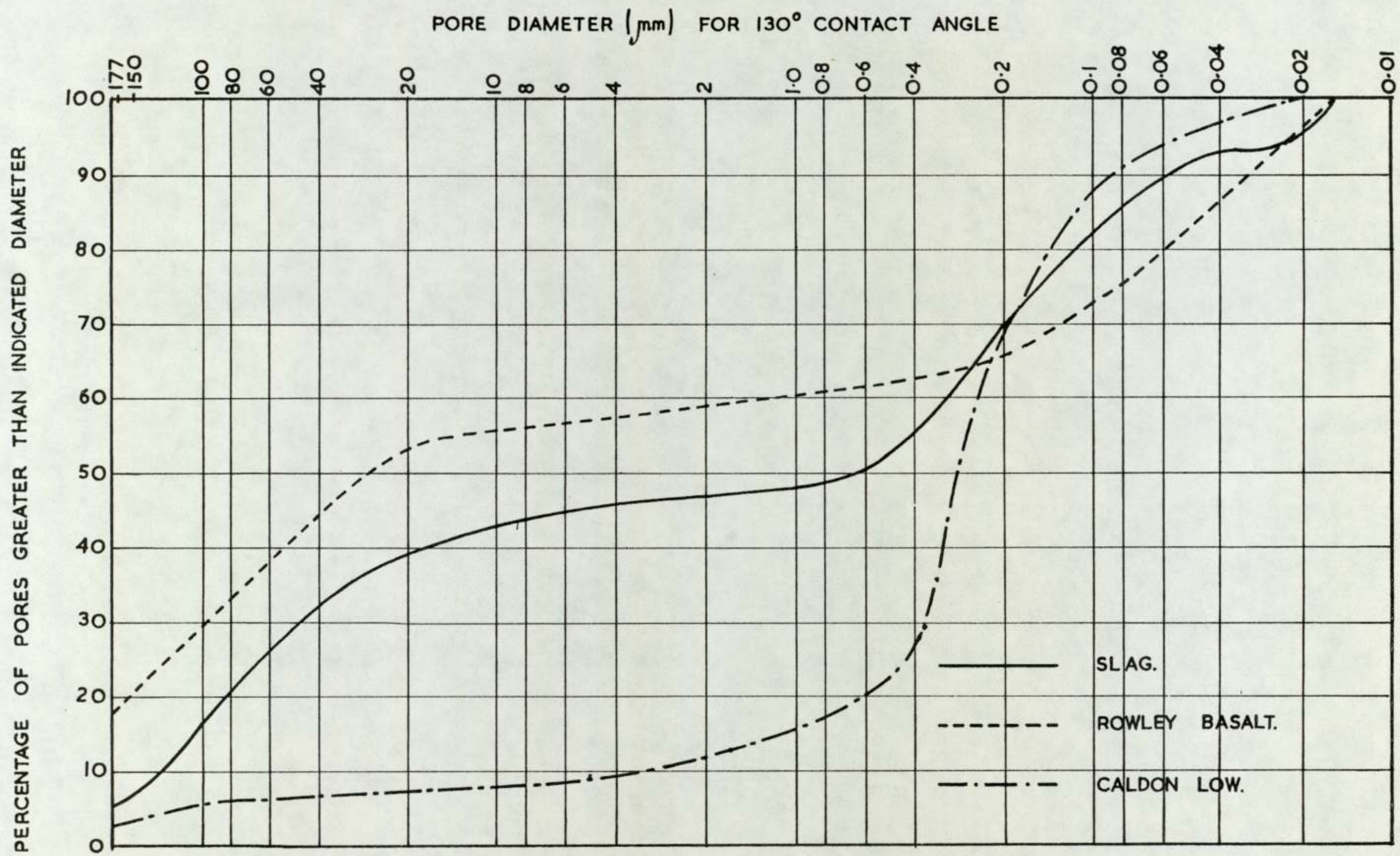


FIG. 4.4. PORE SIZE DISTRIBUTION FOR AGGREGATES.

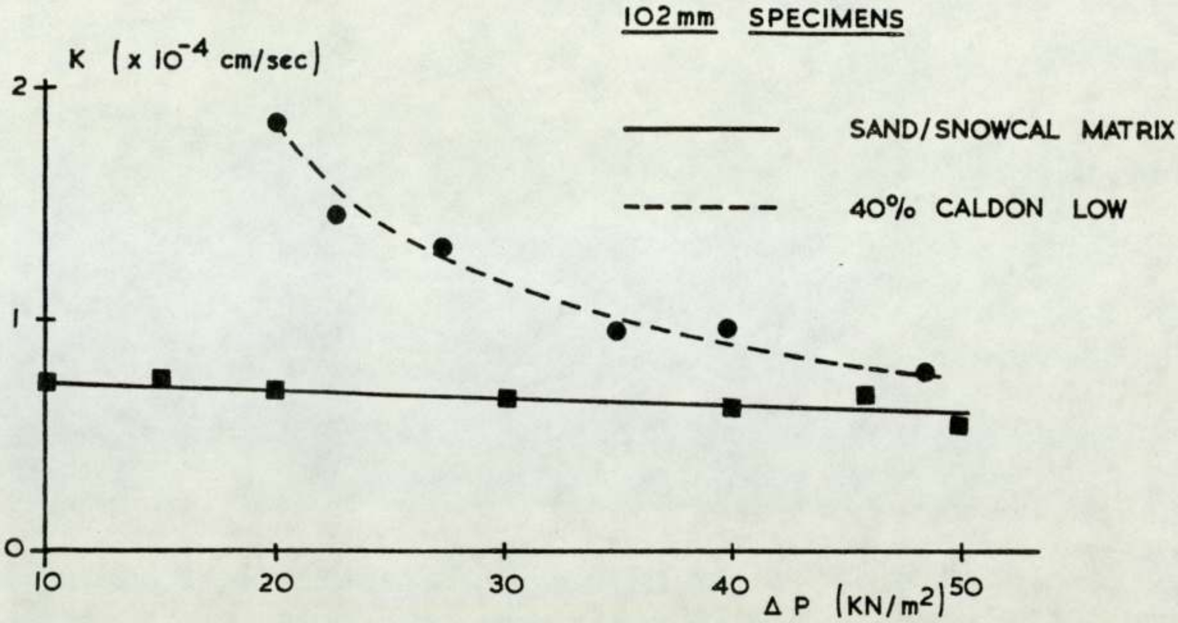


FIG. 4.5. COEFFICIENT OF PERMEABILITY AGAINST HEAD PRESSURE.

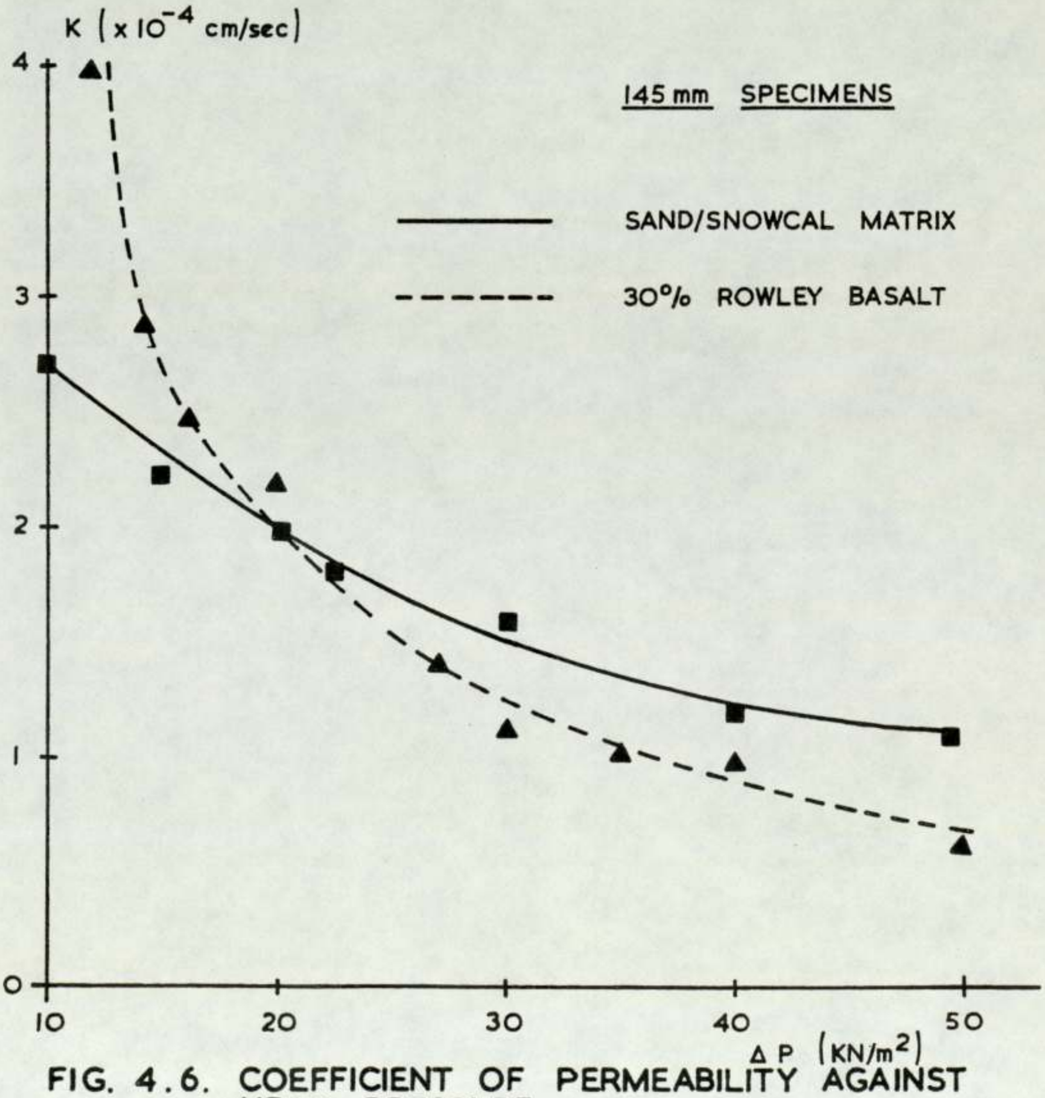


FIG. 4.6. COEFFICIENT OF PERMEABILITY AGAINST HEAD PRESSURE.

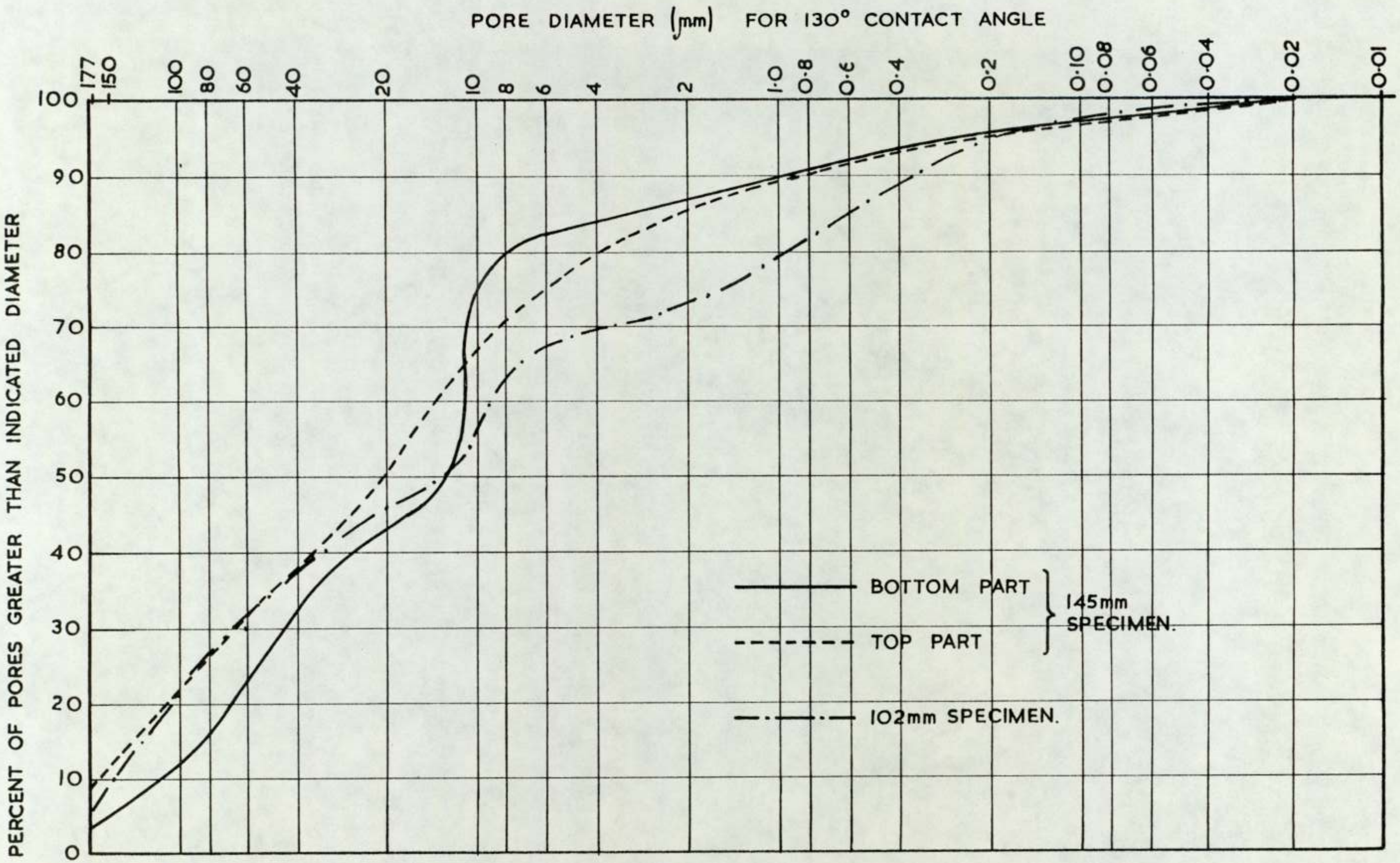


FIG. 4.7. PORE SIZE DISTRIBUTION IN 145mm SPECIMEN AFTER HYDRAULIC CONDUCTIVITY TEST.

A

B

C

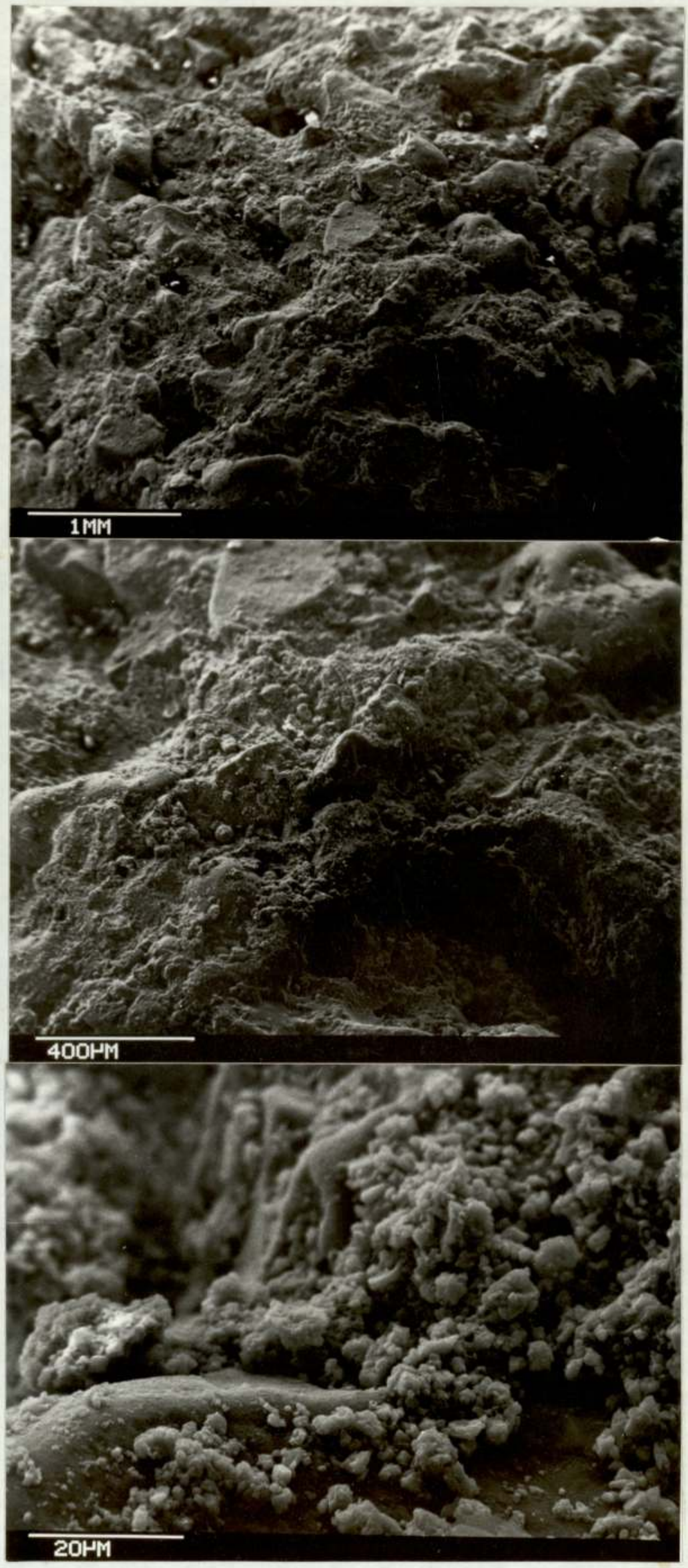


PLATE 4.1 Electronmicrographs of sand/snowcal matrix

A

B

C

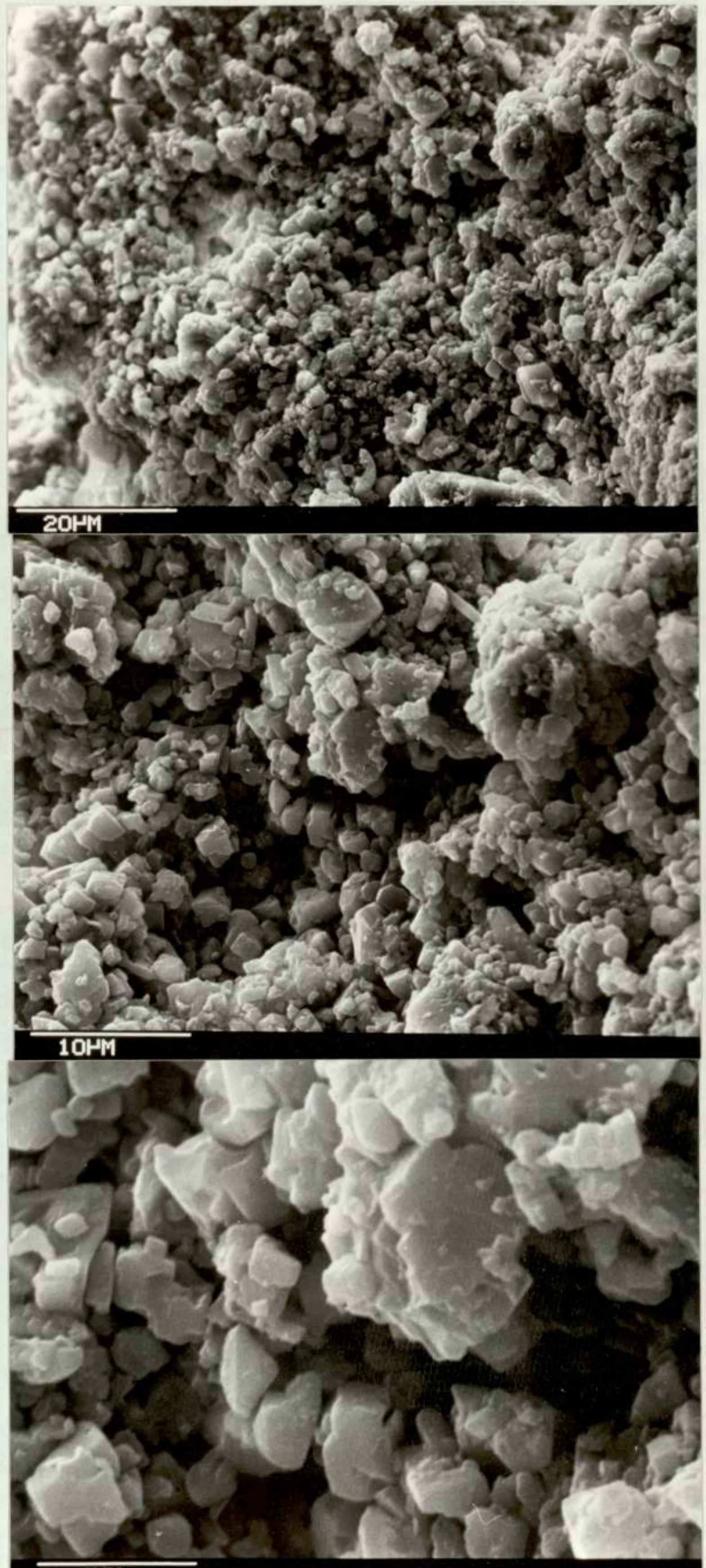
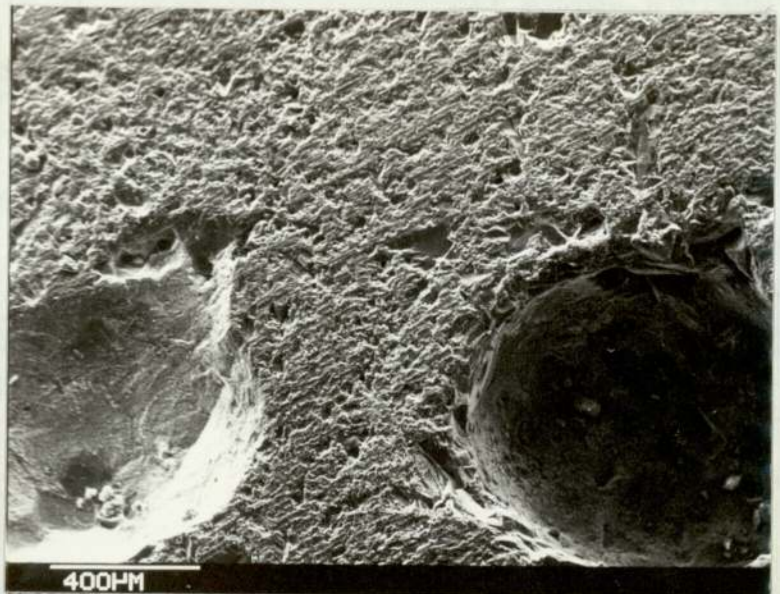


PLATE 4.2 Electronmicrographs of snowcal filler.

Slag aggregate



Rowley basalt

Caldon Low
limestone

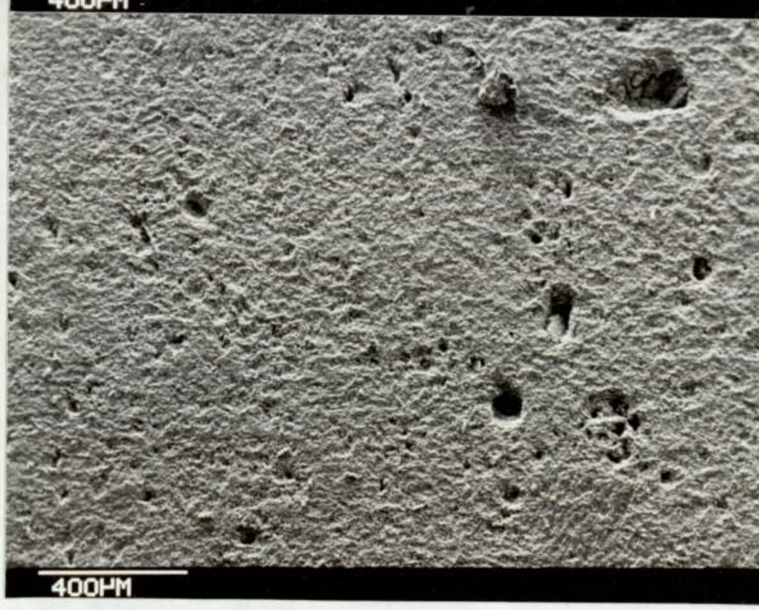
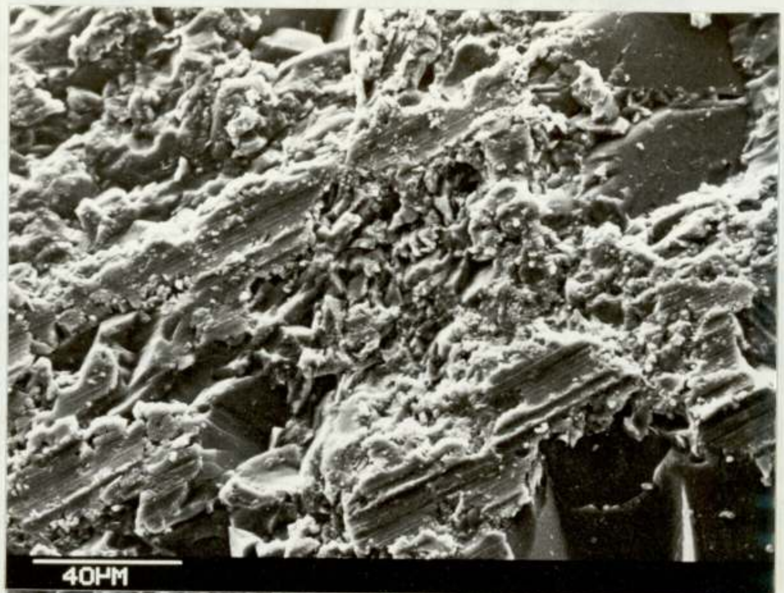


PLATE 4.3 Electronmicrographs of aggregates

Slag aggregate



Rowley basalt

Caldon Low
limestone

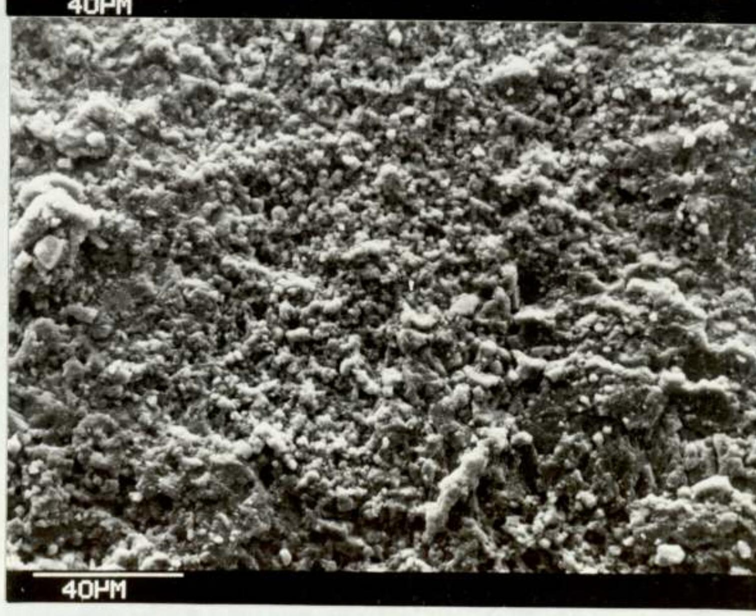


PLATE 4.4 Electronmicrographs of aggregates

Slag aggregate

Rowley basalt

Caldon Low
limestone

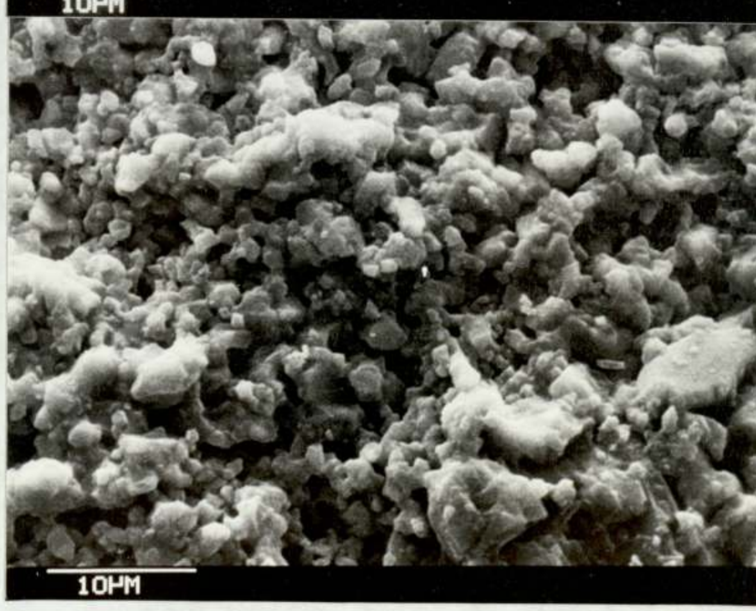


PLATE 4.5 Electronmicrographs of aggregates

PLATE 4.6 Specimen after permeability test

CHAPTER V

DEVELOPMENT OF FROST HEAVE EQUIPMENT AND TEST

5.1 Introduction

The investigation reported in this Chapter is based on the TRRL frost heave test (8) which was developed (79) in 1945 at the then Road Research Laboratory. The original test procedure was described in a research report LR90 (5), published in 1967 and it also included heave criteria for assessing frost susceptibility. Shortly afterwards, these criteria were adopted (80) by the Department of the Environment for classifying the frost susceptibility of unbound and cement stabilised materials for use in highway construction.

As a result, many materials were subjected to the frost heave test and it became clear (61),(67) that the procedure given in LR90 was not sufficiently detailed for routine testing. A further study of the test was, therefore, undertaken at the Transport and Road Research Laboratory. This resulted in the publication of a supplementary report, SR318 (8), which presented a detailed specification for carrying out the test on granular materials. This procedure did not depart significantly from that given in LR90 (5) and so the original heave criteria were retained.

When this investigation commenced the LR90 test procedure was adopted. However, when SR318 was published in 1977, it was decided to follow this procedure, which was, in fact, very similar to that already being pursued. A cold room was used for these tests since the original LR90 procedure was based on such a facility. However, the current trend (81),(82) is towards the use of self refrigerated units (SRU's). A limited number of tests were therefore, undertaken in an SRU so that tests run in the two facilities could be compared.

The lack of a clear specification for the test has led to problems due to the poor reproductibility (61),(81) of the results and so this investigation has been concerned with studying the influence of various factors on the measured heave. A reference material, consisting of a mixture of sand and ground chalk, was used for this initial work and so the study has also examined the effects of both material properties and test parameters on the measured heave.

5.2 Outline of the test procedure

Granular materials are tested at the maximum dry density and the optimum moisture content, determined by BS (Test 12) Compaction test (71). Cylindrical specimens of 102mm diameter and 152mm high are prepared by tamping a required quantity of material in 3 layers into a constant volume mould, and this compacted statically in a compression frame. The specimens are positioned on porous discs within copper carriers. The discs are in contact with water, which is maintained at a temperature of $+4\pm0.5^{\circ}C$ throughout the freezing period. Push rods, resting on caps placed on top of the specimens, allow the heave to be measured. After a 24 hour conditioning period at room temperature, the specimens are exposed to a freezing regime in a cold room operating at a temperature of $-17\pm1^{\circ}C$. The water bath is topped up every 24 hours and the push rod movements are recorded at the same time. The test is completed after 250 hours of freezing. If the heave of the specimen is more than 13mm (in England and Wales) or 18mm (in Scotland) the specimens are considered to be frost susceptible.

5.2.1 Compaction parameters for test specimens

When the research programme was commenced, the test procedure followed the LR90 (5) guidelines. Thus, granular materials were tested at the optimum moisture content and maximum dry density determined from the BS standard compaction (2.5kg rammer) test (71). This level of compaction was adopted in SR318 (8), although interest has been expressed (67),(81),(83) in using the parameters from the vibrating hammer test (71) for specimen preparation. [It does seem likely that this test will be adopted in any further revisions (82) of the test procedure since it produces values closer to those obtained in the field]. However, it was decided to continue with the 2.5kg rammer test as the effect on heave of changing the compaction requirments was not known and the available criteria were based on such a level of compaction.

5.2.2 Preparation of the test specimens

Sufficient material to produce three 102mm diameter specimens was mixed dry in a Hobart food mixer to produce a uniform distribution of fine particles. The required quantity of water was added and the material was thoroughly mixed for 5 minutes. It was immediately transferred to an airtight container. This procedure was repeated until sufficient material was produced for the desired number of specimens.

The mould was assembled in the vertical position with the 25mm spacer placed around the bottom plug and the mould lowered over the plug to rest on the spacer. Sufficient material to produce one specimen, at the specified dry density and moisture content was accurately weighed and introduced to the mould in three approximately equal layers. Each layer was initially compacted with a standard 1.5kg tamper dropped freely from the top of the mould. The first layer received 25 blows, whilst 50 and 75 blows were applied to the second and third layers respectively. The top end plug was inserted and the spacers were removed so that equal gaps were achieved between the mould and each plug to ensure even compaction of the specimen. Final compaction was by static loading in a Denison compression machine. The maximum compaction force did not exceed 200kN for all the specimens. Compaction was regarded as completed (8) if the gap between the mould and plugs did not exceed 2mm after the release of the load.

The specimen was extruded from the wider (bottom) end of the tapered mould. In the first stage, the short extruder (174mm) was forced through the mould using the compression machine. Final extrusion was attained by hand using the long extruder (330mm). To prevent damage to the specimen during this final stage it was decided to use an extraction collar (8) placed on top of the mould and into which the specimen could be extruded. With this arrangement a hydraulic jack could be used for final extrusion.

After extrusion each specimen was wrapped in waterproof paper (200mm x 350mm), secured with adhesive tape. The lower edge of the paper was in line with the base of the specimen so as to give a 50mm upstand at the upper face. The specimen was positioned on top of a porous stone, 103mm diameter and 14mm thick and porous stone was positioned in a copper specimen carrier. A Tufnol disc, 95mm diameter and 5mm thick, was placed on top of the specimen and the complete assembly was transferred into one of the holes in the cradle of the frost cabinet. Prior to placing the specimens in the trolley, the water level in the bath at the base of the trolley had been adjusted to coincide with the top of the porous stone.

When all the specimens had been located in the cabinet, the spaces between them were normally filled with dry sand (5 - 2.36mm Leighton Buzzard) to the level of the tops of the specimens. Push rods, supported by transverse metal bars, were set in the dimples of the centre of each Tufnol disc and the trolley was left to condition for 24 hours at room temperature.

A cold room with a capacity of $7.5m^3$, was constructed at Aston

University from standard sections. Two trolleys can be accommodated with easy access for the daily measurements of heave and topping up the water bath. Although the cold room is normally operated at a temperature of $-17\pm1.0^{\circ}C$, it was designed to maintain a temperature of $-25^{\circ}C$ in an ambient temperature of $26^{\circ}C$. The defrosting of the cold room is fully automatic and can be pre-set according to the number of defrosts required. A "cold curtain" fan was installed above the door to minimise temperature fluctuations inside the cold room when the door is opened for the daily checks.

5.2.3 Test procedure

At the completion of the 24 hour conditioning period the trolley was wheeled into the cold room which was already operating at $-17^{\circ}C\pm 1^{\circ}C$. The water bath was immediately topped up with water until discharge was observed from the overflow pipes and the heaters were connected to the mains via a contact thermometer preset to $+4^{\circ}C$. The push rods were pressed into firm contact with Tufnol discs and the initial readings of their positions, relative to the transverse bars, were recorded with a dial gauge to a precision of ± 0.01mm. Every 24 hours these readings were repeated. The water bath was also topped up until discharge was observed through the overflow pipes, which were thawed each day prior to topping up.

The test period was completed after 250 hours when the final readings were taken. The trolley was wheeled out of the cold room and the packing was removed from between the specimens. The specimens were removed from the trolley, unwrapped and visually inspected. The thickness of unfrozen zone was measured and recorded. This provided an indication that the temperature gradient through each specimen was as expected. Large variations in the thickness of this zone indicated that the boundary conditions were not as required and so the test would be repeated.

5.2.4 Test results

At the completion of the 250 hour freezing period, the total movement of the push rods was calculated. This frost heave was used to assess the frost susceptibility of the material on the basis of the criteria originally given in LR90 (5).

1) Heave less than 13mm - non frost susceptible.
2) Heave between 13 and 18mm - marginally frost susceptible.
3) Heave greater than 18mm - highly frost susceptible.

These criteria are used for road construction in England and Wales (7). In Scotland (84), a single criterion has been adopted with 18mm, providing the division between non-frost susceptible and frost susceptible materials.

5.3 Modifications in specimen preparation and test procedure

5.3.1 Conditioning of material prior to specimen preparation

The test procedure described in LR90 (5) was considered to apply to all materials - cohesive and granular. It implied that all materials would be moulded immediately after mixing. This is clearly inappropriate for cohesive materials. Indeed, in BS1377 (71) a 7 day conditioning period is recommended, for such materials, between mixing and moulding in the standard compaction tests. This problem was appreciated when the interim specification (8) was produced for the testing of granular materials, since a conditioning period was introduced between mixing and moulding for such mixtures.

The reference material used throughout this study consisted of a mixture of 600 - 300 μm sand and ground chalk (Snowcal 2ml) in the ratio of 4:1. It was, therefore, decided to undertake a preliminary investigation of the need for a conditioning period with this mixture. Accordingly, specimens were produced following two separate procedures:

a) immediately after mixing,

b) following storage for 24 hours after the initial mixing.

The remaining procedure for these tests followed that described earlier and the results are summarised in Table 5.1.

These reveal that there was no significant difference between the two sets of results and so it was decided to produce all the specimens immediately after the initial mixing.

Number of specimens	Heave (mm) / Standard deviation (mm)	
	a) procedure	b) procedure
9	23.80 / 1.89	24.98 / 2.02

TABLE 5.1 FROST HEAVE FOR TWO METHODS OF PRODUCING SAMPLES

5.3.2 Temperature gradient through specimens

In the frost heave test the temperature gradient through the specimens is largely a function of the standard air and water bath temperatures, which are, respectively, $-17 \pm 1^{\circ}C$ and $4 \pm 0.5^{\circ}C$. However, since these temperatures may fluctuate within the specified limits, the gradient through the specimens may also vary. This could be a factor contributing to the lack of reproductibility reported (81) with the test and so it was considered essential to investigate the effects of such fluctuations on the temperature gradients and the measured heave.

It was believed that variations in the air temperature, within the specified tolerances, would not significantly influence the temperature at the top of the test specimens, since the Tufnol caps on top of the specimens have a very high thermal resistance. In initial tests, with the air temperature at $-17\pm2^{o}C$, temperature measurements taken by thermocouples on the top of the specimens, indicated that the fluctuations had largely been eliminated by the thermal inertia of the cap. It was, therefore, decided to vary the thermal parameters by adjusting the temperature of the water bath.

Two of the available trolleys were fitted with preset, mercury contact thermometers operating at $4.0\pm0.5^{o}C$, but a third trolley initially had a variable thermostat to control the temperature of the water bath. This trolley was used for this investigation although, for the main study, the variable thermostat was replaced with a preset contact thermometer. To establish the effect of the temperature of the water bath, a series of tests were undertaken with the following conditions:

1) at the normal temperature of $4.0\pm0.5^{o}C$
2) at the higher temperature of $5.5\pm0.5^{o}C$
3) at the lower temperature of $2.5\pm0.5^{o}C$

The temperature gradient was established from thermocouples placed in cement stablised specimens. These were placed at 25mm intervals along the centre line of the specimen. Preference was given to cement stablised specimens since they permitted the thermocouples to be placed permanently at known locations. Additionally, the same specimens could be used throughout the programme of tests, thus permitting comparisons between the results obtained with different test conditions.

It has been suggested (66) that the thermal characteristics of cement stablised specimens can differ from those of unstabilised specimens in the frost heave test. However, as the data was only required for a comparative study, this should not be a significant factor. Had a frost susceptible material been used for the instrumented specimens the temperature of the top surfaces would have varied with time as the specimen protruded through the sand fill insulation. In addition, the locations of the individual thermocouples would change as the specimen heaved so that comparison between tests would become difficult. The temperature gradient through each sample is a function of the thermal conductivity of the material which will be influenced by such factors as material composition, moisture content and density. In this particular study, the main observations were not centred on the behaviour of individual specimens, but rather on the effect of the temperature regime on the overall performance. Thus, the changes in temperature gradient could be monitored by the two (or three) stabilised samples whilst changes in heave could be detected from the behaviour of the remaining seven (or six) unstabilised specimens.

The results of these tests are collected in Figures 5.1 to 5.4 and they clearly indicate the importance of the temperature of the water bath. This temperature appears to influence both the frost heave and the location of the zero isotherm. An increase in this temperature leads to a rise in the location of the zero isotherm and to a significant decrease in the frost heave. A decrease in water bath temperature to below $4.0^{o}C$ results in zero isotherm below the position observed in standard tests and produces an increase in heave.

When the temperature at the bottom of the specimen is increased there will be an increase in the upward heat flow through the specimen. Providing that the remaining boundary conditions are kept constant, the temperature at the top of the specimen will also increase. Indeed, the data in Figure 5.3 indicate that the thermal inertia of the Tufnol discs resulted in changes in the top temperature that were very similar to those at the base of the specimen. Thus, the increased heat flows could not be rapidly dissipated through the discs and so produced the distributions given in Fig. 5.3. It is, therefore, clear that in the frost heave test an increase in the bottom temperature leads to a rise in the location of the zero isotherm.

Frost heave involves the movement of water to the freezing front. The driving force for this flow depends on the magnitude of the suction induced in the freezing soil and this increases as the temperature at the freezing front is decreased. In these tests an increase in the bottom temperature produced an increase in the top temperature, and hence, a decrease in the magnitude of the induced suction. The increase in the bottom temperature also resulted in a rise in the position of the zero isotherm, so enlarging the unfrozen portion of the specimen which thereby increases the flow path for the water. The combination of these two factors - reduced suction and increased flow path - resulted in a reduction in the moisture movement to the freezing front and hence a reduction in the heave. Experiments (85) into water migration in freezing soils, with different top and bottom temperatures, have also indicated that the increases in moisture content were greatest near the freezing front and decreased with distance into the freezing soil. Further, the increases in moisture content at the freezing front were greatest in those specimens with the lowest temperatures and, hence, lowest positions of the zero isotherm. This observation is compatible with behaviour reported in the frost heave tests. In addition, it was reported (85) that at the lower temperatures, increases in moisture content were also detected behind the freezing front and it was suggested (85) that the temperature gradient also induced water migration into the frozen soil behind the freezing front.

The temperature gradient determined in the standard test - air temperature of $-17\pm1^{o}C$ and water bath at $4.0\pm0.5^{o}C$ - was compared with that given in LR90 (5). This comparison is shown in Figure 5.4, together with data reported by Kettle (61), and it is clear that there is good agreement between all three distributions. Throughout the investigation regular checks were made on the temperature distribution, using a single instrumented specimen, and these demonstrated that conditions within the test facility remained sensibly constant.

5.3.3 Position of the water level

In the frost heave test the water surface would be located at the base of the specimen/top of the porous stone interface at the start of the freezing period. It is topped-up to this level every 24 hours throughout the subsequent 250 hour freezing period. Thus, the fluctuations in this water level will be directly dependent on the amount of ice lensing that has occured within each 24 hours. Indeed, these fluctuations in water level can lead to thawing, i.e. specimen conditions, at the base of the ice lenses and such behaviour can be seen from the results of the test (5),(61). In addition, the initial position of the water surface is very dependent on the accuracy of the geometry of the particular trolley being used for any test.

These factors are unlikely to be so important with current SRU's, since in these, the water level is kept constant throughout the test by use of an external Mariotte vessel. However, in this investigation, virtually all the frost heave tests were performed in a cold room using trolleys and so it was considered essential to study the influence of water level on heave.

A series of tests was undertaken on both the sand/snowcal matrix and on the matrix with controlled amounts of Slag coarse aggregate. These tests were performed with the water level at:-

a) the specified location;

b) 8mm above the base of the samples.

With the given geometry of the trolleys, it was not possible to adopt heights greater than 8mm, since water would then have been able to penetrate the cork insulation in the walls of the trolley. Apart from the raised water level, the test procedure followed that detailed in section 5.2. During these tests the temperature gradient was again monitored using two, cement-stabilised specimens that were randomly positioned within the particular trolley.

The results of the tests are collected in Table 5.1a. These clearly demonstrate that for the samples/materials tested, an increase in the water level to 8mm above the porous stones produced a reduction of approximately 35% in the measured heaves. In all the cases these reductions in heave were clearly significant at the 5 percent level.

Material	mean heave with normal water level (mm) (Chapter VI)	mean heave with high water level (mm)	Decrease in heave (%)
sand/snowcal	24.5	16.41	33
10% Slag	18.9	13.0	31
20% Slag	17.0	11.5	32
30% Slag	16.0	10.2	36
50% Slag	9.0	5.9	34

TABLE 5.1a. Frost heave with normal and high water level

A similar trend was observed by Turrill (86) with his frost heave tests. Although the water bath and air temperatures remained constant throughout the series, thermocouple measurements indicated that the temperature distribution within the specimens was influenced by the position of the water level. It is clear that the raised water level also raised the location of the zero isotherm in the specimen and increased the temperature at the top of the specimen i.e. immediately under the Tufnol disc. These changes are shown in Figure 5.5. Thus, the raising of the water level produces similar changes to those observed when the temperature of the water bath was raised. This will have a similar effect on the induced suction and the water path to that described in the previous section, and so the reduction in heave can also be attributed to these factors.

5.4 Influence of specimen size

5.4.1 Background

The frost susceptibility of granular materials is assessed by testing cylindrical specimens measuring 152mm by 102mm diameter. In the original description (5) of the test only material retained on the 50mm(2in) sieve was to be excluded during specimen preparation. However, it became apparent that it was very difficult to prepare satisfactory specimens with granular materials containing large proportions of coarse particles. This has been suggested (61) as one of the possible sources of poor repeatability of the test. When the interim specification was published in 1977 for the heave test this problem was commented upon. However, there was insufficient data available on which to base major modifications in the procedure, but it was recommended that particles retained on the 37.5mm sieve should not be used in the preparation of frost heave specimens. It was considered that this would not result in the exclusion of more than 15 percent of the material as this represented the limit of the grading requirements (7) for granular materials. If this approach is extended to natural soils then the amount of the material excluded could rise to over 15 percent. This decision was based on experimental convenience since the role in frost action of these coarse particles had not been clearly established.

It has been suggested (87) that some of these difficulties could be overcome by using a mould of larger diameter. It was, therefore, considered essential to study the influence of specimen, or mould size on the measured frost heave.

5.4.2 Develop-ment of a larger specimen

In developing a larger specimen it was essential to ensure that it could be accommodated within the existing facilities without major modifications. In concrete technology the ratio between minimum and maximum particle size should be (87) 3:1 and preferably, 4:1 so that for materials containing 50mm particles, the minimum mould dimension should be approximately 150mm. In addition, the specimen should not be too large as it would become increasingly difficult to mould and handle. To minimise the modifications it was decided to maintain the specimen height at 152mm but the diameter was increased to 145mm.

The general details of the large mould were similar to those of the standard mould apart from the increased diameter. The central portion was tapered whilst the depth of end plugs was kept constant at 89mm. Long and short extruders were also produced for the larger specimen together with the appropriate sized copper specimen carriers, porous stones and Tufnol caps. Four of these specimens could be accommodated in the trolley and so an inner box was constructed to support these specimens in their carriers, etc. Specimen preparation followed the general procedure given in Section 5.2 with the weights being adjusted to produce the required levels of compaction. Initially, the specimens were surrounded with dry sand and the freezing procedure followed 5.2.3.

The initial results of tests with the 145mm specimens are summarised in Table 5.2 together with those from standard tests using the 102mm moulds.

102mm specimens			145mm specimens		
Number of specimens tested	mean heave (mm)	standard deviation (mm)	Number of specimens tested	mean heave (mm)	standard deviation (mm)
9	25.80	1.65	4	29.92	1.88
6	25.10	2.00	4	30.80	2.05

TABLE 5.2 Mean heave for sand/snowcal matrix of 102mm and 145mm specimens

A statistical analysis clearly demonstrated that the heave of the 145mm specimens was significantly different from that of the 102mm specimens. To investigate this behaviour, four 102mm specimens were tested in the box constructed for the 145m specimens. In this arrangement there was a 25mm gap between each specimen and its carrier and, in order to prevent the sand insulation coming into contact with the water, this gap was filled with creased polythene. The mean heave of these four specimens was 28.6mm with a standard deviation of 1.8mm. A comparison with the data in Table 5.2 indicates the heave of these specimens was significantly different from that of the 102mm specimens subjected to standard testing and, in addition, it was comparable with that of the 145mm specimens. It therefore appeared that the frost heave was being influenced by the location of the specimen in the trolley rather than solely by specimen size.

It was considered that information concerning the temperature gradients through the specimens could be useful in understanding this behaviour. The gradients in the 102mm could, initially, be obtained by incorporating the cement stabilised specimens to the test series. In addition, four 145mm specimens were produced using a cement stablised mixture. Thermocouples were incorporated in these specimens at similar locations to those in the 102mm specimens. It was also decided to measure the temperature distribution in the sand insulation between the specimens. This was achieved by forcing wooden dowels through the sand fill - each dowel carried three thermocouples fixed to the dowel at known locations with respect to the base of the inner box. The results of these observations are given in Figure 5.6.

Within each trolley, the depth of the frozen portion of each specimen and the temperature distributions both inside and between the specimens were in good agreement. However, as is shown in Figure 5.6, there were clear differences between these parameters for the two sizes of specimen. In particular, the penetration of the zero isotherm was greater in the 145mm specimens and so the depth of the frozen portion was larger in these specimens. In the particular tests arrangements the spacing between the 145mm specimens was 85mm whereas for the 102mm specimens it was only 35mm, and so this difference could be expected to influence the lateral heat losses. For instance, it is apparent from Figure 5.6 that the temperature in the sand fill, 25mm above the base of the specimen was 1.3^{o}C higher with the 102mm specimens.

The sand insulation was exposed directly to the air at -17^{o}C, unlike the specimens which were covered with Tufnol caps. Hence, the temperature at the top of the sand was much lower than that at the top of the specimen being approximately $-15^{o}C$ irrespective of the size of specimen. Thus, the temperature of the sand was lower than that of the specimen at the same elevation, and so there would be a lateral heat flow from the specimen to the sand insulation which effectively acted as a cold reservoir to which heat was transferred. The colder the sand isulation then the greater would be the heat flow. It is clear from Figure 5.6, that this reservoir was considerably broader with the 145mm specimens and so colder temperatures were produced within the sand. Thus, even though all the specimens had similar top temperatures, the additional cooling from the sides resulted in an increased frost penetration in the 145mm specimens, and this would account for the increased heave exhibited by these specimens. Such additional cooling would also have occured when 102mm specimens were tested in the inner box for the 145mm specimens and the increased heave of these specimens could also be attributed to this phenomenon.

It was, therefore, essential that this lateral cooling should be eliminated, or at least controlled, before a reliable assessment could be made of the influence of specimen size on frost heave. This lateral cooling has been commented (70) on in other investigations with the test, and it has been suggested (67) that the sand insulation should be replaced with vermiculite, or a similar insulator. However, in the test procedure, even following recent revision (8),(82), a coarse dry sand is the only permitted filling material. It was considered that, for an effective study of specimen size, the lateral heat flows should be controlled and so tests were run with granulated vermiculite in place of sand. Initially tests were performed on the cement stabilised specimens so that the temperature distributions could be obtained. This exercise was similar to that reported earlier in the section and the results are presented in Figure 5.7. These show that the temperature distributions through the vermiculite were similar for both systems with the temperature difference 25mm above the base of the specimen being reduced from 1.3°C to 0.4°C. In addition, the temperature gradients through the specimens were comparable with the depth of frost penetration being the same for both sizes of specimens. The detailed temperature gradients through the specimens are shown in Figure 5.8 and confirm this comparability. It was, therefore, decided to use vermiculite for this part of the investigation and the remaining results reported in this Chapter used vermiculite as insulation.

5.5 Discussion of the results

5.5.1 Preliminary tests with 102mm specimens

This preliminary study was performed on specimens of sand and snowcal (4:1) moulded to a dry density of 2.02Mg/m^3 at a moisture content of 9.5 percent. The cold room could accommodate two trolleys, located alongside each other in the room, and so it was decided to examine whether these locations (a and b) could influence the heave. Such data could also demonstrate whether the location of the specimen in an individual trolley could influence the heave. A total of 54 specimens was tested in three trials with nine specimens in each trolley. The location of the trolleys for each test run is shown in Figure 5.9 together with the layout of individual specimens in each trolley. The individual frost heave values are given in Table 5.3. These results were subjected to a two-way Analysis of Variance and the details are given in Appendix A with the ANOVA Table. The F-ratios clearly demonstrate that, at the 5 percent level of significance, both specimen location and trolley location did not influence the measured frost heave.

No of trial	No of trolley	1	2	3	4	5	6	7	8	9	MEAN
1	I a	28.13	23.45	23.61	24.39	21.46	24.80	25.73	28.66	25.32	25.06
1	II b	24.03	22.46	25.55	22.80	25.02	24.52	25.22	26.00	23.50	24.01
2	I b	23.29	27.10	30.54	22.58	20.26	22.62	26.84	25.13	21.20	24.39
2	II a	21.28	23.07	25.05	22.02	24.89	26.35	23.56	24.68	29.13	24.45
3	I a	22.36	21.19	25.12	21.25	28.50	25.59	22.96	23.78	23.80	23.84
3	II b	22.15	25.64	23.12	24.59	23.15	25.84	25.16	27.03	23.10	24.42

TABLE 5.3 Frost heave for individual specimens in different trials

No of trial	No of trolley	All	1,2,3	4,5,6	7,8,9	1,4,7	2,5,8	3,6,9
1	I	25.06	25.06	23.55	26.57	26.08	24.52	24.58
1	II	24.01	24.01	23.11	24.91	24.02	23.49	24.52
2	I	24.39	26.98	21.82	24.39	24.24	24.16	24.79
2	II	24.45	23.13	24.42	25.79	22.29	24.21	26.84
3	I	23.84	22.89	25.11	23.51	22.19	24.49	24.84
3	II	24.42	23.64	24.53	25.10	23.97	25.27	24.02
MEAN / STANDARD DEVIATION		24.36 / 0.42	24.28 / 1.52	23.75 / 1.19	25.04 / 1.07	23.80 / 1.44	24.36 / 0.58	24.93 / 0.98

TABLE 5.4 Analysis of the means and standard deviations of sub-groups of specimens

An inspection of the values in Table 5.3 indicates that, with the exception of trolley I - trial 3, the central specimen (5) exhibited lower heave than the other specimens. This lower heave is probably due to the specimen's relative location in the trolley where it is surrounded by eight other specimens rather than being adjacent to the insulated walls of the trolley. However, as materials are always tested in groups of at least three, the slightly lower heave of (5) may not significantly offset the average heave of the group. It was, therefore, considered essential to investigate whether the particular arrangement of sub-groups within the trolley would influence the mean heave of the sub-group. An indication of the overall range of values in a typical test run is illustrated in Figure 5.10. The analysis of sub-groups was similar to that reported (61) by others who have performed the test and consisted of comparing the means and standard deviations of the selected sub-groups of three with the appropriate values for the full runs of nine specimens. This analysis is given in Appendix A using the "Students t" test.

The means of each sub-group were in good agreement with the grand mean. It was decided to adopt the longitudinal groups (1-4-7, 2-5-8 and 3-6-9) for testing of materials in sets of three. This simple arrangement had the advantage that it would minimise the effects of any local temperature fluctuations caused by the opening of the door of the cold room. These longitudinal groups also tended to have lower standard deviations than the transverse groups.

5.5.2 Preliminary tests with 145mm specimens

This study was also performed on sand and snowcal (4:1) specimens produced to the same compaction state as the 102mm specimens. A total of 16 specimens was tested in 4 trials with 4 specimens in each trolley. In the first and third trials the trolley was positioned at the left-hand side of the cold room (a), and in the second and fourth trials at the right-hand side (b). The results are summarised in Table 5.5 and a typical plot of heave against time is shown in Figure 5.11.

No of trial	1	2	3	4	MEAN HEAVE (mm)	Standard Deviation (mm)
1	29.96	23.56	24.78	27.35	26.41	2.84
2	30.10	28.98	27.27	26.60	28.23	1.59
3	30.72	27.60	26.24	22.14	26.67	3.56
4	25.90	23.89	27.42	24.30	25.38	1.61
Grand mean (mm)					26.67	
Grand standard deviation (mm)					1.18	

TABLE 5.5 Frost heave for individual specimens in different trials

These results were also subjected to a two-way Analysis of Variance and the details are given in Appendix A with the ANOVA Table. The F-ratio clearly demonstrated that, at the 5 percent level of significance, both specimen location and trolley location did not influence the measured frost heave. In view of the range of individual heaves in single tests, it was considered inappropriate to divide specimens in sub-groups of less than three, so that for the 145mm specimens a test size of four was adopted. Thus, the full anaylsis undertaken with the 102mm specimens was not performed.

5.5.3 Effect of specimen size on frost heave

The results presented in sections 5.5.1 and 5.5.2 have been collected together in Table 5.6 to permit comparison. An initial inspection indicates that the 145mm specimens appear to produce higher heave than 102mm specimens. To extend this comparison, the results

No No	Size of of specimen	No of specimens	Mean heave (mm)	Standard deviation (mm)
1	102	9	25.06	2.27
2	102	9	24.01	1.42
3	102	9	24.39	3.29
4	102	9	24.45	2.36
5	102	9	23.84	2.32
6	102	9	24.42	1.62
7	145	4	26.41	2.84
8	145	4	28.23	1.59
9	145	4	26.67	3.56
10	145	4	25.38	1.61
Grand mean for 102mm		Grand Standard Deviation	24.42	2.17
Grand mean for 145mm		Grand Standard Deviation	26.68	2.42

TABLE 5.6 Mean heaves for 102mm and 145mm specimens

were subjected to statistical analysis, initially on the pooled results for the two sizes of specimen which are given at the foot of Table 5.6. Although these mean values appear to be close, within the expected (82) experimental error, the "Students-t" test given in Appendix A indicates that the two sets of data are significantly different. However, a detailed examination of the individual trials indicated that of the 24 possible combinations only 4 were significantly different. These four all involved trial 8 which was uniquely characterised by having the highest mean heave and the lowest standard deviation. In view of the relatively good agreement between the individual trials it was decided to use 145mm specimens for the subsequent testing of mixtures containing large particles of up to 40mm.

It would, however, appear that there are differences between the results of the two sizes of specimen which require further comment. It is suggested that in the larger specimen the effect of wall friction, between the specimen and the mould during compaction, would be less pronounced. Thus, although both specimens would have the same average dry density, there could be differences in the distribution of the local densities through the specimen. This hypothesis is supported by the hydraulic conductivity values determined with the two specimens. Tests with the 102mm specimen gave a value of 0.61 x 10^{-4}cm/sec whereas a higher value of 1.54 x 10^{-4}cm/sec was determined on the 145mm specimen. This suggests differences in the pore distribution in the two specimens which can be attributed to the relative influence of wall friction during compaction. In the larger specimens, wall friction would have less effect across the cross-section. This would produce a more homogeneous pore structure through the centre of the specimen resulting in an increase in permeability.

In the test each specimen is supported in a copper carrier and it has been demonstrated (70) that the thermal flow through the carrier, from the water bath, influences the result of the test. The 145mm specimens have a reduced ratio of surface area to volume, as compared with that for the 102mm specimens, and so the heat flow through the carrier was relatively reduced in 145mm specimens. This would, therefore, have marginally increased the penetration of the zero isotherm and so influence the heave of these specimens. This could account for the very slight differences in the location of the zero isotherm indicated in Figures 5.7 and 5.8.

As the specimens developed ice lenses the water surface at the base of the specimens would be lowered. Any differences in this lowering in tests with the two sizes of specimen could influence the results (as has been discussed elsewhere (61)). However, the ratio of total specimens cross-sectional area to water bath area is virtually the same for all tests, with either nine 102mm specimens or four 145mm specimens, so that the movements of the water surface would be similar and would not be expected to influence the heave. In view of the similarity of these two ratios the total heat flow, from water bath to the air above the specimens, would not differ significantly in the two test arrangements. These comments support the decision to use the larger specimen for testing mixtures containing coarse particles in the range 37.5 - 20mm.

Frost heave against time at different temperatures of water bath.

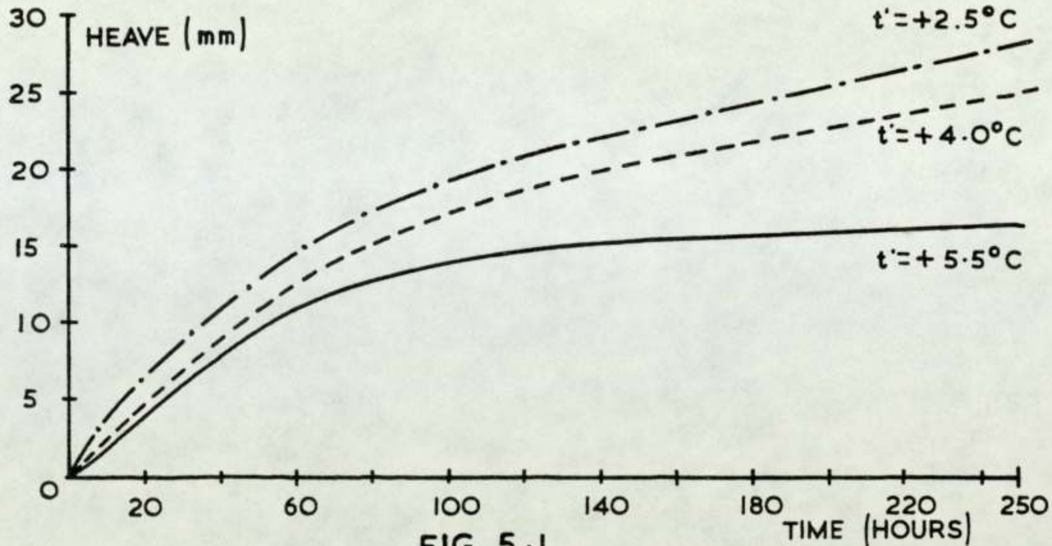


FIG. 5·1

Frost heave against time. Water bath temperature is altered during the test.

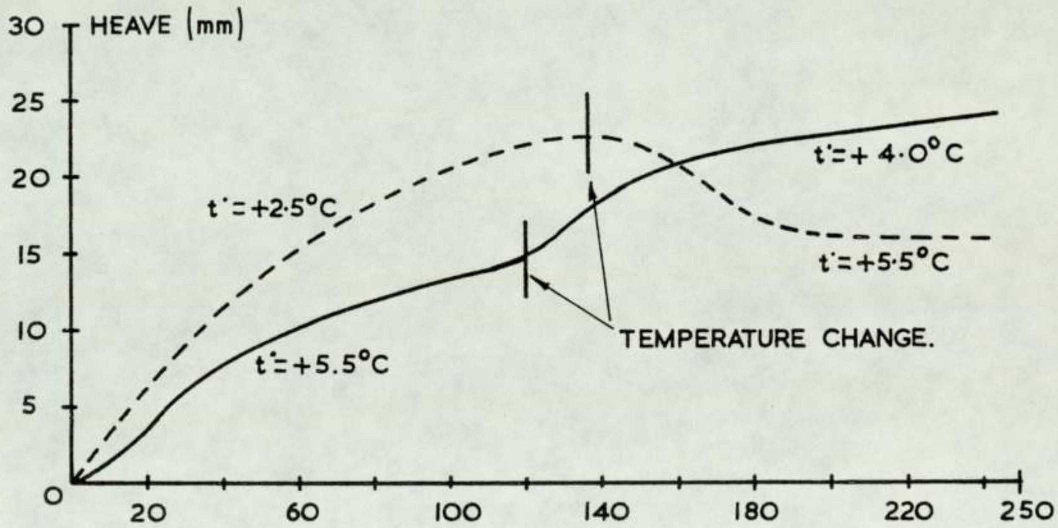


FIG. 5·2

Temperature gradient at different temperatures of water bath.

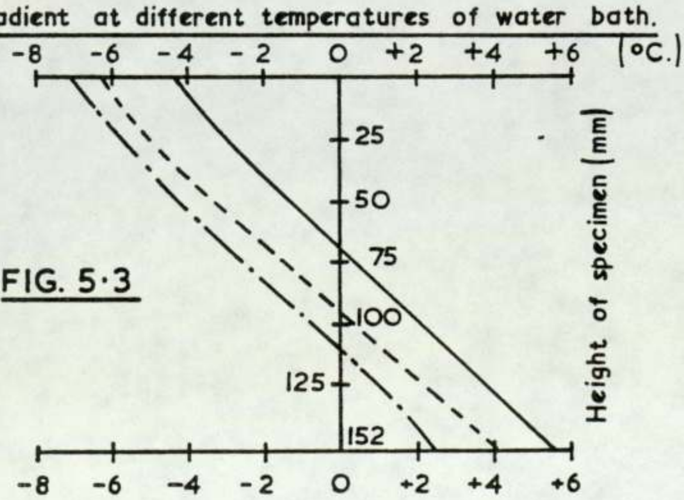


FIG. 5·3

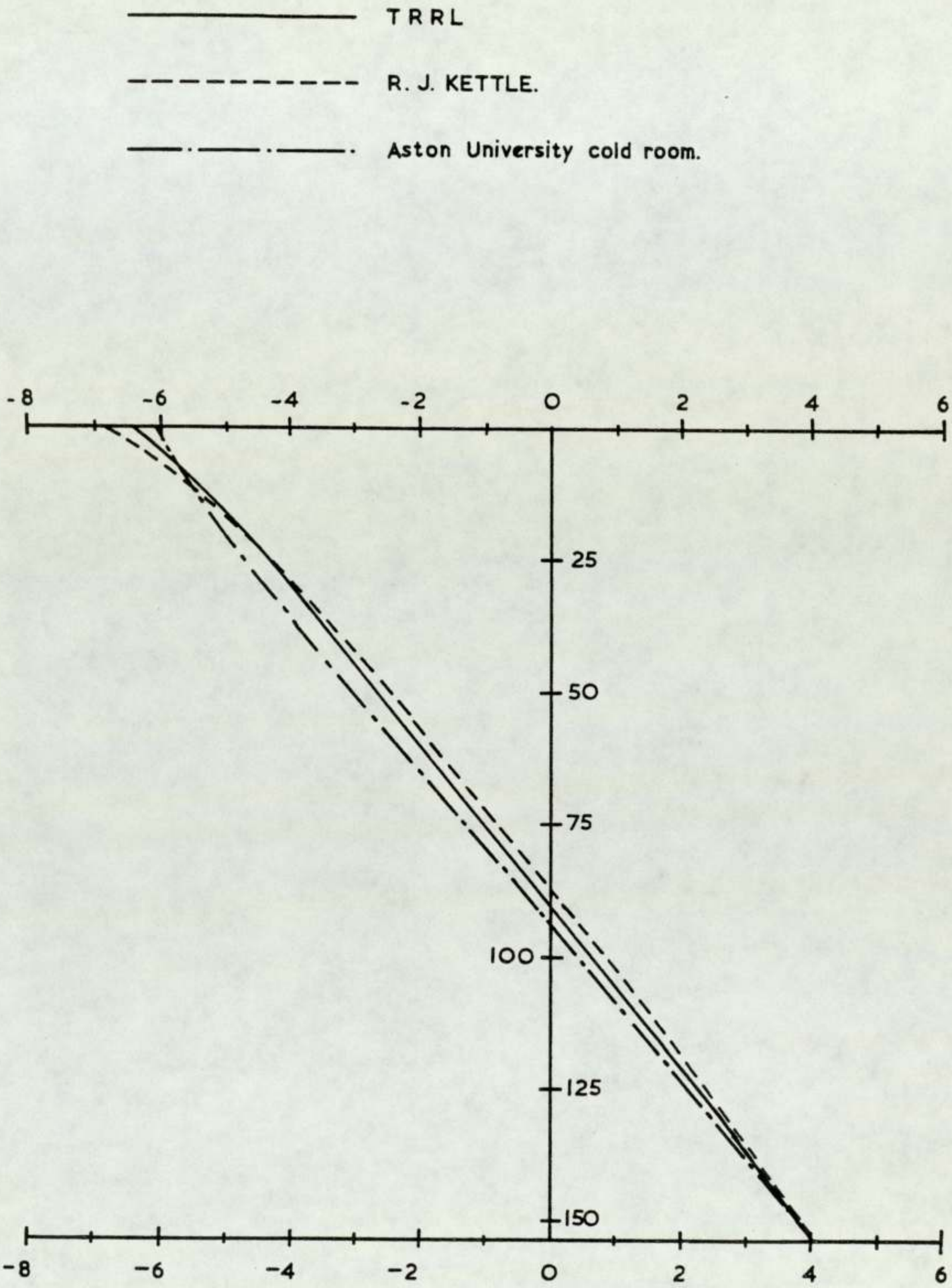


FIG. 5·4 Temperature gradient through cement stabilised specimen.

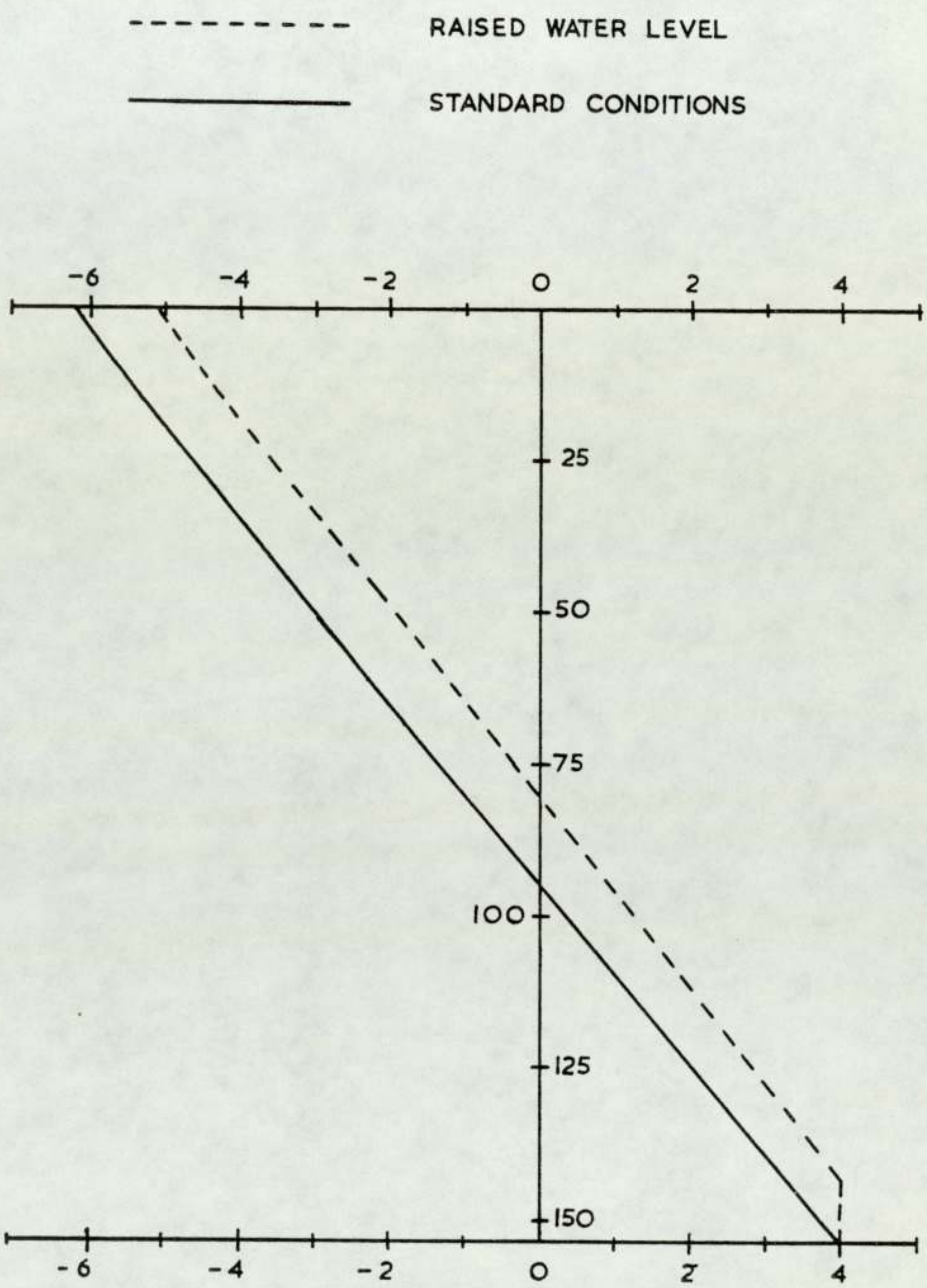
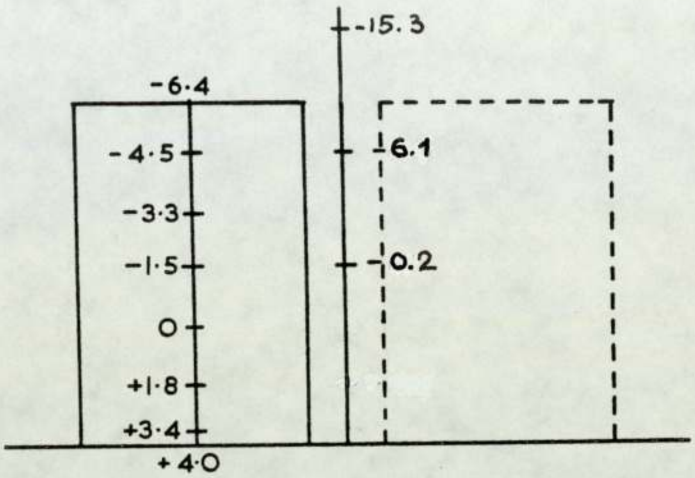
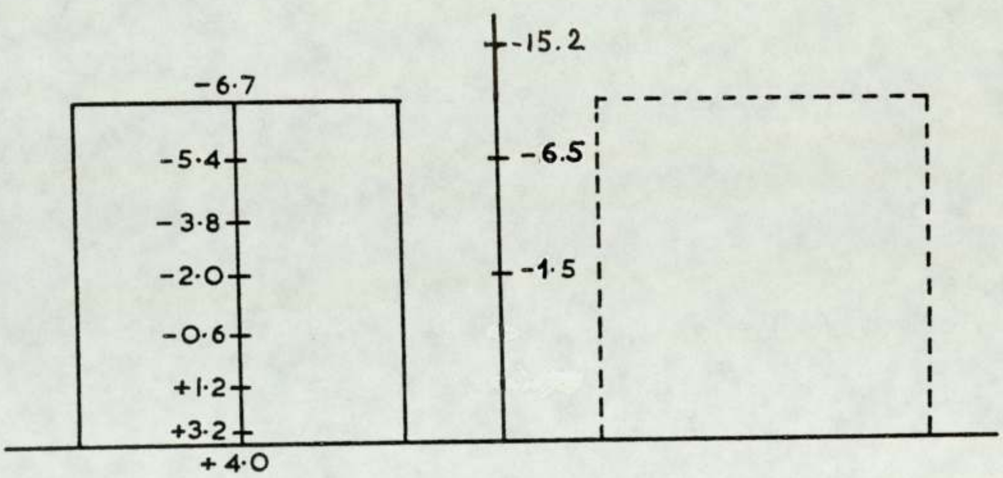


FIG. 5.5. TEMPERATURE GRADIENT THROUGH STABILISED SPECIMEN WITH RAISED WATER LEVEL.

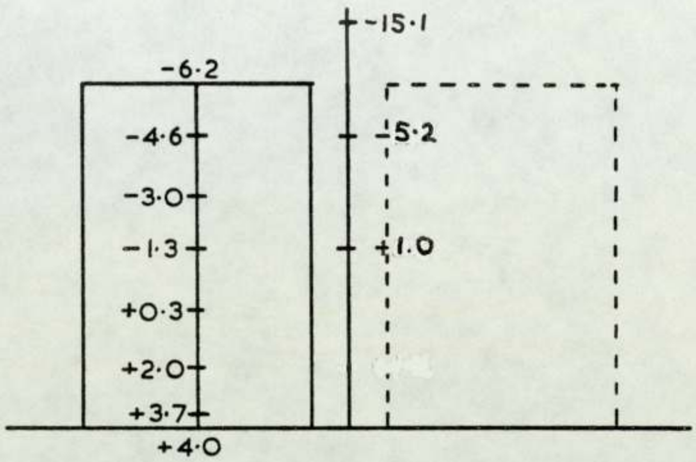


a) 102mm specimens.

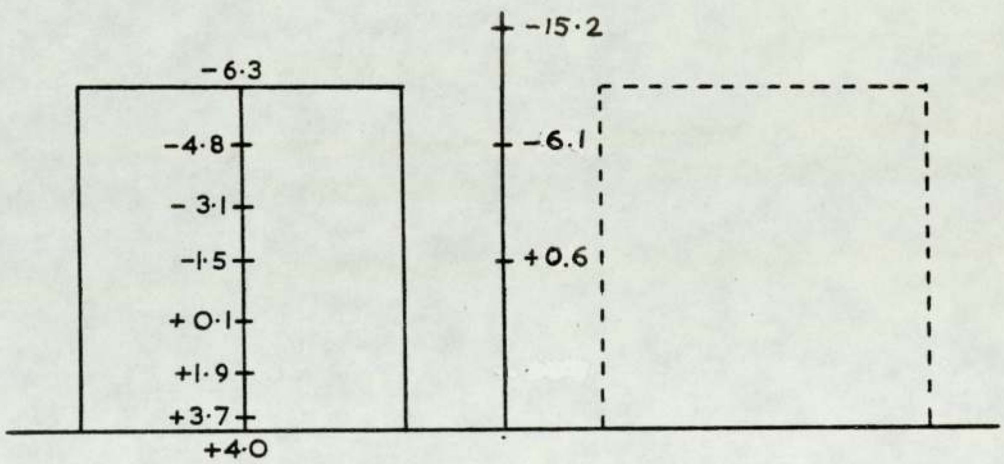


b) 145mm specimens.

FIG. 5·6. Temperature readings through specimens – Gravel insulation.



a) 102mm specimens.



b) 145mm specimens.

FIG. 5.7. Temperature readings through specimens - Vermiculite insulation.

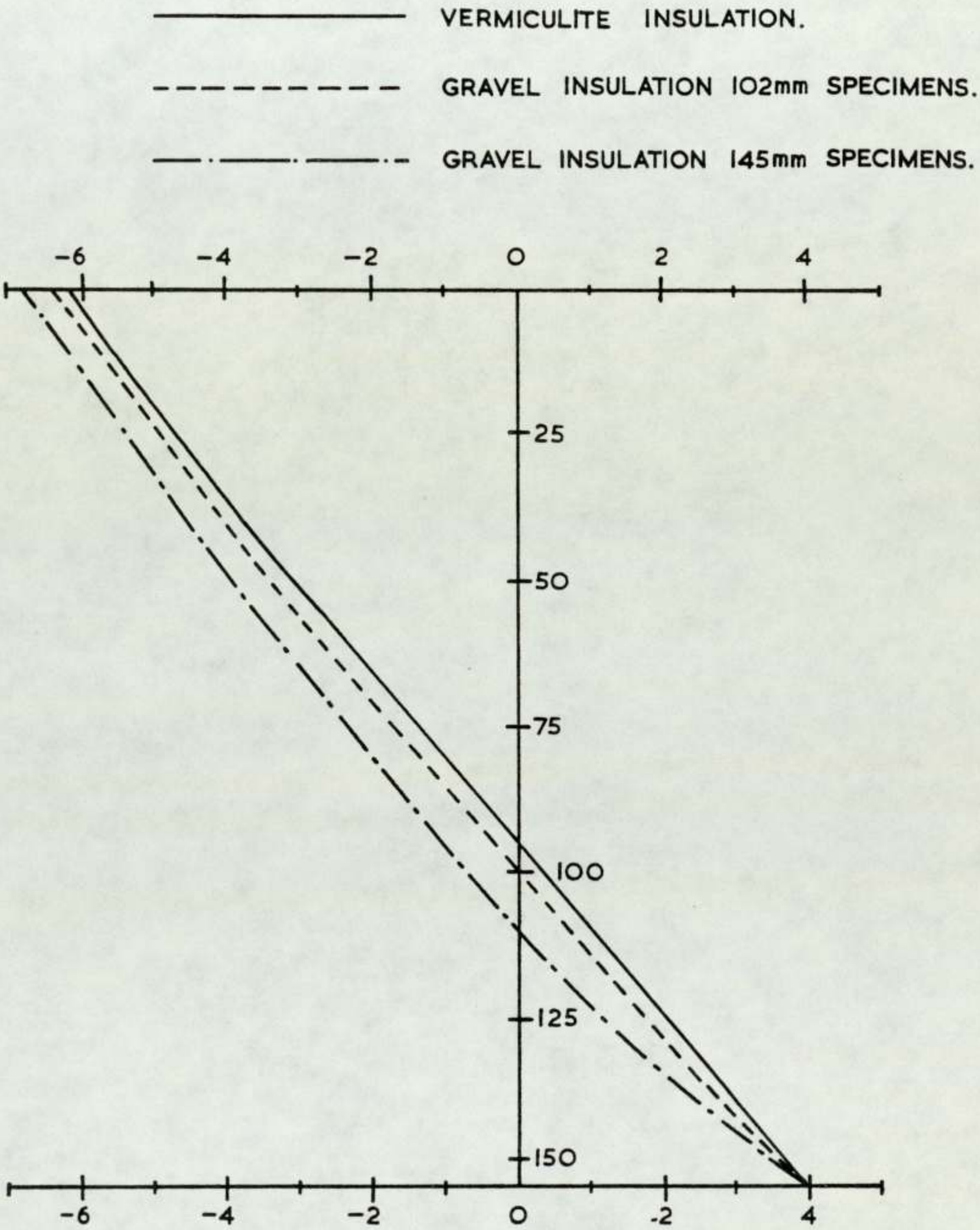
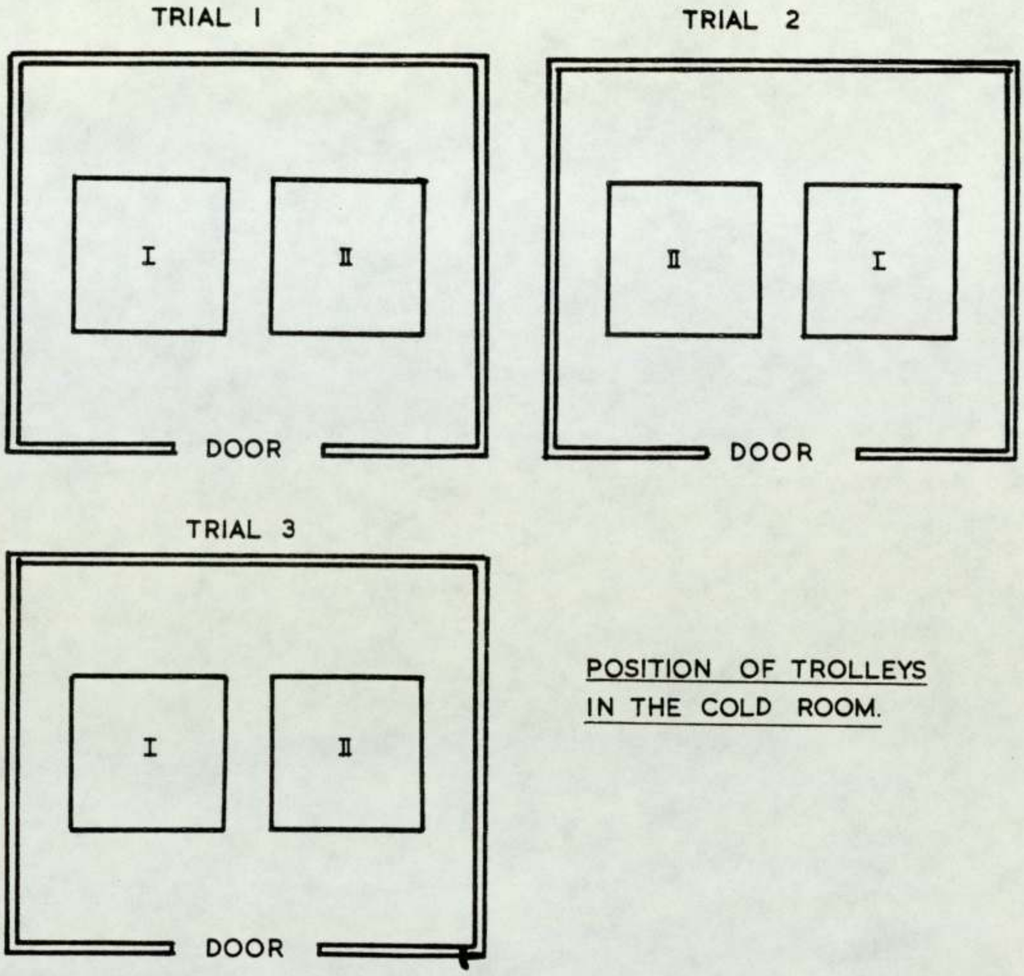


FIG. 5·8. Temperature gradient through stabilised specimen with different insulation.



POSITION OF TROLLEYS IN THE COLD ROOM.

POSITION OF SPECIMENS INSIDE TROLLEYS.

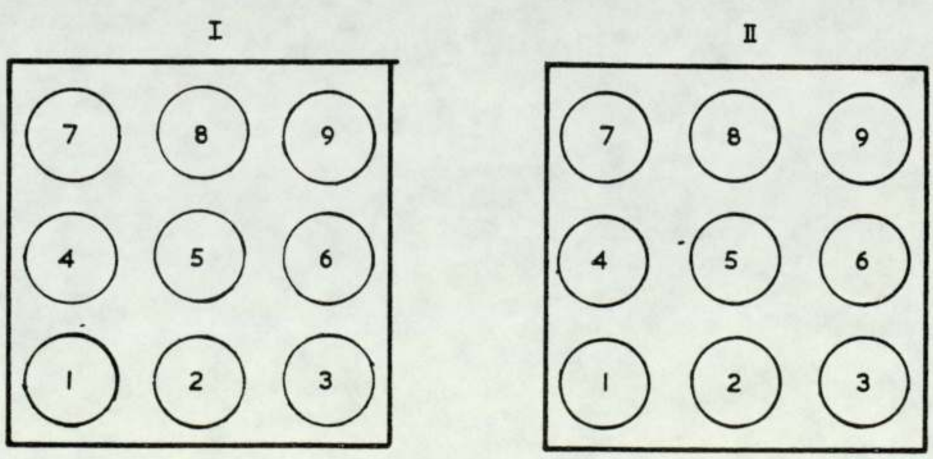


FIG. 5·9

Frost heave against time for sand/snowcal matrix 102 mm specimens.

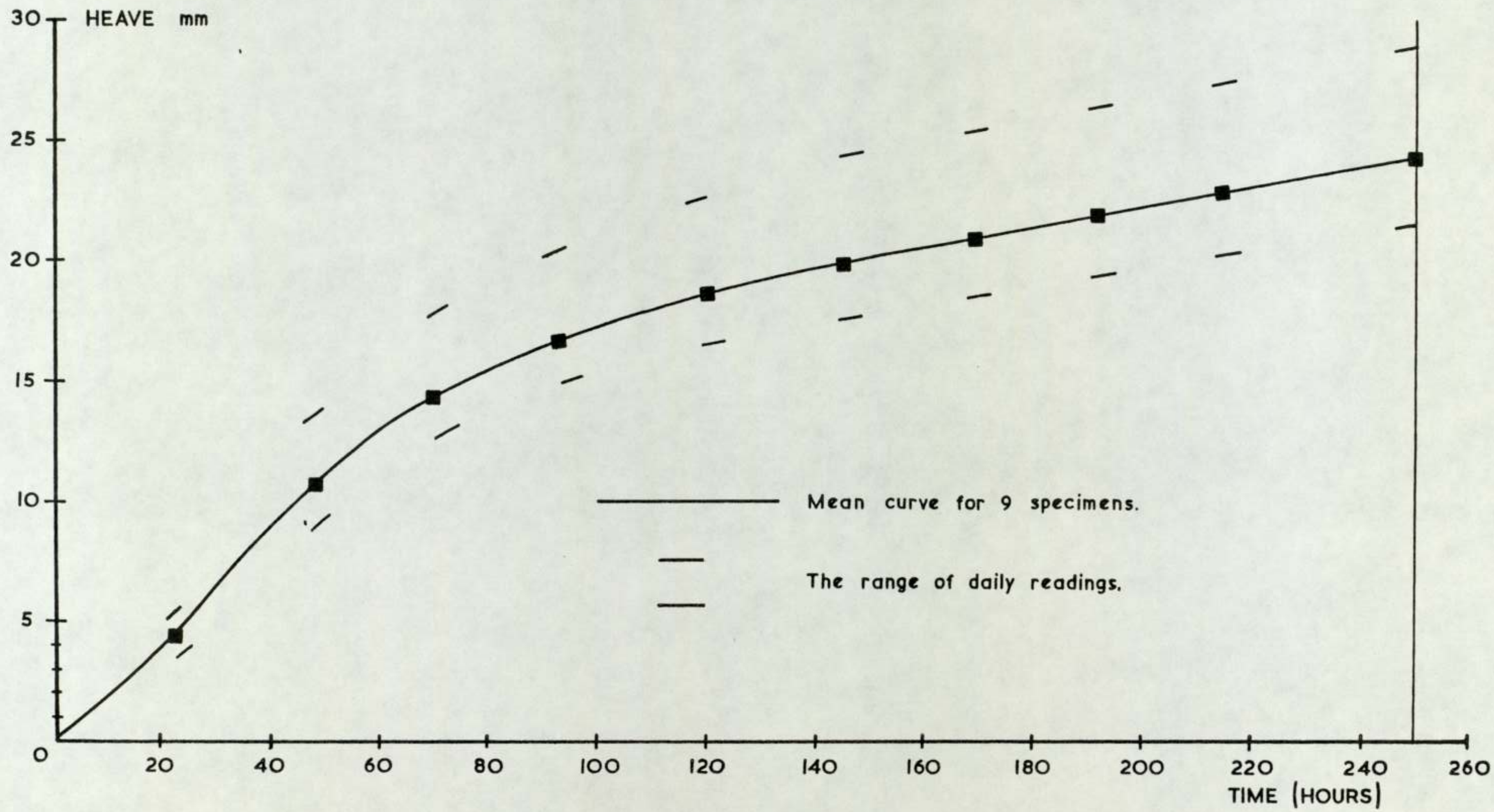


FIG. 5·10.

Frost heave against time for sand/snowcal matrix 145mm specimens.

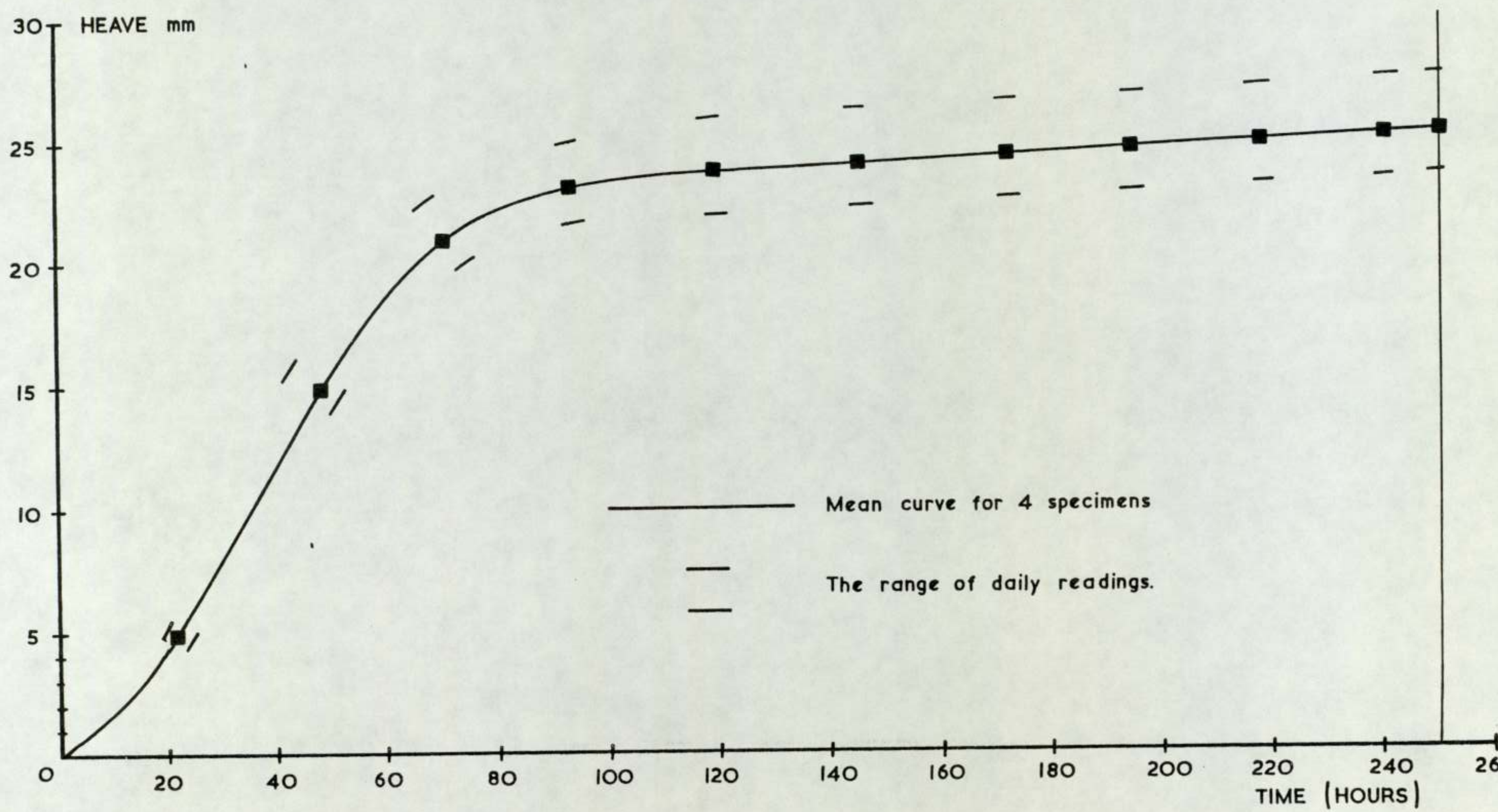


FIG. 5·11.

CHAPTER VI

FROST HEAVE.

INFLUENCE OF MATERIAL PROPERTIES

6.1 Introduction

Coarse-grained soils are widely used in highway construction. Indeed, such unbound granular materials have been used in pavement construction since the earliest of times. Granular materials have also been extensively used in hydraulic engineering. Whilst extensive study has been made of the properties of granular soils, it has been suggested (12) that detailed investigation should be undertaken to examine the role of the individual particles in coarse-grained soils.

Almost all the frost susceptibility criteria (13),(48),(49) that are based on grain size, are related to the percentage of fine particles present in the soil. The role of the coarse particles on the freezing behaviour has not been extensively studied although it has been shown (12) that an increase in the amount of large particles by 10 to 20 percent can significantly alter the properties of a soil. In order to accurately quantify the influence of these coarse particles on frost heave, a program of frost heave testing was undertaken. All the materials had a standard matrix of sand and ground chalk into which was added various proportions of selected coarse particles. The results were also related to the physical properties of the materials to assess the feasibility of using these properties to predict frost susceptibility. The measurement of these properties has been described in Chapter IV and the ones included in this study were:-

1) saturated hydraulic conductivity
2) nature of the aggregate
3) particle size
4) total porosity
5) porosity of the aggregate and the matrix.

6.2 Materials

A range of materials was produced by blending various proportions of selected coarse particles into the standard matrix used in the preliminary testing described in Chapter V. Three type of aggregate were investigated:-

1) Blastfurnace Slag
2) Rowley Basalt
3) Caldon Low Limestone.

These particles were supplied in sizes ranging from 40mm to 3mm and the properties are described in Chapter IV.

The particles were introduced to the matrix in increments of 10 percent and the individual contents ranged from 10 percent up to a maximum of 50 percent. It was found to be impractical to introduce more than 50 percent of coarse particles since the frost heave specimens became too fragile to handle. This was observed with all three aggregates and so 50 percent represented the upper bound for the test programme. In mixtures with less than 30-35 percent of coarse particles, the aggregate merely floats (89) in the matrix and there are no grain-to-grain contacts. The particles, providing they are uniformly distributed, will be totally surrounded by the matrix. As the content of coarse particles is increased, and approaches 50 percent, a stone skeleton is formed with the individual particles coming into contact with adjacent particles. In such mixtures the matrix acts as a filler between the individual grains.

The physical properties of these mixtures have been reported in Chapter IV and these data are referred to in the subsequent discussion of the frost heave behaviour.

6.3 Frost heave tests

6.3.1 Specimen preparation

Sufficient material for three samples was weighed out with the coarse aggregate and matrix being batched separately. The sand-snowcal matrix was initially dry mixed in the Hobart mixer to achieve even distribution of the fines in the sand. An amount of water, equivalent to the optimum moisture content of the total mixture, was added and mixing was continued for five minutes. Finally the desired amount of selected aggregate was added and the total mixture was gently mixed until it was judged to have a uniform appearance. The extent of this final mixing was minimised to limit any damage to the aggregate particles which would change the grading. The remaining stages in specimen preparation followed the procedure described in Chapter V.

6.3.2 Test procedure

The freezing procedure followed the standard method detailed in Chapter V with all the tests being performed in the cold room.

6.3.3 Specimen size

Specimens containing 3.35mm to 20mm particles were produced in the standard 102mm mould. However, with materials containing 20mm - 37.5mm particles, it became increasingly difficult to produce satisfactory 102mm specimens. This was particularly apparent when the amount of coarse particles exceeded 20 percent. Some zones in these specimens were clearly undercompacted, with the large gaps between particles being unfilled with matrix, whilst others appeared to be overcompacted, with some particles clearly being fractured. This variation in density can be attributed to boundary/wall effects, similar behaviour having been reported (88) in concrete test specimens.

It was, therefore, decided to prepare samples containing 20mm to 37.5mm particles in the 145mm mould.

It was shown in Chapter V that the frost heave values determined with 145mm specimens were slightly higher than those from the 102mm specimens. This was based on tests using the standard matrix and so, before commencing the main series of tests, it was decided to perform some further correlations using mixtures of the matrix and coarse particles. These tests were performed on mixtures containing 10 percent and 30 percent of Slag aggregate and 30 percent of Rowley Basalt. The 145mm specimens contained 37.5 - 20mm particles whilst the 102mm specimens contained similar 20 - 3.35mm particles. Parallel frost heave tests were undertaken and the results summarised in Table 6.1. These clearly show that heave values determined from the 102mm specimens are lower than those from the corresponding 145mm specimens.

Mixtures	Mean heave values (mm)				$\frac{102mm}{145mm}$
	102mm specimens		145mm specimens		
	37.5-20mm	20-3.35mm	37.5-20mm	20-3.35mm	20-3.35mm
sand/snowcal	-	24.36	-	26.67	0.91
10% slag	-	18.9	22.5	20.1	0.94
30% slag	-	16.0	18.1	17.6	0.91
30% Rowley Basalt	-	16.4	18.6	17.8	0.92
Mean ratio $\frac{102mm}{145mm}$					0.92

TABLE 6.1 Mean heave values for 102mm and 145mm specimens containing 37.5-20mm and 20-3.35mm particles

A statistical analysis of these results indicates that the results obtained with the two different specimens are significantly different for 20-3.35mm particles, but the results of a common specimen size - 145mm, were not significantly different for the two particle size groups.

A comparison of the mean heaves, using all the results in Table 6.1 indicates that ratio of the heaves is within the range 0.91 to 0.94 and give consistently good correlation between the two sizes of specimen. Based on these results, it was possible to derive a relationship between the mean heaves for the two sizes of specimens:-

$$(\text{Mean heave})_{102} = 0.92\ (\text{Mean heave})_{145}$$

This expression was used for the necessary conversions during the subsequent study, but it must be noted that it is only applicable to mean values and should not be applied to individual parameters.

6.4 Results of frost heave tests

The results are presented in Tables 6.2 and 6.3, with Table 6.2 containing those for the 102mm specimens and 6.3 containing those for the 145mm specimens. In Table 6.3 both the observed and the adjusted heave values are included. Plots of heave against time for all the materials are shown in Figures 6.1 to 6.6.

6.4.1 Size of the coarse particles

By comparing the results in Tables 6.2 and 6.3 it can be seen that, for incorporations of up to 30 percent of coarse particles, the frost heave shows a greater reduction with 3.35-20mm particles than with 20-37.5mm particles. For introduction of 30 to 50 percent the frost heave values are very similar for both particle sizes although, with the Caldon Low Limestone, the 3.35-20mm particles continue to show a greater reduction in heave than the 20-37.5mm particles.

For given freezing conditions, the extent of frost action in granular mixtures is largely dependent on pore size. This concept is

Type of aggregate	% of aggregate in matrix	Number of specimens tested	MEAN frost heave (mm)	Standard deviation (mm)
sand/snowcal matrix		54	24.36	2.22
Slag	10	9	18.9	0.90
	20	9	17.0	0.89
	30	9	16.0	0.73
	40	6	11.2	0.43
	50	3	9.0	0.51
Rowley Basalt	10	6	19.5	1.06
	20	3	17.3	0.53
	30	3	16.4	1.14
	40	6	14.4	0.36
	50	3	11.6	0.65
Caldon Low Limestone	10	9	18.4	1.29
	20	3	16.4	0.86
	30	3	15.2	0.50
	40	3	14.3	0.78
	50	6	13.6	1.04

TABLE 6.2 Frost heave values for 102mm specimens containing 20-3.35mm particles

Type of aggregate	% of aggregate in matrix	Number of specimens tested	MEAN frost heave (mm)	Standard deviation (mm)	Mean heave X 0.92
sand/snowcal matrix		16	26.67	2.51	24.5
Slag	10	4	22.5	2.00	20.7
	20	4	20.2	1.18	18.6
	30	4	18.1	1.36	16.6
	40	4	12.8	1.43	11.8
	50	4	10.7	0.82	9.8
Rowley Basalt	10	4	23.4	2.80	21.5
	20	4	20.7	3.00	19.0
	30	4	18.6	1.39	17.1
	40	4	15.5	0.83	14.3
	50	4	12.6	1.44	11.6
Caldon Low Limestone	10	4	23.2	2.9	21.3
	20	4	21.2	2.5	19.5
	30	4	19.8	1.23	18.2
	40	4	18.0	0.57	16.6
	50	4	15.8	2.09	14.5

TABLE 6.3 Frost heave values for 145mm specimens containing 37.5-20mm particles

common to all the explanations advanced for frost action, with the freezing forces being inversely proportional to pore size, providing that water is freely available at the freezing front. The pore structure is very dependent on grain size and, since coarser materials will contain considerably fewer fines per unit volume (also per unit cross-section in a given plane) of material, they will exhibit reduced heave characteristics.

With porous coarse materials, ice lensing could occur within the particles and this would contribute to frost action in such materials. The exact effect would depend on the relationship between the pore structure within the particle and that of the surrounding matrix. Such behaviour has been reported with porous limestones (62) and with colliery shales (61). The three aggregates used in this investigation had absorption values below 2 percent, and so ice lensing within the particles is unlikely to have been a significant feature in the tests. Large particles will also lie across the freezing plane with a portion of the particle above and a portion below and so will offer frictional and displacement resistance to the heave forces located in the plane of freezing (60).

With aggregate contents of less than 30 - 35 percent, the particles are evenly distributed as if floating or suspended in the matrix. Both groups will occupy the same volume in the specimen but the 3.35-20mm group will possess a larger particle surface area. Thus, compared with the 20-37.5mm particles, these particles would occupy a greater proportion of any freezing plane in the specimen and so would be expected to be more effective in reducing the amount of heave. At low concentrations the influence of the 20-37.5mm particles would also be more localised than that of the more numerous 3.35-20mm particles. In addition, the increased surface area of these particles would increase the frictional and displacement resistance to the heaving forces at the freezing front. Similar behaviour has been reported by Brandl (90) using large scale freezing tests on gravel mixtures. He noted that the frost susceptibility of such soils could be reduced by the addition of a graded mixture, rather than through the addition of individual large stones.

As the aggregate content increases to 40 percent and more, the relative influence of the 20-37.5mm particles will also increase since they are not localised but, as with the 3.35-20mm particles, they start to form a skeleton type structure with the matrix filling the spaces between the large particles. Thus the two groups of particles have similar effects in reducing the heave and frost susceptibility of the soil as the amount of coarse particles is increased above 30-35 percent.

6.4.2 Content of coarse particles

As has been explained in the preceding section, the frost susceptibility of the matrix was reduced by the inclusion of coarse particles. Whilst the major effect has been attributed to changes in pore structure and to the generation of internal restraints, other factors such as changes in the thermal properties and hydraulic conductivity should also be considered. The data in Tables 6.2 and 6.3 show that the effect of the coarse particles is dependent on both the type of particle and the amount of coarse particles added to the matrix. Tsytowich, in his studies with mixed soils also reported (12) that the major properties were dependent on the content of coarse particles.

To establish the effect of particle content, the results in Tables 6.2 and 6.3 have been analysed to relate the change in heave and the particle content. This information is given in Tables 6.4 and 6.5 and the individual relationships are plotted in Figures 6.7 and 6.8. From Figure 6.7 it is apparent that the introduction of only 10 percent of 3.35-20mm particles produces a sharp reduction in heave. For subsequent increases, there is a linear relationship between coarse particle content and frost heave although the rate of reduction in heave is less marked than that recorded for the 10 percent inclusion. All three aggregates exhibit similar behaviour as shown by the individual relationships in Figure 6.7. For the 20-37.5mm particles, heave and particle content were linearly related throughout the range (0 - 50 percent) of particle contents and the individual relationships are given in Figure 6.8.

The main difference between the effects of the two particle groupings is apparent for particle contents of 10 to 30 percent. This is clear from a comparison of the average values given in Tables 6.4 and 6.5. It is again suggested that this is due to the higher surface area of the 3.35-20mm particles as compared with that of the 20-37.5mm particles. At the lower contents, these smaller particles would occupy comparatively more of any freezing plane, thereby reducing the magnitude of the heaving forces and, additionally, producing more internal resistance due to surface friction. At the higher particle contents, the extent of the reduction in activity at the freezing front is similar with both grouping since the coarse particles begin to form a continuous skeleton.

As a further check on this behaviour, the results of the tests performed on 3.35-20mm Slag and Rowley Basalt mixtures in the 145mm specimens are added to Table 6.5. These clearly show that the reductions in heave are similar to the appropriate values in Table 6.4 rather than those in Table 6.5 and so, further demonstrate the influence of the size of coarse particles in the heaving process.

Specimen size	Type of aggregate	Reduction of heave (%) % of aggregate in matrix				
		10%	20%	30%	40%	50%
(3.35-20mm group)	Slag	22	30	34	54	63
102mm	Rowley Basalt	20	29	33	41	52
	Caldon Low Limestone	24	33	38	41	44
	Average	22	31	35	45	53

TABLE 6.4 Reduction of heave with introduction of 3.35-20mm particles

Foot Note: The data in Table 6.4 is relevant to the mean heave of sand/ snowcal matrix of 102mm specimens

Specimen size	Type of aggregate	Reduction of heave (%) % of aggregate in matrix				
		10%	20%	30%	40%	50%
(20-37.5mm group)	Slag	16	24	32	52	60
145mm	Rowley Basalt	12	22	30	41	53
	Caldon Low Limestone	13	20	26	32	41
	Average	14	22	29	42	51
(3.35-20mm group)	Slag	25	-	34	-	-
	Rowley Basalt	-	-	33	-	-

TABLE 6.5 Reduction of heave with introduction of 20-37.5mm particles

Foot Note: The data in Table 6.5 is relevant to the mean have of sand/snowcal matrix of 145mm specimens.

6.4.3 Type of coarse particle

All three types of coarse aggregate reduced frost heave, but a close inspection of the results in Tables 6.4 and 6.5 indicates that these reductions were most marked with the Slag aggregate. This effect is most pronounced at the higher aggregate contents of 40 to 50 percent. Similar difference have been reported (91),(92) elsewhere, and Kalcheff and Nichols (91) have noted that materials from different sources, but with identical grading, did not produce identical rates of heave when subjected to a standard freezing procedure. Aguirre-Puente (93) has stated that "the occurence of interface phenomena in frost susceptible soils leads to differences in behaviour that depends greatly on the nature of the particles" and this is supported by experimental data.

At low particle contents, the characteristics of the individual particles are unlikely to have a major effect as they are present in low concentrations. At such levels the freezing behaviour is modified by the presence of, effectively, inert particles. However, at higher concentrations differences in behaviour are detected that can also be attributed to the characteristics of the individual particles. This is particularly apparent from the data in Tables 6.4 and 6.5 for particle contents greater than 30 percent, where the Slag particles are more effective in reducing heave than the other two types of particle.

The rate of growth of an ice lens depends, particularly, on the rate of heat extraction and the rate of water flow towards the growing lens (93). For given boundary conditions, the heat transfer is a function of the thermal properties of the material such as thermal conductivity, specific heat, volumetric heat capacity and diffusivity (63). The composite mixtures can be considered as two-phase materials so that the thermal properties will depend on the characteristics of the two phases, matrix and coarse particles, and their relative proportions in any given mixture.

The three types of coarse particle will have different thermal characteristics and, although these were not measured, an indication of the range of values can be obtained from published data (94). At the higher concentrations these parameters would produce differences in the characteristics of the composite materials . It is suggested that such differences will account, at least partially, for the differences in heave reported at the 50 percent concentrations. Additionally, differences in particle shape and texture could influence the mechanism of the internal restraint, whilst particle porosity will influence the rate of water transport through the unfrozen material to the frozen front. The mineral composition of the fine grains in a material have clearly been shown (95) to influence freezing behaviour, and it is also suggested (92) that the mineral composition of the coarse particles could influence the behaviour.

It is clear from the results in Tables 6.2 and 6.3 that the addition of 40 percent of Slag aggregate, to the matrix, is sufficient to transform it from being highly frost susceptible material to being non-frost susceptible. However, even with the addition of 50 percent of Caldon Low Limestone, the material was still marginally frost susceptible. It is, therefore, apparent that the evaluation of frost susceptibility cannot be solely based on particle size considerations. The type of coarse aggregate must also be involved in such considerations.

6.5 Frost susceptibility and material properties

6.5.1 Fine fraction in the material

Most frost susceptibility criteria are based on particle size distribution and such criteria are still widely used in Europe and North America (13). Limitations on the percentage of fine material form the basis for most of these criteria (47),(48),(49). This is most clearly exemplified by the Casagrande criteria (47):-

> ".... one should expect considerable ice segregation in non-uniform soil containing more than 3 percent of grains smaller than 0.02mm, and in very uniform soils containing more than 10 percent smaller than 0.02mm. No ice segregation was observed in soils containing less than 1 percent smaller than 0.02mm ..."

Whilst the Casagrande criteria were advanced for particular climatic conditions, they have been widely adopted. Indeed, there has been little success in developing comprehensive criteria that more successfully predict the frost susceptibility of soils. It was, therefore, considered useful to examine their relationship with the experimental behaviour.

All the soils in the present investigation are non-uniform, and so mixtures with more than 3 percent of particles finer than 0.02mm would be regarded as frost susceptible. The Casagrande ratings are compared with the experimental classifications in Tables 6.6 and 6.7. The fine material is derived from the sand/snowcal matrix and so, for all the aggregate-matrix mixtures, the amount of material finer than 0.02mm depends only on the coarse particle content.

According to the Casagrande criteria all the materials in the present study should be classified as frost susceptible. However, the frost susceptibility of these materials, based on direct freezing (5), covers a range of classifications and the individual decisions appear to be influenced by both the percentage of fines and the type of coarse aggregate. If the percentage of fine grains was the only major factor involved in soil freezing, all mixtures with the same fines content should have the same classification. An inspection of experimental behaviour of the 40 percent mixtures, in both Tables 6.7

% of aggregate	% of particles smaller than 0.02mm	Type of aggregate			Casagrande criteria
		Slag	Basalt	Limestone	
0%	56	FS	FS	FS	FS
10%	10.1	FS	FS	FS	FS
20%	8.9	MFS	MFS	MFS	FS
30%	7.8	MFS	MFS	MFS	FS
40%	6.7	NFS	MFS	MFS	FS
50%	5.6	NFS	NFS	MFS	FS

TABLE 6.6 Frost susceptibility classification for 3.35-20mm particles

% of aggregate	% of particles smaller than 0.02mm	Type of aggregate			Casagrande criteria
		Slag	Basalt	Limestone	
10%	10.1	FS	FS	FS	FS
20%	8.9	FS	FS	FS	FS
30%	7.8	FS	FS	FS	FS
40%	6.7	NFS	MFS	MFS	FS
50%	5.6	NFS	NFS	MFS	FS

TABLE 6.7 Frost susceptibility classification for 20-37.5mm particles

Note: FS - frost susceptible

MFS - marginally frost susceptible

NFS - non frost susceptible

and 6.8, demonstrates this feature with the Slag being more effective at reducing heave than the other two aggregates. Kalcheff and Nicholls (91) have also criticised such grain size criteria when applied to granular soils. It would appear that such borderline materials should have their frost susceptibility assessed by direct freezing (14). This may be due to the observation (96) that such grain size criteria do not take into account such factors as permeability and mineralogical nature that influence the behaviour of freezing soils.

6.5.2 Permeability

The freezing behaviour of a soil is not directly related to its saturated permeability, since the upward flow is induced by a suction gradient where the unsaturated permeability would be more appropriate (63). However, the saturated permeability does reflect the resistance of the soil to the passage of moisture and so the transport of water to the freezing front would be influenced by the degree of resistance to moisture transfer.

Research by Önalp (97) suggested that the saturated permeability alone was not sufficient for an assessment of frost susceptibility of soil. He implied that, whilst it strongly effects the rate of heave, it does not ideally reflect the freezing behaviour of soils. He did suggest that soils should be regarded as non-frost susceptible when the permeability was beyond the limits 1×10^{-7} cm/sec and 1×10^{-3} cm/sec. He also suggested that soils with a coefficient of permeability within the range 1.7×10^{-4} to 1.3×10^{-7} cm/sec can be frost susceptible and those beyond non-frost susceptible. A comparison between the permeability values and the experimental frost susceptibility is given in Table 6.8, whilst typical relationships between frost heave and permeability are shown in Figure 6.9.

Based on Önalp's guidelines, all the mixtures have permeability in the critical range, 1.7×10^{-4} to 1.3×10^{-7} cm/sec. The frost classification, based on the frost heave values, clearly show that this range only provides very approximate guides and demonstrates the need to test such materials to establish their frost susceptibility. Indeed, for the granular materials tested, the permeability values are quite similar, in spite of the different frost susceptibilities and no correlation was established between permeability and frost susceptibility.

Material tested		Permeability (cm/sec)	Experimental work
sand/snowcal		6.1×10^{-5}	FS
Slag	10%	1.32×10^{-4}	FS
	20%	1.60×10^{-4}	MFS
	30%	1.96×10^{-4}	MFS
	40%	2.20×10^{-4}	NFS
	50%	2.59×10^{-4}	NFS
R. Basalt	10%	1.96×10^{-4}	FS
	20%	1.64×10^{-4}	MFS
	30%	1.51×10^{-4}	MFS
	40%	7.10×10^{-5}	MFS
	50%	6.50×10^{-5}	NFS
Caldon Low	10%	2.18×10^{-4}	FS
	20%	1.60×10^{-4}	MFS
	30%	1.46×10^{-4}	MFS
	40%	1.30×10^{-4}	MFS
	50%	1.10×10^{-4}	MFS

TABLE 6.8 Permeability and frost susceptibility

From Figure 6.9 it can be seen that when 10 percent of coarse particles are introduced into the matrix, the permeability increases. This could be a result of the formation of large pores at the interface between the coarse aggregate and the matrix, and is also reflected in the compacted density. With further additions of coarse aggregate to the non-uniformly graded mixture, the smaller particles will fill the pore space between large particles. The large particles such as Rowley Basalt and Caldon Low Limestone being almost impermeable, will form an obstruction to the flow of water, and so make the configuration of the flow path more tortuous. Therefore, the permeability will tend to decrease with further introduction of these particles. The reduction in permeability could also be attributed to the migration of fine particles that was discussed in some detail in Chapter IV. On the contrary, the Slag aggregate has a higher porosity and lower compacted density and so permitting water to pass more freely, therefore with further increases in the percentage of Slag aggregate the permeability increased.

The results in Figure 6.9 clearly show that frost heave and, hence, frost susceptibility is not uniquely related to permeability. Reductions in frost heave are apparent for both increases and decreases in permeability. Indeed, the heave depends on the mass flow of water to the freezing front and as Zoller (14) has indicated, this movement involves permeability, capillarity and induced suction so that any single factor is unlikely to provide unique criteria for heave prediction. Frost susceptibility criteria related to moisture movement would have to involve all the appropriate factors and in this limited study such a comprehensive investigation was not undertaken. However, the study of saturated permeability provides some evidence of the structure of the soil and may, therefore, be useful in the selection of suitable aggregates for the mechanical stabilisation of frost susceptible soils.

6.5.3 Total porosity

The dry density of the soil can have significant effects (61),(49) on frost heave, and frost susceptibility. An increase in density will reduce the sizes of individual pores and this will increase the capillarity, and reduce the permeability. An increase in capillarity leads to an increase in heave (14) whilst the reduction in permeability would reduce heave. These two conflicting processes can lead to a critical density, for a particular soil, at which frost heaving is maximised.

The dry density of the soil depends on the size, shape and specific gravity of the particles as well as its moisture content. However, the total porosity, which is effectively the ratio of the volume of the pores to the total volume of the soil, reflects the dry density and makes for easier comparisons between soils with different mineralogies and moisture contents. In Figure 6.10, frost heave is plotted against total porosity for mixtures containing up to 50 percent of 3.35-20mm particles. The detailed results are given in Table 6.9.

The introduction of 10 percent of coarse aggregate increases the porosity of the material and this increase may well reflect a new soil structure with comparatively large pores being formed between the coarse particles and the matrix. This accompanying change in pore structure may well account for the reduced heave values apparent with these mixtures.

Aggregate		Porosity	Heave (mm)	
Type	Content		3.35-20mm particles	20-40mm particles
Matrix	0	0.25	24.36	26.67
Slag	10%	0.27	18.9	22.5
	20%	0.24	17.0	20.2
	30%	0.23	16.0	18.1
	40%	0.22	11.2	12.8
	50%	0.23	9.0	10.7
Rowley Basalt	10%	0.27	19.5	23.4
	20%	0.25	17.3	20.7
	30%	0.23	16.4	18.6
	40%	0.21	14.4	15.5
	50%	0.20	11.6	12.6
Caldon Low Limestone	10%	0.26	18.4	23.2
	20%	0.23	16.4	21.2
	30%	0.22	15.2	19.8
	40%	0.19	14.3	18.0
	50%	0.17	13.6	15.8

TABLE 6.9. Frost heave and total porosity

Further additions of coarse aggregate leads to a subsequent decrease in total porosity, since in such non-uniform soils, the fine particles will fill the space between aggregate. In such mixed materials, the total porosity will depend on the ability of the fine matrix to fill the large voids between the individual aggregrate particles. In addition, the porosity of the coarse particles will have to be considered since as the content of such particles is increased, the porous matrix is being replaced by a single lump of low porosity. Thus, the frost heave decreases as the porosity of the mixed material is reduced although the change in porosity is only one of many related facts that should be considered.

As the aggregate content approaches 50 percent, large pores will be created as the coarse particles interact with each other and so it may not be possible for fines to enter such pores during the compaction process. This could produce an increase in porosity. Such incompletely filled pores could be seen in some specimens and the accompanying increase in porosity can be seen in the results for the Slag and Rowley Basalt mixtures. At these large aggregate contents the porosity of individual particles will be reflected in total porosity. Therefore, the correlations between heave and total porosity are quite complex.

From the experimental results for the particular soils, the frost heave is related to the total porosity. For all frost susceptible mixtures their frost heave was reduced with a decrease in total porosity. Indeed, for low aggregate contents up to 30 percent, the frost heave is directly connected to the total porosity. For different aggregate contents the frost heave is similar for mixtures with the same porosity and this is illustrated by the data in Table 6.10. At low particle contents, the individual particles are distributed in the matrix, and so the pore distribution within the matrix and the configuration of pores between the particles and the matrix have a controlling effect. When the percentage of coarse aggregate increases the soil transforms from a non-skeleton type to a skeleton type and the coarse particles will have a more significant effect with shape, texture, etc. becoming important.

Porosity	Heave (mm)	Material
0.27 - 0.26	18.9 19.5 18.4	10% Slag 10% Basalt 10% Limestone
0.25 - 0.24	17.0 17.3	20% Slag 20% Basalt
0.23	16.0 16.4 16.4	30% Slag 30% Basalt 20% Limestone

TABLE 6.10 Frost heave and total porosity

However, for heave values below 13mm (i.e. frost susceptibility criterion) the previous relationship between heave and porosity was not apparent. The limited data indicates that the heave decreases with increase in total porosity. These values relate to the high aggregate content mixtures where particle interactions could create isolated large pores. This would interfere with the moisture movement and so limit the extent of heaving. In order to produce a criterion based on total porosity a more thorough investigation would be essential. It is, tentatively, suggested that granular soils, with a coarse particle content greater than 40 percent and a total porosity in excess of 0.18, could be expected to be non-frost susceptible. Thus total porosity, together with the composition of soil, could be considered for the future prediction of frost susceptibility.

Frost heave against time for Slag Aggregate. (3·35 – 20mm.)

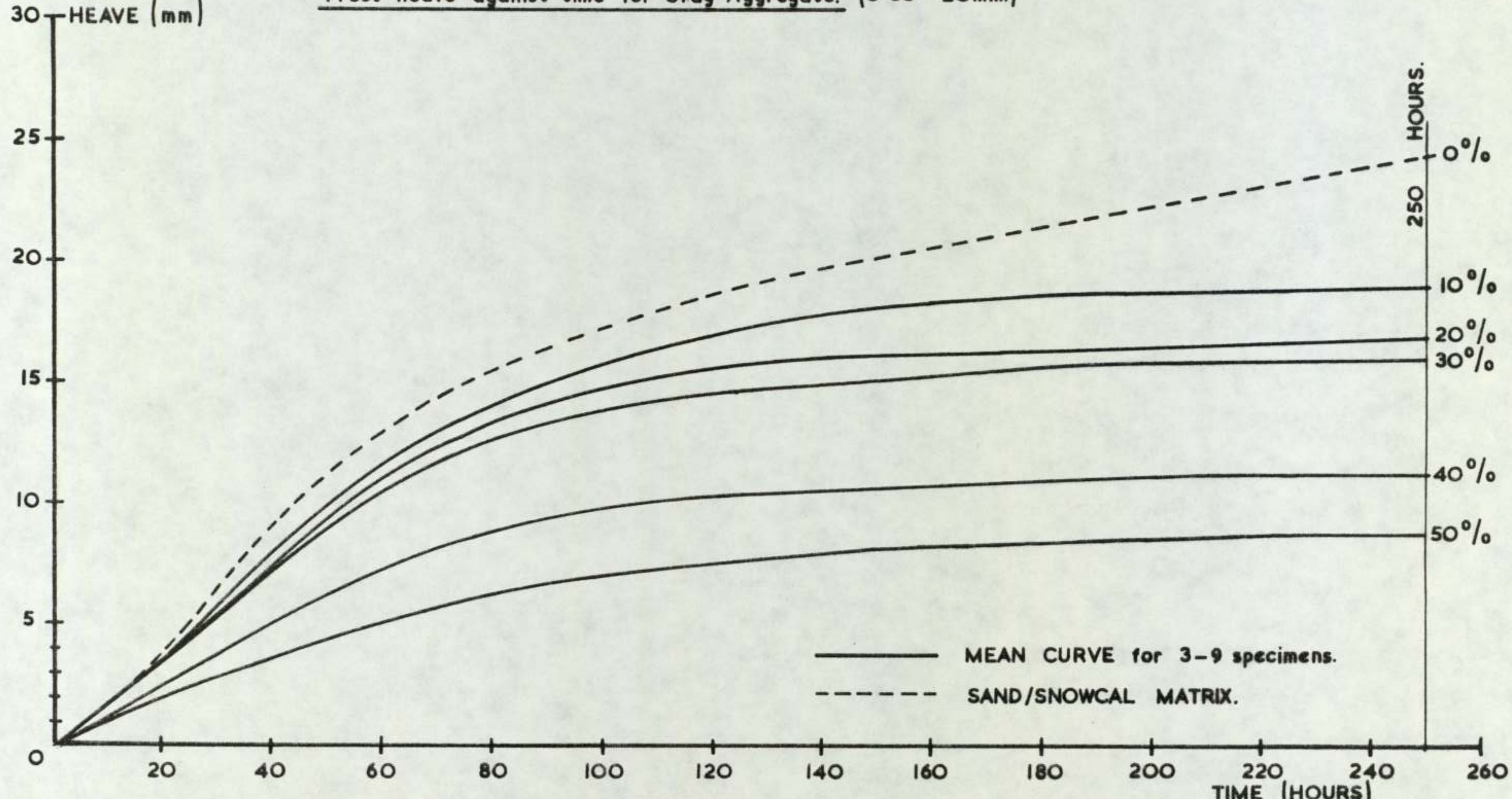


FIG. 6·1.

Frost heave against time for Rowley Basalt. (3·35 – 20mm.)

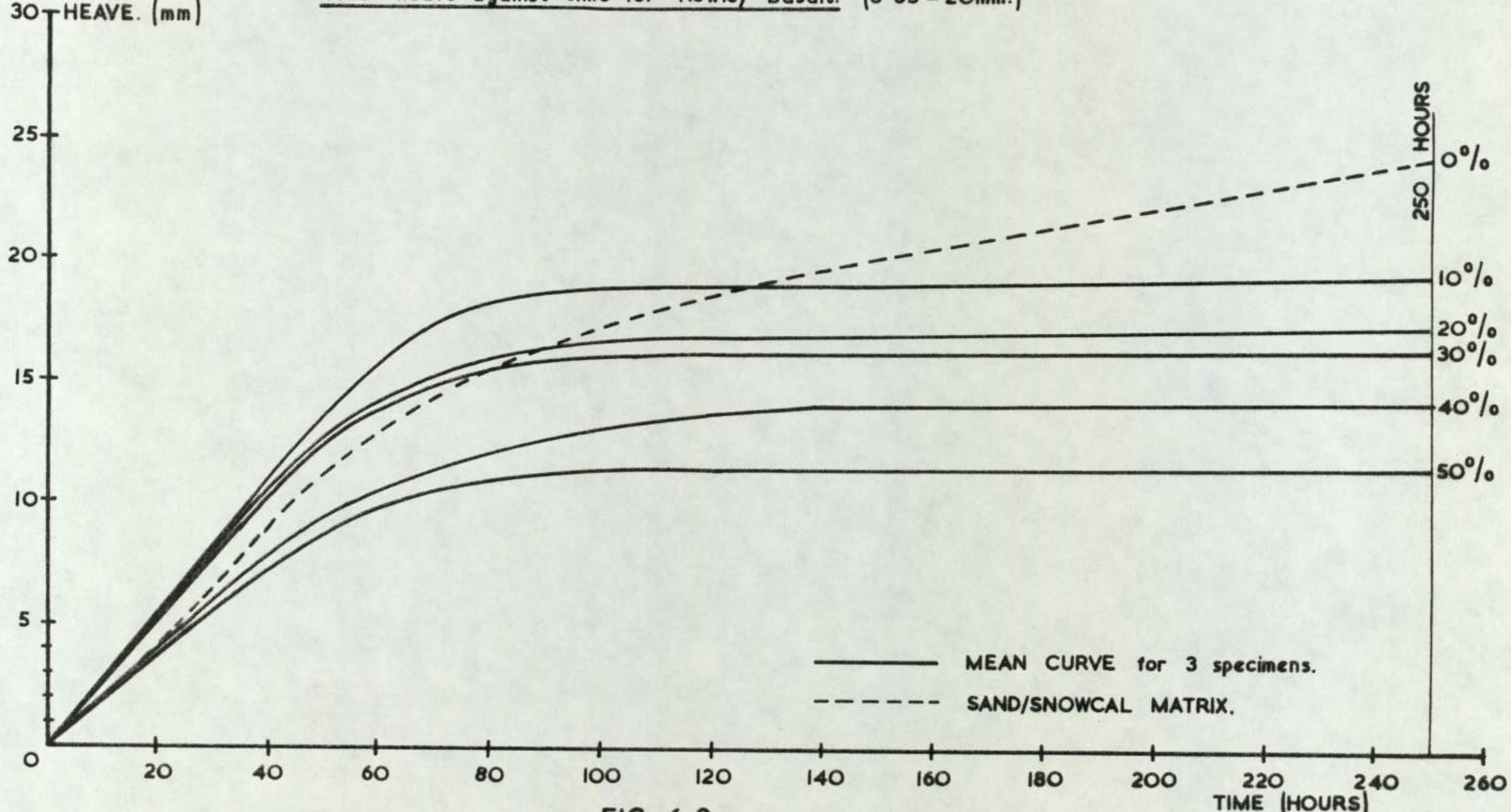


FIG. 6·2.

Frost heave against time for Caldon Low. (3·35 - 20mm)

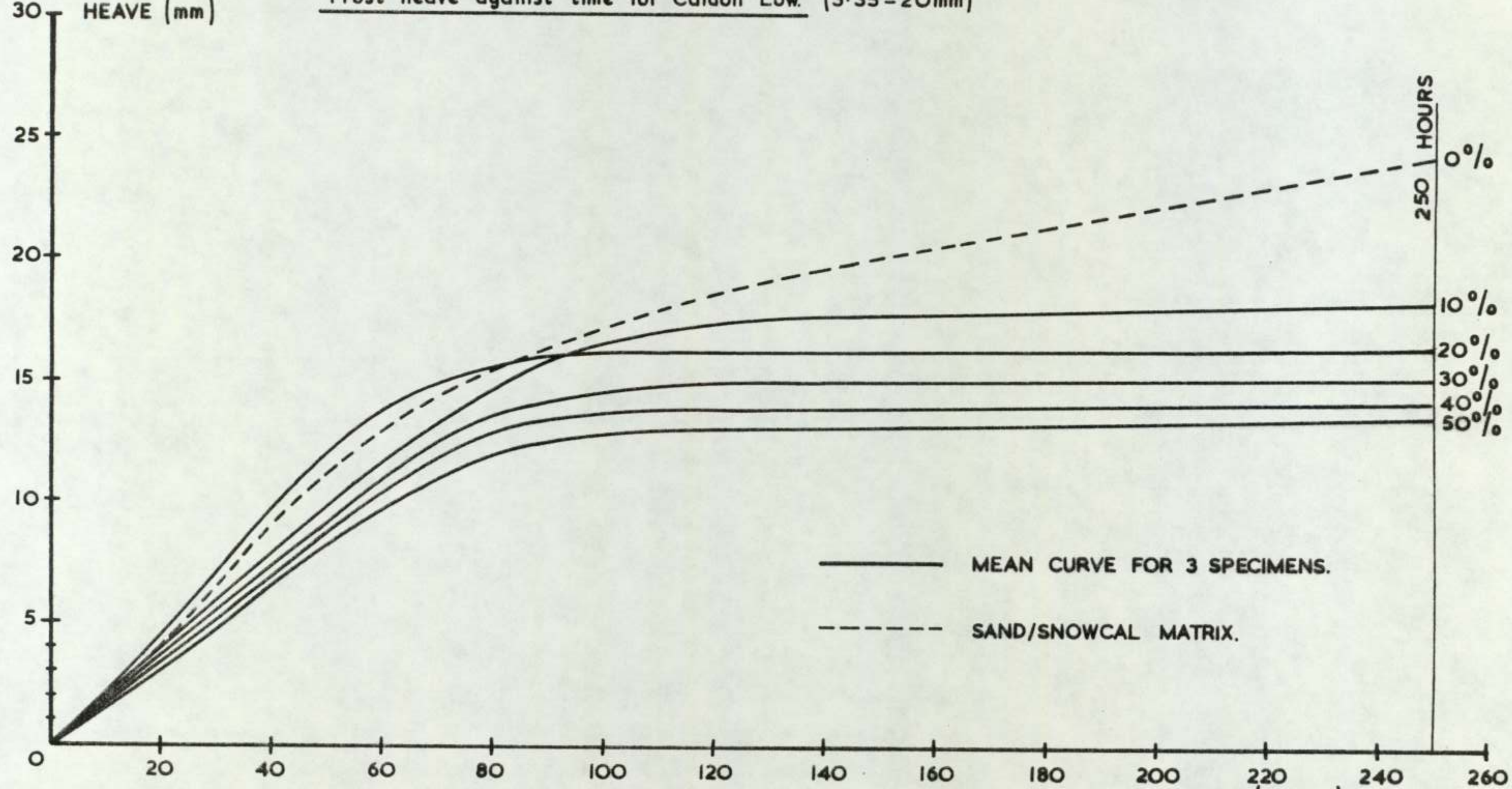


FIG. 6·3.

Frost heave against time for Slag Aggregate. (20 - 37.5 mm.)

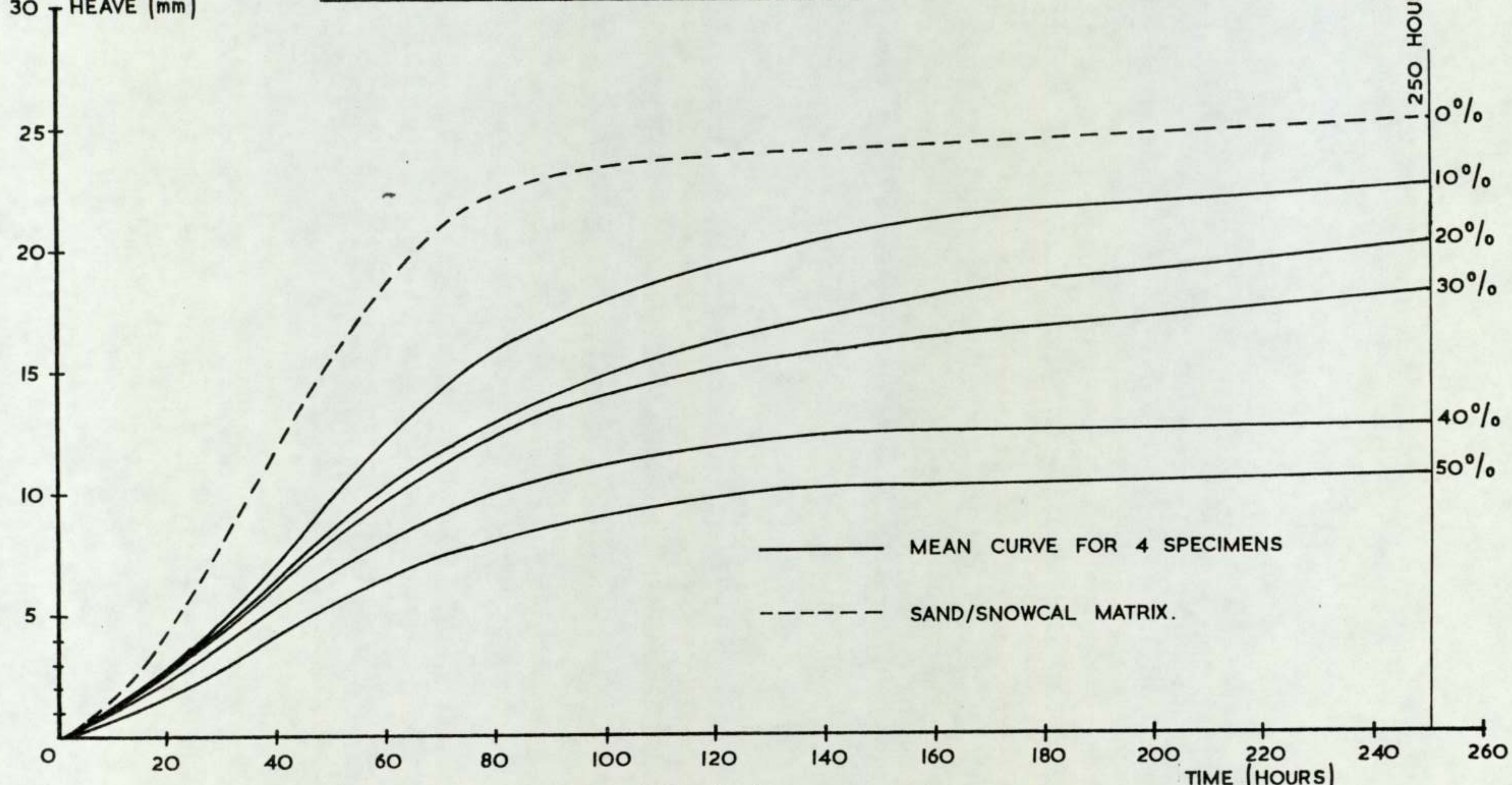


FIG. 6·4.

Frost heave against time for Rowley Basalt. (20–37·5mm)

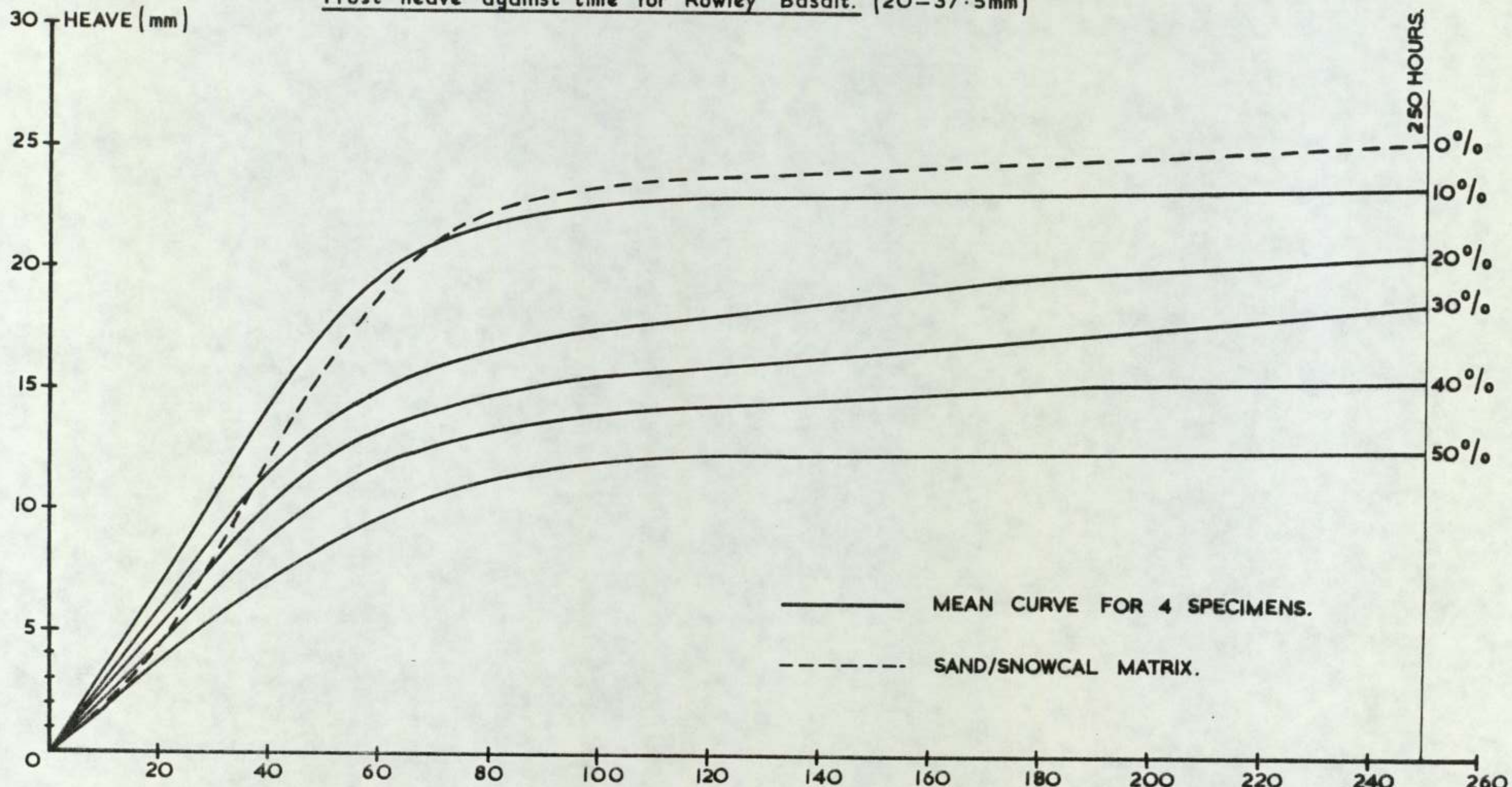


FIG. 6·5.

Frost heave against time for Caldon Low. (20 – 37·5mm.)

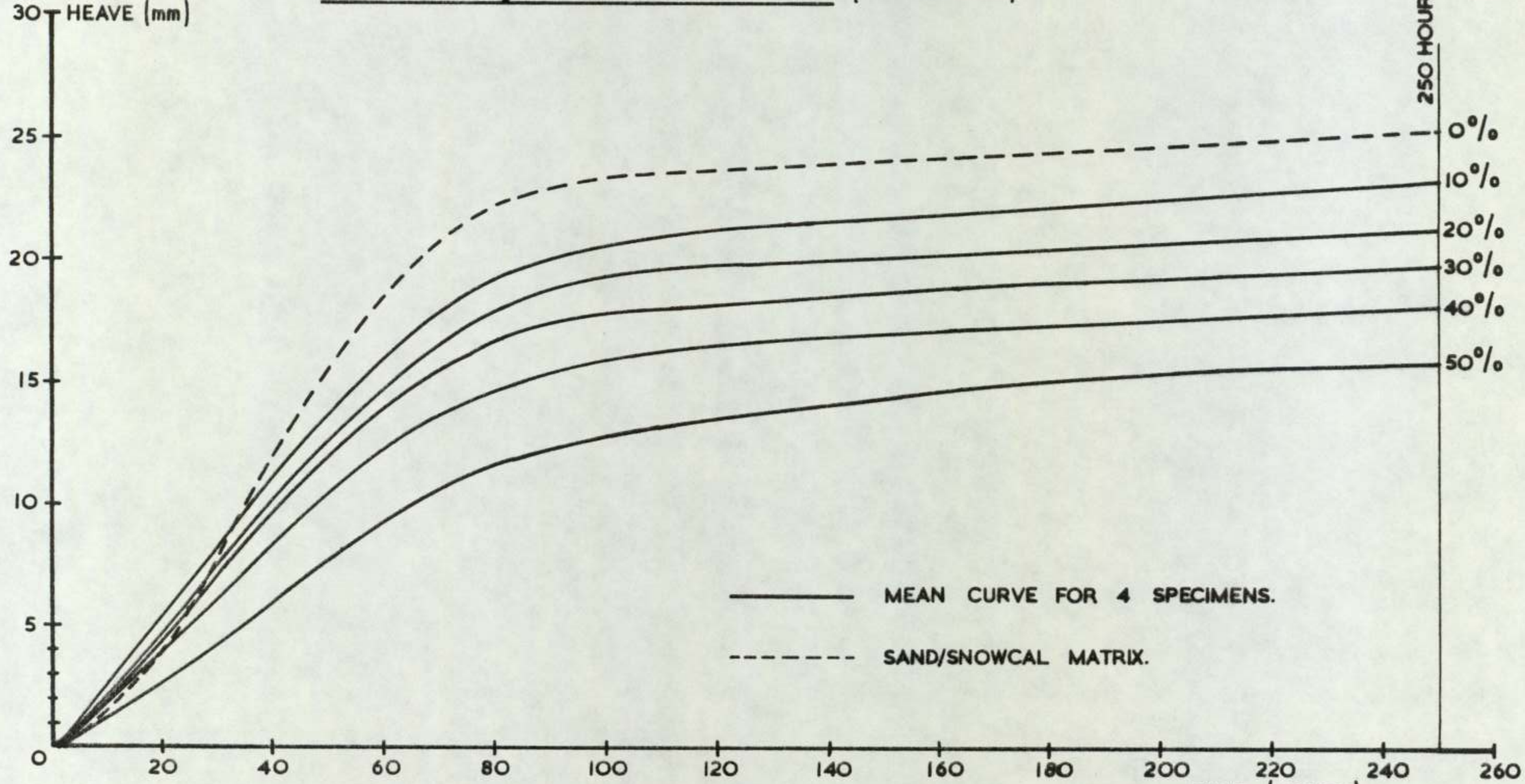


FIG. 6·6.

FROST HEAVE AGAINST PERCENTAGE OF AGGREGATE.

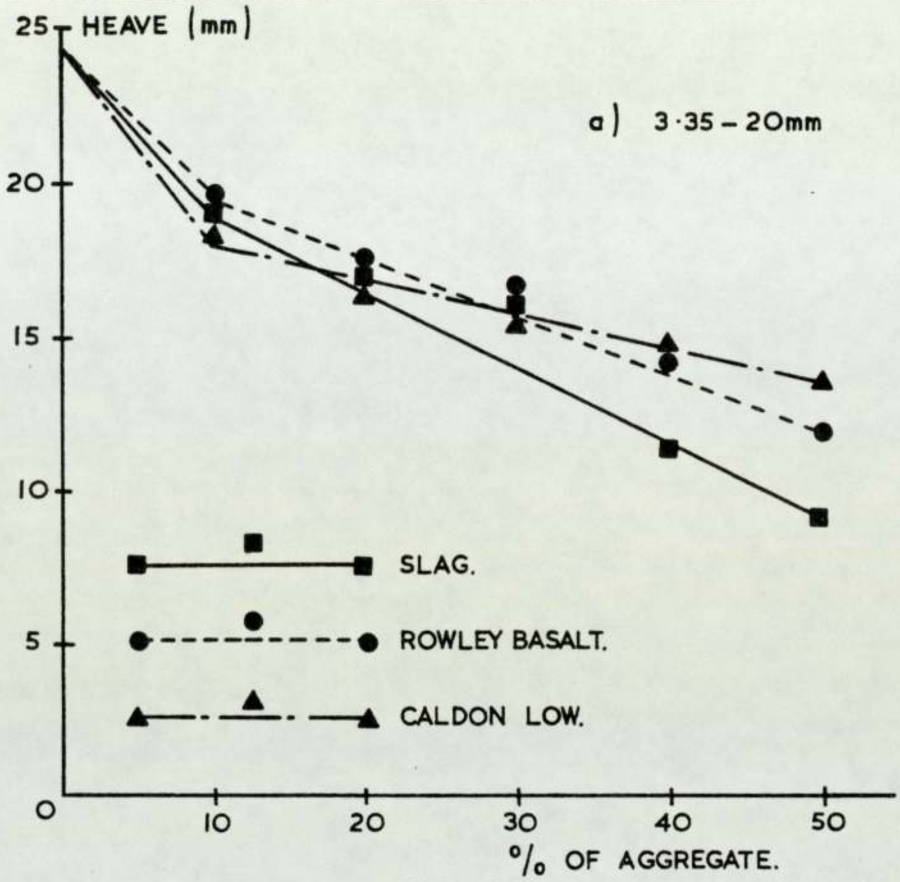


FIG. 6.7.

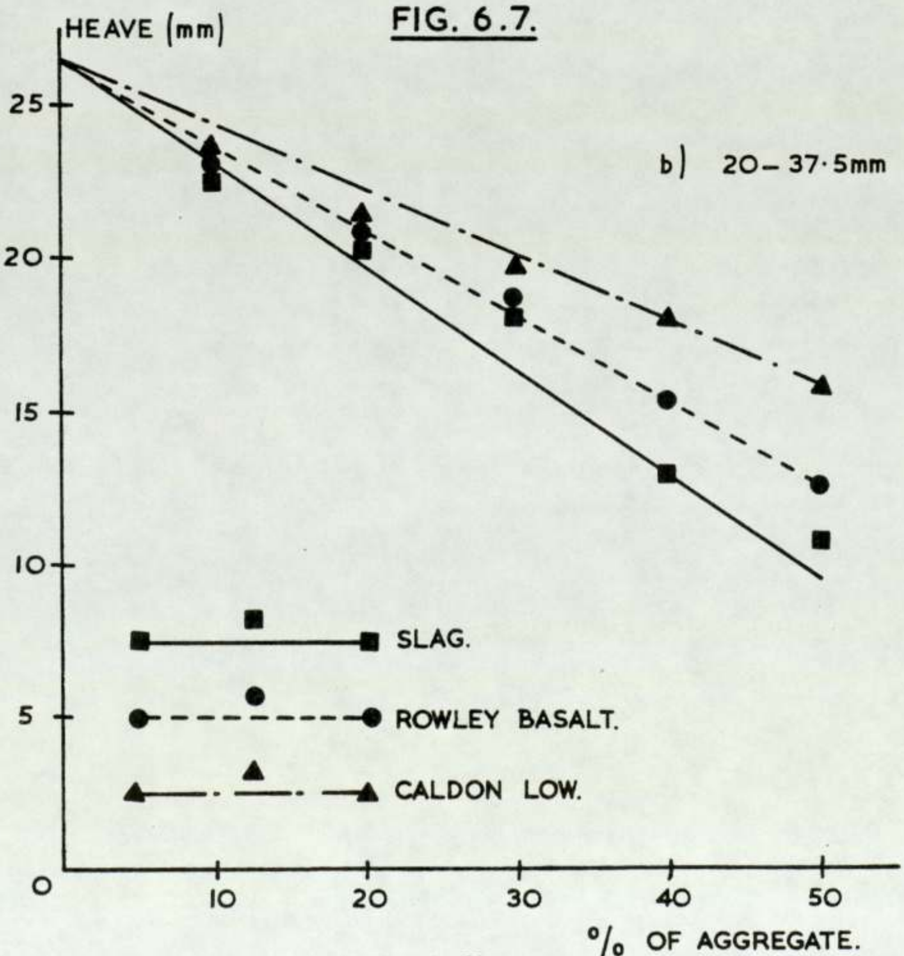


FIG. 6.8.

Frost heave against coefficient of permeability for 3·35–20mm aggregates.

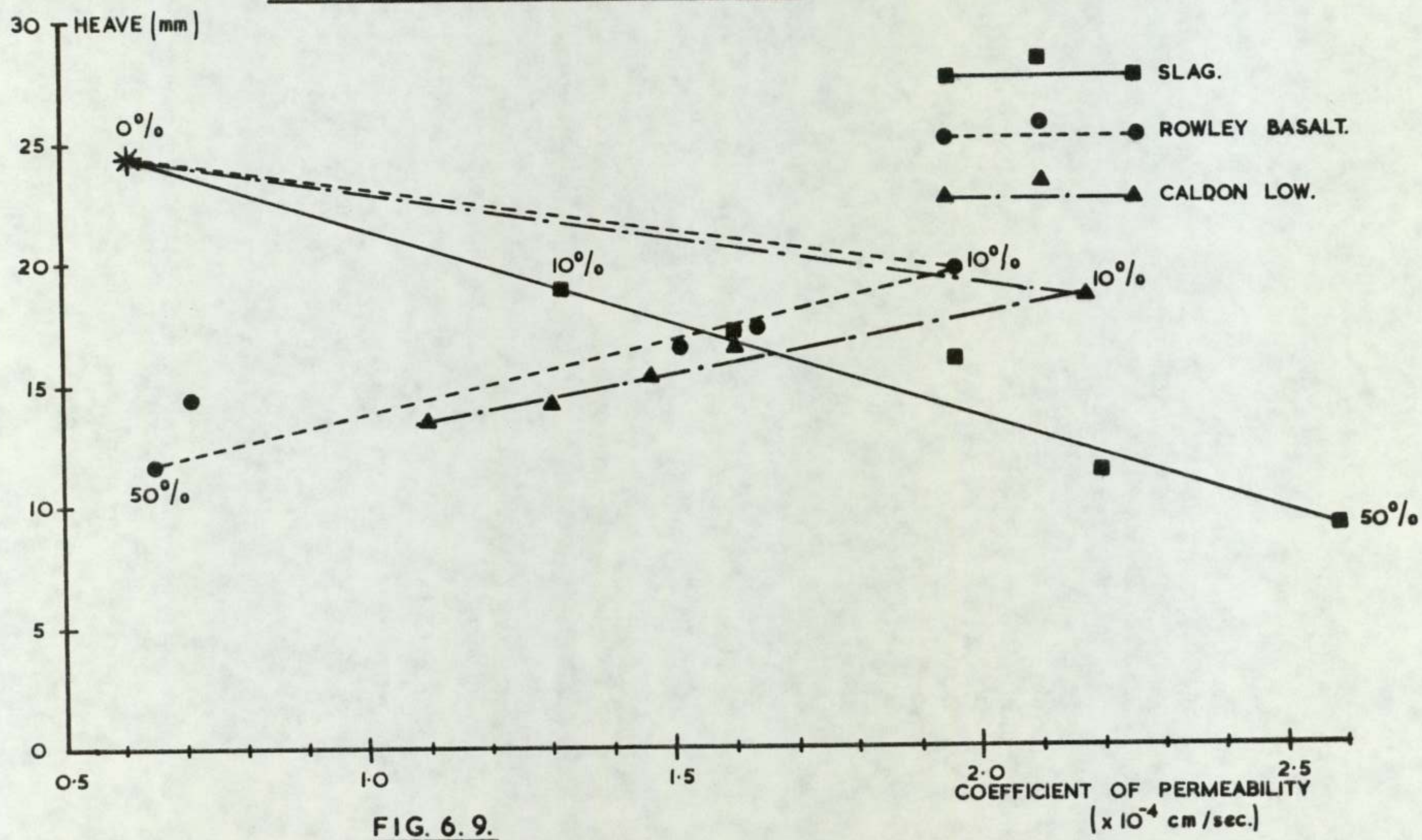


FIG. 6. 9.

Frost heave against total porosity (3·35-20mm aggregates.)

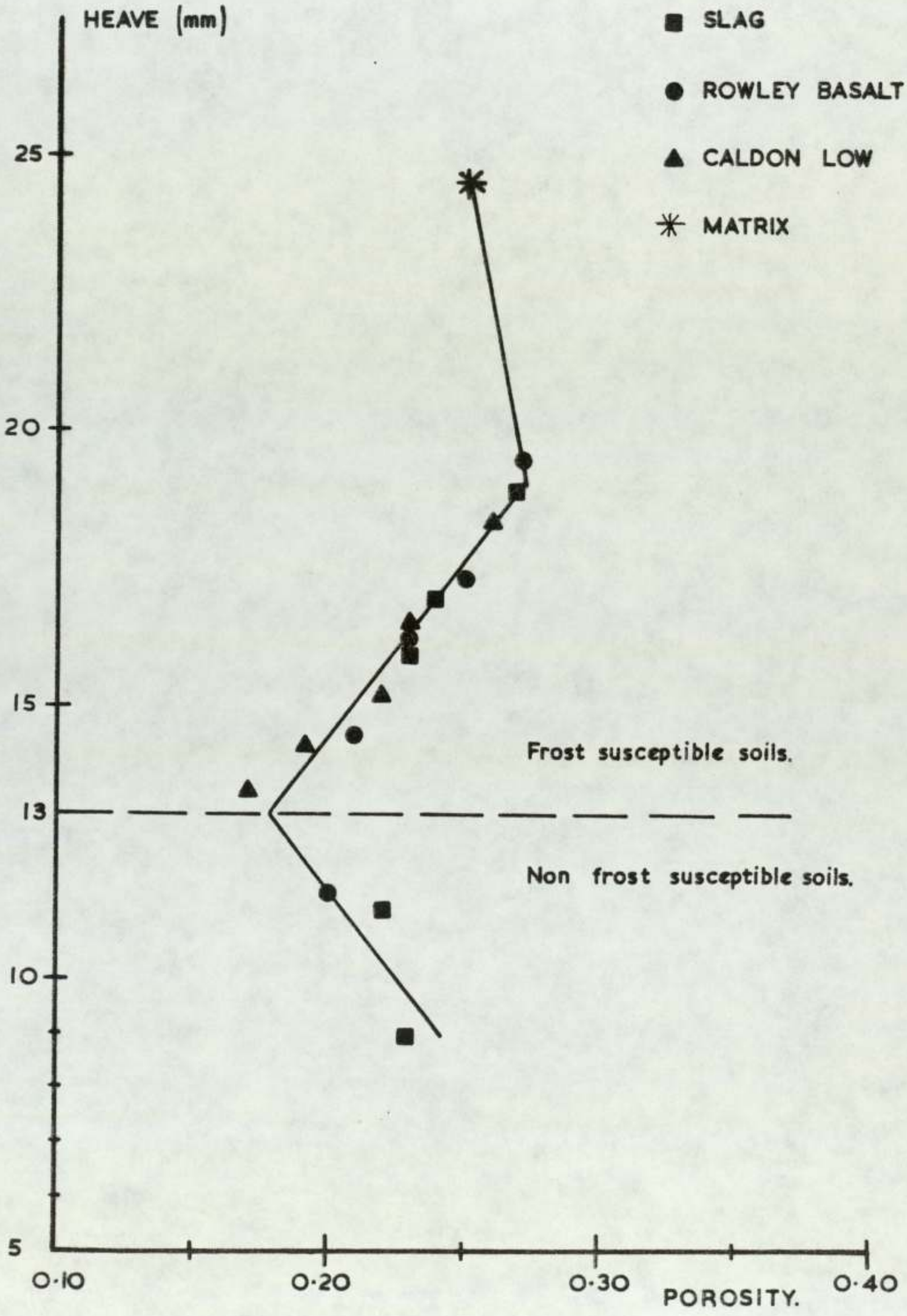


FIG. 6.10.

CHAPTER VII

HEAVING PRESSURES

7.1 Introduction

When heat is extracted from a soil and freezing is initiated, the growing ice crystals form planar ice lenses. These ice lenses grow by the transport of additional water from the unfrozen soil below the freezing zone. If the soil is frost susceptible, the accumulation of ice lenses will be significant.

The continued growth of the ice lenses leads to frost heave or, if the movement is restricted, to the build up of heaving pressures. Such frost heaving forces act perpendicular to the surface of the particular structure that restricts or prevents the increase in soil volume. Ice lenses will continue to grow until the balance between major governing factors is disturbed. The important factors include:-

a) the rate of heat removal

b) the upward flux of soil water

c) confining pressure

d) configuration of ice-water interface.

The magnitude of frost heaving pressures is influenced by a number of factors.

1) the properties of the soils - particle size, adsorption, the level of particle surface free energy, pore size distribution etc.

2) the compressibility of the underlying soil layer

3) the external pressure on the soil

4) the rigidity of any structures adjacent to the freezing soil.

Heaving pressures may be predicted theoretically but the risk of either over-estimation or under-estimation of the predicted value still exists (98) (54).

7.2 The origin of heaving pressures

During the freezing process when ice lenses are enlarged by the flux of water from below, it was noticed (21) that ice crystals reject foreign particles such as soil matrix, solutes etc., and with slow crystallization the tendency to form large crystals is more noticeable. Therefore, the crystallization pressure was associated with theoretical upper limit of heaving pressures, so that heaving pressures are related to the energy liberated by supercooling (21),(61). Theoretically, this heaving pressure might be high, but in practice it depends on moisture availability, temperature conditions, configuration of ice-water interface, etc.

When ice lenses are formed, the energy released on freezing is used partly to lift the overlying soil-overburden and partly to stimulate water migration towards the freezing front. Therefore, at relatively high overburden pressures, less energy will be available for water transport to feed ice lenses and so with a reduction in the water flux the growth of the ice lenses will also be restricted. Indeed such considerations gave rise to the concept (45) of a "shut-off pressure" which would stop further ice lensing. However, it now seems that such shut-off pressures do not exist (46) and that the cold side temperature is the key factor controlling the heaving pressure. Accordingly, heaving pressures can build up slowly but almost indefinitely as long as the process is given sufficient geological time (54). In laboratory studies where the freezing is a constant factor, the concept of maximum heaving pressure may be appropriate providing that the freezing period is clearly stated.

It is accepted now that the energy involved in the work of frost heaving is related to differences between the energy states of the ice and the associated soil water (21),(59),(20),(28).

Penner (59) adopted the equation of Everett and Haynes (99) for a close pack of uniform beads:-

$$\Delta P = \frac{2\sigma_{iw}}{r_i} + \frac{2}{r}(\sigma_{is} - \sigma_{ws}) \tag{7.1}$$

where:

σ_{iw} = ice-water interfacial energy

σ_{is} = ice-particle interfacial energy

σ_{ws} = water-particle interfacial energy

r_i = radius of pore

r = radius of particle.

In this equation the first component on the right hand side was associated with a drop of pressure across the curved ice-water interface in the pore, while the second was related to the floatation effects, as demonstrated by Corte (41), where soil particles were shown to be lifted by growing ice lenses.

Williams (20) adopted the same relationship in a slightly different form. He also considered the pressure difference across the curved ice-water interface in terms of the ice pressure and the pore water pressure in the associated water film. The heaving pressure is a confining pressure which is equal to the ice pressure P_i and P_w is the pore water pressure in the film water at the freezing front. The pore pressure decrease ($P_i - P_w$) depends on the limitation of the size of the crystals which is imposed by the soil pores, since heaving occurs only if the ice is forming outside the pores. He expressed this with a capillarity relationship for the coexisting ice and water:-

$$P_i - P_w = 2\sigma_{iw}/r \tag{7.2}$$

σ_{iw} = surface tension for ice-water interface r = effective radius of crystal, $\approx$ radius of pore.

Then the heaving pressure could be expressed:-

$$P_i = P_w + \frac{2\sigma_{iw}}{r} \qquad (7.3)$$

Where heaving occurs against rigid structures, the heaving pressure developed upon freezing may be transmitted to the unfrozen soil. This may result in a significant rise in the pore water pressure which in turn leads to an increase in the heaving pressure by an equal amount. It was noticed (20) to be relevant to compressible soils of low permeability.

Penner (59) clearly demonstrated that the measured heaving pressures were related to the soil texture. He attempted to relate his observation to the Everett equation (7.3) but only achieved a reasonable correlation when he assumed that the smaller pores were controlling the induced pressures. He considered that the freezing front must adopt an undulating configuration containing these smaller pores, although this explanation has been rejected by Miller (25) among others. This approach lead Penner (59) to discuss grain size as a possible frost susceptibility criteria.

The important soil factor is the pore size rather than particle size, although particle size will influence the pore size distribution since a significant number of small pores will only occur with small grains. It has been suggested (58) that the number of small pores is important since, if they are only present in a limited number, the freezing front could by-pass them. Again Hoekstra et al (58) concluded that the maximum heaving pressure would only be developed as the ice interface proliferates through the smallest pores.

Most experimental studies had related the measured heaving pressures to those predicted by the capillary theory. However, during the past ten years this approach has become suspect with the development of alternative theories for frost action (28),(29). It has become evident that the capillary model severely underestimates the maximum heaving pressure in non-colloidal soils (25),(27).

Hoekstra (29) connected the development of heaving pressures with the surface energy differences between ice and water and he stressed that the pressure originated at the boundary between the frozen and unfrozen soil. He was, therefore, involving the concept of a frozen fringe (28) or zone of diffused freezing (39). He attributed the differences between granular and clay soils to the conductivity of water through the frozen soil.

Other experimental work (100),(101) had also demonstrated that water moves through the liquid films on the soil particle surfaces towards the cold side and this flow depends on temperature and the surface area of the soil. Ice lenses can break the continuity of such films and so restrict, or even prevent, water migration. Thus, in a saturated, granular soil the rate of water flow in the frozen soil is small and so significant ice lensing does not occur behind the freezing front. In such soils, the heaving pressures would be related to the capillary model. However, in clay type soils ice lenses grow behind the freezing front at temperature below $0^{o}C$. Thus, the major difference between granular and clay type soils is, that in the latter type, the pressure depends on the temperature (29) and so is likely to be related to the secondary heaving model (29) or the adsorption model (39).

7.2.1 <u>Heaving pressures of coarse granular soils</u>

Heaving pressure will depend on accumulation of ice lenses at the freezing front and will correspond to the capillary rise theory. The pressures are related (20) to pore size through this expression:-

$$P_i - P_w = \frac{2\sigma_{iw}}{r} \tag{7.2}$$

Thus providing that the temperature is below ΔT, given by

$$\Delta T = \frac{2\sigma_{iw} T_o V_w}{rL} \tag{7.4}$$

where

ΔT = freezing point depression

T_o = normal freezing point

V_w = specific volume of water

L = latent heat of fusion

the generated pressures will be independent of temperature. The key factors influencing the heaving pressure will be:-

1) pore size (particle size)

2) the rate of heat removal

3) tension of ice-water interface

4) hydraulic conductivity of unfrozen soil

5) availability of water.

7.2.2 Heaving presures of clay materials

For clay materials the capillary theory will contribute to primary heaving or primary heaving pressure, while secondary heaving will considerably contribute to the magnitude of heaving pressures. From Miller's theory of secondary heaving (28) the heaving pressure will have to satisfy the equation:-

$$(P_i)_{max} = e_i[(P_w)_o/e_w + \Delta H_f \, \Delta T_o/T] \tag{7.5}$$

where:

$e_{i,w}$ = density of ice or water

$(P_w)_o$ = the pore water pressure

ΔH_f = the heat of phase transition

ΔT_o = the temperature at the base of the nominal ice lens

T = the absolute temperature

The magnitude of these pressures will depend on the factors given in 7.2.1 together with:-

1) hydraulic conductivity of frozen soil
2) hydraulic conductivity of the frozen fringe
3) temperature gradient in the frozen fringe
4) compressibility of the unfrozen soil.

It should also be noted that the adsorption force theory would be applicable to frost action in such soils so that heaving pressure expressions derived by Takagi (39) should also be noted in such materials.

7.2.3 Mixed materials

For mixed materials such as those studied in this investigation the amount of fines will largely dictate which of the theories will predominate and heaving pressure will depend greatly on temperature gradient and mobility of water both towards freezing front and through the liquid films on the surface of the soil particles in the frozen zone.

7.3 Measurement of heaving pressure

7.3.1 Initial apparatus

This was based on equipment developed by Kettle (61) from the original system employed at CRREL (58) and it is outlined in Figure 7.1. It consisted of a cylindrical steel mould, 101.6mm diameter by 133.3mm, with a recessed steel base, housing a porous stone, attached to the lower end of the mould. To reduce friction between the specimen and the mould, the inside of the mould was tapered and coated with PTFE dry lubricant.

A thermoelectric device (TED) was used for freezing of the specimen and this was placed on an aluminium cooling plate at the top of the specimen. The cooling plate was sealed against the mould by a "U"-seal to minimise heat transfer between the cooling plate and the cylinder. The fluid cooled, thermoelectric device had a rated capacity of 19 watts. It was operated from a low voltage direct current supply with maximum output of 6.0 amps at 4.8 volts. The rate of heat removal depends on the power input to the TED. The current was calibrated against the temperature at the top of the specimen so that a suitable setting could be selected to achieve the desired top temperature. It was established that a current of between 3 and 3.5 amps would produce the desired top temperature of $-4.2^{o}C$. In the original study (61) the TED was cooled directly with mains water, but it was apparent that this could fluctuate and so produce slight variations in the rate of heat removal. A Grant FH15 flow cooler, with a circulating pump, was therefore used to cool the thermoelectric device. The circulating water was maintained at a constant temperature of about $+4.0^{o}C$ and so kept the rate of heat removal constant. Mounted above the cooling plate and taking the thrust was a load cell bearing against a reaction frame. The load cell has a capacity of 4.5kN and was regularly calibrated in a standard loading frame. The output from the load cell was plotted on a trace recorder.

7.3.2 Test procedure

The dry material for individual specimens was mixed in a Hobart mixer to ensure even distribution of fines. Water was introduced to this mixed material and the mixing was continued for a further 5 minutes. The specimens were made up at the optimum moisture content previously determined by the B.S. compaction test (71), and were produced at the same dry density as the specimens subject to the frost heave test.

The cylindrical mould was bolted to a steel base plate and the material was compacted, as in the compaction test (71), in three layers, each layer being given 27 blows with a 2.5kg hammer. After compaction the specimen was trimmed to give height of 115mm and weighed to check on density value. If the weight of the specimen differed by more than 1% from the calculated value, it was rejected and compaction was repeated, using fresh material.

The mould and sample were removed from the steel plate and bolted to the recessed plate which contained the porous stone. The upper cooling plate was positioned, together with the load cell, and the whole assembly was placed in the reaction frame inside the deep freeze cabinet. A water supply was connected to the base plate and the specimen was left to condition for 24 hours, as in the frost heave test. During this period the temperature was gradually reduced from room temperature to $+4.0^{\circ}C$.

At the end of the conditioning period, the load cell was rigidly secured against the reaction frame. The load cell, thermoelectric device, water cooler and trace recorder were switched on and the test continued until maximum heaving pressure was achieved.

7.4 Modification of the equipment

It soon became apparent that, despite the tapering of the mould and the use of PTFE, significant sidewall resistance was developed.

This was clearly demonstrated at the completion of the test for considerable force was required to eject the partially frozen specimen from the mould. The sidewall resistance is due both to adfreeze and frictional restraint. In earlier investigations (61) with the equipment, reference was made to this sidewall restraint, but it was not accurately quantified. It was, therefore, considered essential to modify the apparatus before commencing the major study. In particular, as this study involved the measurement of the heaving pressures developed by granular soils, which are lower than those developed by fine-grained, any sidewall resistance would have a significant effect on the test result.

Sidewall resistance in soil freezing tests has been commented on by many workers and several have proposed multi-ring systems for supporting the specimen (14),(90),(102) and limiting the sidewall resistance. This technique was adopted and a series of five rings was employed. Four of the rings were 25mm deep and the fifth was 15mm, giving the same specimen height, 115mm as in the original tests. The rings were made from the perspex tubing with an internal diameter of 120mm, thus, increasing the diameter of the specimen. A new steel mould was made to accommodate these rings with 1mm clearance all round. This system was used for support both during compaction and freezing.

The rings were secured together with cellotape, with an additional top ring of 25mm to make up the 137mm height of the mould. They were inserted into the mould, which had already been bolted to the steel base plate, and were secured by a ring clamp, fixed to the upper edge of the mould, to prevent relative movement of the rings during compaction.

Compaction was carried out as described in 7.3.2 but 35 blows were given to each layer due to the increased volume of the specimen. After compaction the steel base was unbolted, the mould was lifted away and the upper ring removed. The specimen was trimmed to a height of 115mm following the procedure used for the standard compaction test. The specimen, complete with supporting rings, was placed on top of the porous stone located in the recessed steel base plate. The cellotape was removed from the rings which were lightly coated with silicon grease before the mould was slid back over the rings. The specimen was ready for test and the remaining procedure followed that detailed in 7.3.2.

Although the multi-ring system eliminated the frictional component of sidewall resistance, moisture exuded between the rings during compaction and subsequent testing could produce adfreeze. After compaction and trimming of the specimen, the rings were coated with silicon grease. A rubber membrane was slid over the greased rings and a further coat of silicon grease was applied to the outside of the membrane. In addition to presenting the exudation of water into the annular gap between the mould and specimen, this system also eliminated friction at this interface. The steel mould was placed over the rings and the rest of the procedure was as described in 7.3.2. The modified equipment is shown in Figure 7.2.

An initial programme of tests was carried out to assess the effects of the modifications on the measured pressures. A number of tests were performed on sand/snowcal mixtures. These tests were performed in the original rig without modification, the modified rig with only the multi-ring system and finally the modified rig with multi-rings and rubber membrane. At least three tests were performed for each modification and the results are summarised in Figure 7.3. They clearly demonstrate the influence of sidewall resistance. The final modifications produced a 200 percent increase in the heaving pressure compared with that established in the original system.

Visual observation also indicated that the sidewall resisance had been eliminated for, at the completion of the test, the specimen and rings could be removed by simply inverting the mould allowing the assembly to slide out under its self weight. It is, therefore, believed that sidewall resistance is virtually eliminated and that further modifications would not produce significant increases in the measured pressures. The modified system was accepted as the basic system for all further tests.

One further alteration has been made to the equipment during the course of the investigation, and this is concerned with the method of freezing the specimens. The TED was replaced by a cooling plate containing circulating refrigerant from a central cryostat. This has achieved similar temperature control to that maintained by the TED but provides greater flexibility since several tests can be run simultaneously from the cryostat. It, therefore, permitted direct comparison between two specimens of different materials or sizes.

Additional tests were undertaken to compare value of heaving pressures recorded with the TED and the cryostat. The results were not significantly different, providing that the temperature on the top of the specimen was the same. Therefore, the subsequent results are not distinguished by the kind of equipment used for freezing of the specimens.

7.5 Preliminary tests

A series of tests were undertaken, on samples of the sand/snowcal matrix using the modified equipment to study the repeatability of the test. Prior to these tests, it was important to establish the boundary conditions for routine testing, as it had been shown (see Chapter V) that the temperature gradient through a sample had a significant influence on its freezing behaviour. The initial rationale for the measurement of the heaving pressures was to relate them to the frost heaves and, hence, to frost susceptibility. It was, therefore, decided to test the specimens under similar temperature conditions to those recorded in the heave test. The heaving pressure specimens, however, were 37mm shorter than the frost heave specimens and so, when the temperature of the cooling plate was the same as that at the top of the frost heave specimen, the specimens were frozen almost to the level of the porous stone. It was decided that it would be more appropriate to position the zero isotherm, in the heaving pressure specimen, so that the ratio between the frozen and unfrozen zones was the same as that in the frost heave specimens.

Holes were drilled in the middle of each perspex ring and thermocouples-needles were inserted into the specimen so that the temperature gradient could be recorded for different cold plate temperatures. It was established that, with the temperature of the cooling plate at $-4.5^{o}C$, the temperature distribution through the sample was proportionally similar to that in frost heave specimen and this temperature gradient is shown in Figure 7.4.

The temperature of the cabinet was maintained at $+4.0 \pm 0.5^{o}C$ and this controlled the temperature of the water feeding the porous stone. However, due to the heat extraction by the specimen, the temperature at the bottom of the specimen was $+3.5^{o}C$ since the test system did not have a positive source of temperature control in the water bath.

Once the boundary temperature had been fixed, it was decided to investigate the penetration of the zero isotherm into the sample and a typical plot is given in Figure 7.5. As the soil starts to freeze, the penetration of the zero isotherm during the first 30 to 45 minutes was very rapid and it normally penetrated to a depth of about 15-20mm during that time. Indeed, due to the contraction of the specimen, the recorder showed a slight reduction in the initial preload. Similar behaviour has been reported by Osler (103) who attributed such behaviour to initial supercooling of the water prior to ice nucleation. This rapid penetration of the zero isotherm was followed by a sudden retreat, to a depth of about 10mm. This is attributed to the release of the latent heat as nucleation occured and was followed by a prolonged period of penetration although at a slower rate than that recorded initially. After the initial release of latent heat heaving pressures were recorded and the onset of such pressures was taken as the time zero when interpreting the results and plotting the graphs. After about 8-10 hours of freezing the zero isotherm reached a stable position and no further penetration was observed, providing that the boundary conditions remained unchanged.

It was suggested (58) that initially the development of heaving pressure is due to the expansion of water during freezing. The maximum pressure was developed when the position of the freezing front has become stabilised in the soil. Therefore, the heaving pressures generated after about 8-10 hours could be regarded as pressures due to ice formation at the freezing front.

The test method was now considered satisfactory, with the boundary temperatures specified and the sidewall resistance eliminated, and so a study was undertaken to assess the repeatability of the test. A series of five tests was performed on samples of the standard sand/snowcal mixture. All the specimens were produced following the adopted procedure and the weight of each specimen was within one percent of the target value. The results are collected in

Table 7.1 and clearly show that the test method is very reliable. Typical curves of heaving pressure against time are shown for three of the specimens in Figure 7.6. The coefficient of variation from the five tests was 2 percent and this compares very favourably with the frost heave test, where the coefficient of variation is usually in the range 10-40 percent. Thus, in the subsequent research programme, it was considered that appropriate values could be established by performing two separate tests on each individual material. Indeed, single specimens may be sufficient for future routine testing providing that the specified test conditions are adopted.

Number of test	1	2	3	4	5
Heaving pressure (kN/m^2)	294	295	308	304	298
Mean heaving pressure (kN/m^2)	299.8				
Standard deviation (kN/m^2)	6.01				
Coefficient of variation (%)	2.0				

TABLE 7.1 Heaving pressures for sand/snowcal specimens

7.6 Definition of maximum heaving pressure

In their original work, Hoekstra et al (58) suggested that, once the freezing front had reached a stable location, the maximum heaving pressures were largely dependent on the propagation of the ice through the smallest pores. Thus a system with a large proportion of small pores would exhibit increases in heaving pressure for a considerable time, although the increases would be at an ever decreasing rate.

From the capillary model of frost heaving it can be shown that heaving pressure is inversely related to pore size (99),(92) and it has been suggested (22),(104) that the maximum pressure will particularly depend on smaller pores. However, in freezing tests it is essential to consider both this primary heaving and secondary heaving (25),(28) with ice lenses growing behind the freezing front. This produces heaving pressures considerably greater than those predicted by the capillary theory (25). It has been reported (26),(105) that these pressures are dependent on both the temperature of the cold plate and soil type. The measurement of such pressures can involve freezing periods in excess of 100 days since the terminal value is approached at an ever decreasing rate (26),(98). Therefore, in order to limit the present test programme, it was decided to adopt an arbitrary definition for the maximum heaving pressure.

In earlier work (61) the maximum heaving pressure was arbitrarily defined as that pressure recorded when the rate of increase was less than $0.001MN/m^2/hr$ ($1KN/m^2/hr$). This criterion has the advantage of limiting the testing time especially when the soil is being tested for classification purposes, although it is not an absolute parameter.

To justify this assumption, a test was undertaken on the sand/snowcal matrix for a period of 500 hours. Between 100 and 150 hours the rate of increase in heaving pressure was less than $0.3kN/m^3/hr$. After 200 hours freezing, the rate increase further diminished and between 250 and 500 hours no increase was recorded. As the experimental programme was concerned with granular materials and as the time to reach limiting heaving pressures was relatively short (150 hours or less) it was decided to measure heaving pressure until the increase is less than $0.1KN/m^2/hr$. The heaving pressure corresponding to this value is reported as the maximum heaving pressure.

When measuring heaving pressures, consideration must be given to the degree of restraint applied to the freezing soils. In earlier experimental work, using hard and soft proving rings to provide the restraint, Osler (103) demonstrated that the greatest heaving pressures were generated against the stiffest constraints. He suggested that the total frost heave consists of three elements:-

1) an initial volumetric contraction
2) free heave when zero isotherm penetrates into the soil which is almost exactly 9 percent
3) heave associated with ice lensing when the position of freezing front is established.

The soft proving ring permitted some surface heave and so only heaving pressures due to ice lensing were recorded. On the contrary, the constraint provided by the stiff load cell lead to the development of pressures that involved all the elements and so included the pressures due to the volumetric expansion of the soil water.

In the frost heave test, the total frost heave includes the volumetric expansion of water as well as the frost heave due to the formation of ice lenses. It was, therefore, decided to measure the heaving pressure under stiff constraint as provided by a hard load cell. Indeed, in practical application where surface heave is important, both frost heave and heaving pressures assessments should include volumetric expansion of water.

7.7 Influence of thermal parameters

Following a recent experimental study, Takashi et al (26) have suggested that the upper limit of the heaving pressure is related to the temperature of the cooling plate as follows:-

$$\sigma_u = -11.4\theta_c \qquad (7.6)$$

where

σ_u = upper limit of heaving pressure

θ_c = temperature of cooling plate.

Thus, as the temperature of the cooling plate is reduced, the heaving pressure increases. However, Takashi et al (26) demonstrated that this linear relationship was not suitable at lower temperatures and at such lower temperature the heaving pressure appeared to approach a limiting value $(\sigma_u)_{max}$. This maximum pressure may be substituted into equation 7.6 and the calculated temperature is referred (26) to as θ_{crit}. Both this critical temperature and the temperature at which the relationship diverge from the linear form, given in 7.6, depends on soil type. For a silt the linear behaviour was only apparent between 0°C and -4°C, whereas similar tests on a clay-type soil revealed a linear relationship down to -25°C.

In addition, to the influence of cold plate temperature Loch and Miller (27) had underlined the dependence of heaving pressure on temperature gradient and had suggested that the maximum heaving pressures were produced, in their tests, with temperature gradients between 1.0 and 2.5°C/cm. It, therefore, seemed appropriate to study the role of the thermal parameters before commencing the major programme. It had become apparent during the preliminary trials with the equipment that even slight deviations from the specified temperature of cooling plate (±0.5°C) would produce changes in the measured pressures.

As has been indicated in section 7.5, the initial boundary conditions in the heaving pressure test were designed to produce a temperature gradient through the specimen similar to that recorded in frost heave specimens. Thus, the temperature at the top of the specimen was -4.5°C, whilst the water bath at +4.0°C produced +3.5°C at the base of the specimen. These values were used as the datum to assess the effects of changes in the boundary conditions on the pressure.

7.7.1 Temperature of the cooling plate

This study was performed on specimens prepared from the highly frost susceptible matrix. Thermocouples were inserted through the centre of each ring so that the temperature gradient through the specimen could be determined. The preliminary trial revealed that, with cooling plate temperatures below -6^{o}C, the zero isotherm could penetrate through the porous stone. The temperature control at the base of the specimen was, therefore, modified. The porous stone in the base plate was replaced by a perforated brass plate with filter paper placed on the upper face. By connecting the two pipes in the base plate to a thermostatically controlled, circulating bath, it was possible to control the water temperature to close limits. In this test, the water bath was operating at +4^{o}C. Comparative tests were performed using this arrangement and the original water bath and, providing the boundary temperatures were constant, no significant differences were found in the measured heaving pressures. The controlled bath was, therefore, adopted for this study.

After 24 hours conditioning at +4.0^{o}C, the specimens were frozen from the top with the top temperatures subjected to step changes when the heaving pressure reached its arbitrarily defined maximum at a given temperature. The temperature of the cold plate was reduced by a specified amount and again held steady until a new maximum pressure was obtained. The initial temperature of the cooling plate was -2.0^{o}C. The temperature was reduced in increments of approximately 1.0^{o}C but, due to the coarseness of the temperature control on the cryostat, exact increments could not be achieved. However, once a given setting had been achieved, the cryostat maintained the temperature of the cold plate within $\pm 0.1^{\circ}C$.

The temperature distribution through the sample was recorded every hour whilst the freezing front was penetrating through the sample and, once it had stabilised, the temperature gradient was checked at least four times every day. This procedure was followed for each cooling plate temperature. In addition, the temperature of the water circulating through the brass plate was maintained at $+4.0^{\circ}C$. The curve of heaving pressure against time, for various cooling plate temperatures, is shown in Figure 7.7. The maximum pressures, for each temperature, have been abstracted from Figure 7.7 and Figure 7.8 presents a plot of maximum pressure against cooling plate temperature and the corresponding temperature gradients are given in Figure 7.9.

At temperatures above $-2.0^{\circ}C$ no pressures were detected and this may be due to:-

i) insensitivity of the equipment

ii) initial ice nucleation not achieved

iii) insufficient time allowed for the generation of suction in pore water and the subsequent transport of water.

With a top temperature of $-1^{\circ}C$, heaving pressures were not detected even after an exposure in excess of 48 hours and so estimated trends are given for pressures in the range 0 to $-2.0^{\circ}C$.

As the temperature of the cooling plate is reduced, the heaving pressure increases linearly between $-2.0^{\circ}C$ and $-4.5^{\circ}C$ as can be seen in Figure 7.8. At temperatures below $-4.5^{\circ}C$, the relationship deviates from the initial line and the pressure increases at a diminishing rate. Similar behaviour has been reported by Takashi (26). It was not possible to continue the tests at temperatures below $-9.0^{\circ}C$ as the cryostat could not constantly maintain such low temperatures. As the top temperature decreases, the zero isotherm penetrates through the specimen as can be seen from the distributions in Figure 7.9. Although the circulating water was maintained at +4.0^{o}C, the penetrating zero isotherm also decreased the temperature at the bottom of the specimen so producing a temperature gradient through the brass plate. This would appear to demonstrate that the heaving pressure is influenced by the rate of heat removal. Similar behaviour has been reported for heave tests, where Penner (24),(107) has demonstrated that the heaving rate is largely controlled by the rate of heat removal.

It has been suggested (107),(108) that the rate of frost heaving is dependent on the amount of heat removed from the freezing front and Gorle has shown (109) that the heaving activity is also influenced by the temperature gradient under the ice front. Another series of tests was, therefore, undertaken to examine the role of the temperature gradient on the generation of heaving pressures.

7.7.2 Temperature gradient

It was decided to maintain the freezing front (zero isotherm) at a constant location but to vary the temperature gradient in the frozen zone. The specimens were again prepared from the highly frost susceptible matrix and the temperature gradient was determined using thermocouples inserted through each ring. The initial freezing procedure followed that detailed in section 7.7.1 with a step changes in temperature being applied to the cooling plate. The zero isotherm was located in the position corresponding to the normal test conditions - top temperature -4.5^{o}C, bottom temperature +3.5^{o}C. Thus, as the temperature of the cooling plate was further reduced, it was necessary to increase the temperature of the circulating water so as to maintain a stationary zero isotherm.

Figure 7.10 shows the relationship between heaving pressure and total freezing time for the various cooling plate temperatures with a stationary isotherm. The data from this graph has been summarised in Figure 7.11 where maximum heaving pressure is plotted against cooling plate temperature, the corresponding temperature gradients are given in Figure 7.12. It should be noted that although the bottom temperature remained sensibly constant at 3.5 to 4.0°C, this was only achieved by progressively raising the temperature of the circulating water from +4.0°C to + 7.0°C as the cooling plate temperature was reduced from -5.0 to -9.0°C.

A comparison of Figure 7.8 with Figure 7.11 indicates good agreement between the results of the two tests in the range 0 to -4.5°C. At lower temperatures the heaving pressure continues to increase, albeit at a decreasing rate, in both tests. However, at these lower temperatures the heaving pressure increases more rapidly with the stationary freezing front than with penetrating freezing front.

In both tests the freezing rates, or cooling plate temperatures, were the same but, as can be seen from Figures 7.9 and 7.12, larger temperature gradients were obtained with the stationary freezing front. This is attributed to the higher temperatures at the bottom of the specimen which indicate an increase in the rate of heat extraction. It, therefore, appears that an increase in the rate of heat removed from the freezing front produces an increase in the heaving pressure. Gorle (109) has suggested that the flow of water to the freezing front is influenced by the temperature gradient under the ice front and a comparison of the data also indicates that this temperature gradient may influence the heaving pressure.

The observed behaviour is also compatible with the experimental work of Horiguchi (108) and Penner (24) who have demonstrated that the rate of frost heaving increases as the rate of heat removal is increased. The linear relationship (equation 7.6) between cooling plate temperature and heaving pressure, presented by Takashi et al (26) has only been demonstrated with fine-grained soils. For coarse-grained materials, Takashi (110) has indicated that the deviation from the linear relationship occurs between -0.2 and -0.5°C. Thereafter the heaving pressure increases at an ever decreasing rate with further reduction in the temperature of the cooling plate. The experimental results from this study are compatible with this behaviour, considering that different granular materials were tested. Indeed, it seems that equation 7.6 is inappropriate for evaluating the maximum heaving pressure developed by coarse grained soils.

For both experiments the deviation of the heaving pressure relationship from the initial linear relation was at approximately -4.5°C for the test material. With such a cooling plate temperature, the temperature gradient and location of the freezing front are similar to those of the frost heave specimen. Absolute compatibility is not possible due to differences in the height of the two specimens e.g. 115mm and 150mm. To minimise differences in procedure between the heaving pressure and the frost heave tests, it was decided to test the heaving pressure specimens under these conditions i.e. cooling plate at -4.5°C and circulating water bath at +4.0°C. This, it was hoped, would permit subsequent comparisons between the results of the two tests.

7.8 Influence of specimen size

One of the objects of this project was to investigate the effects of the inclusion of coarse particles on the heaving pressures. To study the effects of the largest particles 37.5-20mm, it was decided that a larger specimen of 145mm diameter should be used, this being similar to that used in the modified frost heave tests reported in Chapters V and VI. The specimen height was kept constant at 115mm and the arrangement of the rings was as for 120mm diameter specimen. It has been shown that the specimen size can influence the heave recorded in the frost heave test. It was, therefore, decided to undertake a series of tests to examine whether such differences could be observed in the heaving pressure tests.

These tests were performed on specimens of the sand/snowcal matrix. Specimen preparation and subsequent testing followed the procedure given in 7.3, although, the number of blows per layer was increased to 52 in view of the increased size of the 145mm specimen. With the cryostat it was possible to test two specimens simultaneously so that direct comparison could be made between the results obtained with different sized specimens under the same boundary conditions. The two specimens were, therefore, prepared together so as to minimise any possible variation during specimen preparation. The results of these tests are given in Table 7.2.

Size	120 and 145 tested at different time		120 and 145 tested together		MEAN (kN/m^2)	Standard deviation	coefficient of variation (%)
	1	2	3	4			
120mm	296	302	305	298	300.25	4.03	1.3
145mm	300	308	291	304	300.75	7.27	2.4

TABLE 7.2 Heaving pressures for 120 and 145mm specimens

It is clear that the results obtained with both the 120mm and the 145mm specimens are very close, giving similar standard deviations and coefficients of variation. This good agreement can also be seen by comparing the respective plots of heaving pressure against time shown in Figures 7.13 and 7.14. The results are also in good agreement with those obtained during the repeatability study with the 120mm specimen. It is, therefore, clear that the size of the specimen did not have any significant effect on the measured heaving pressures. This is different to the effects observed in the frost heave study.

This may be attributed to the method of compaction which, unlike that used for the frost heave specimens, should not be too markedly influenced by sidewall friction since the compaction hammer involves a kneading action. In addition, both specimens are surrounded by rings with an air gap of about 1mm between the rings and the mould. This restricts lateral heat flow from specimens during freezing, and so, more positively, encourages unidirectional freezing than in the frost heave test. Further, as the diameter of the small mould was selected as 120mm, in comparison with the 102mm of the frost heave mould, the effect of the increase to 145mm would be expected to be less significant.

It can be concluded from these experiments that, if the same material is tested in both moulds under standard conditions, the results of the tests are in good agreement and vary within experimental error of the test. It was, therefore, decided to use the 145mm mould for further research to investigate the influence of large particles on heaving pressures generated in freezing soil.

7.9 Influence of material properties

7.9.1 Materials

Controlled amounts of three aggregates were mixed into the standard sand/snowcal matrix. The aggregates were the slag, basalt and limestone used in the frost heave study and their properties are detailed in Chapter IV. Each material was sub-divided into 37.5-20mm particles and 20-3.35mm particles.

7.9.2 Specimen preparation

To reduce the risk of crushing the aggregate, the mixing procedure was modified. The matrix was initially dry mixed, the water was added to this mixture and mixing was continued until a uniform texture was apparent. A mixing blade was substituted for the mixing hook and the aggregate was added. Further mixing was kept to a minimum and was stopped when the aggregate was evenly distributed in the matrix. The material was transferred to an airtight container and stored for 4 hours. This enabled the aggregate to absorb moisture and so stabilised the moisture distribution. Thereafter, specimen preparation followed the procedure detailed in 7.3.2.

7.9.3 Specimen size

Mixtures containing 20-3.35mm particles were tested in 120mm specimens. Both groups were tested under the same conditions using the cryostat for cooling. This enables simultaneous testing of two specimens as detailed in section 7.8. Minimum of two specimen were tested for each mixture. The duration of each test depended on the time that the specimen took to reach the observed maximum value. The detailed results are given in Figures 7.15 to 7.20 which show the relationship between heaving pressure and freezing time. The results are summarised in Table 7.3, which provide a basis for discussion.

TYPE OF AGGREGATE	Percentage of aggregate in matrix(%)	HEAVING PRESSURE	
		3.35-20mm particles (kN/m^2)	20-37.5mm particles (kN/m^2)
Slag	0	300	301
	10	242	246
	20	220	224
	30	192	198
	40	160	172
	50	127	140
Rowley Basalt	0	300	301
	10	280	282
	20	258	264
	30	250	255
	40	238	240
	50	225	230
Caldon Low Limestone	0	300	301
	10	254	265
	20	246	250
	30	230	236
	40	218	228
	50	200	215

TABLE 7.3 Heaving pressure for 20-3.35mm and 37.5-20mm particles

7.9.4 Aggregate content

The relationships between heaving pressure and the percentage of aggregate are shown in Figures 7.21 and 7.22 for the two aggregate groups, 20-3.35mm and 37.5-20mm. As aggregate content increases, the heaving pressure is reduced. In general, relationships between heaving pressure and aggregate content are linear for all the materials tested. However, the individual relationships are very dependent on aggregate type, this being apparent with both aggregate size groupings. The importance of aggregate type becomes more marked as the content increases.

For given freezing conditions, the extent of frost action in granular mixtures is related to pore size (99) with heaving pressure being inversely related to pore size, providing that water is freely available at the freezing front. The pore structure is influenced by grain size and, since coarser materials will contain considerably fewer fines per unit volume (also per unit cross-section in a given plane) of material, they will exhibit reduced frost activity. Large particles will also lie across the freezing plane with a portion of the particle above and a portion below and so will offer frictional and displacement resistance to the heave forces located in the plane of freezing (60).

With porous coarse particles, ice lensing could occur within the particles and this would contribute to the development of heaving pressure. The exact effect would depend on the relationship between pore structure within the particle and that of the surrounding matrix. Such behaviour has been reported with some aggregates (61). The three aggregates used in this study had low absorption values and so ice lensing within the particles is unlikely to have been a significant factor in these tests. However, the differences in effect between the three aggregates may be due to difference in their internal pore structure. Similarly the three aggregates would have differing effects on the thermal properties of the material, particularly in the region immediately adjacent to each particle, and so this would also account for different trends reported in the three aggregates.

One further observation is of note, concerning the freezing time each material required before it approached a limiting pressure. An inspection of the curves in Figures 7.15 to 7.20 clearly shows that as the aggregate content is increased, the freezing time is reduced. With the Slag mixtures in Figure 7.15, the material containing 50 percent of coarse aggregates reached the limiting pressure in 50 hours, whereas the mixture with 10 percent required approximately 100 hours. It would, therefore, appear that in the coarser mixtures prolonged freezing is unlikely to produce additional ice lensing. This modification in behaviour is more marked with the 20-3.35mm particles than with the 37.5-20mm particles.

7.9.5 Particle size

From the results in Table 7.3 it appears that both aggregate groups 20-3.35mm and 37.5-20mm have similar effects on heaving pressure. As the aggregate content increases it appears that the 20-3.35mm particles may be more effective in reducing heaving pressure than 37.5-20mm particles. This is most apparent with the Slag and Limestone mixtures although the individual differences are not significant. The 20-3.35mm particles consistently produce lower pressures than the 37.5-20mm particles. However, the differences are within the expected experimental errors since it has been shown in Tables 7.1 and 7.2 that standard deviation is of the order of 5-7kN/m^2 for both sizes of specimen.

At a given aggregate content, both groups would occupy the same volume in the specimen but the 20-3.35mm fraction will possess a larger particle surface area. Thus, compared with the 37.5-20mm particles, these particles would occupy a greater proportion of any freezing plane, and so would be expected to be more effective in reducing forces associated with frost action, in this case, the heaving pressure. In addition, the increased surface area of the 20-3.35mm particles would increase the frictional and displacement resistance to the heaving forces at the freezing front.

INITIAL FORM OF THE EQUIPMENT.

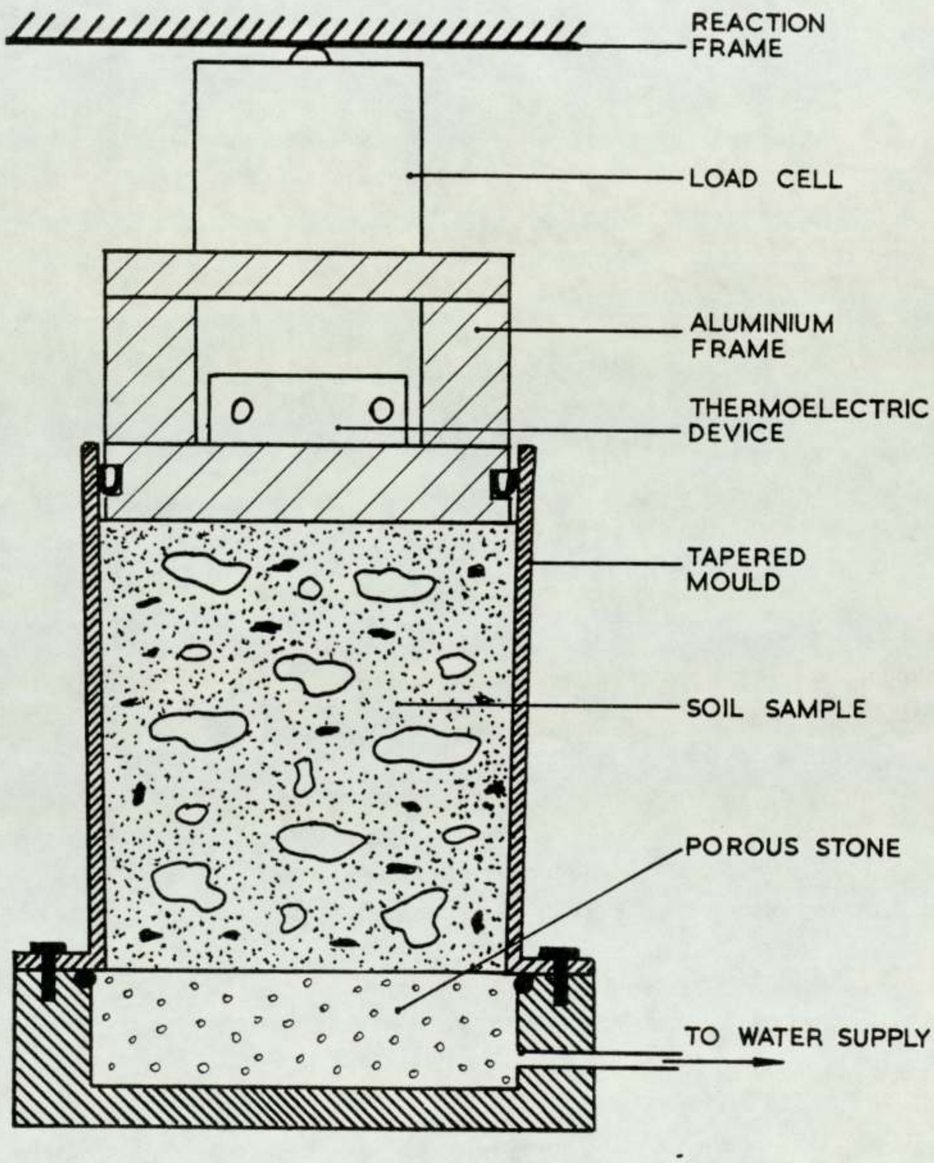


FIG. 7.1.

FINAL FORM OF THE EQUIPMENT.

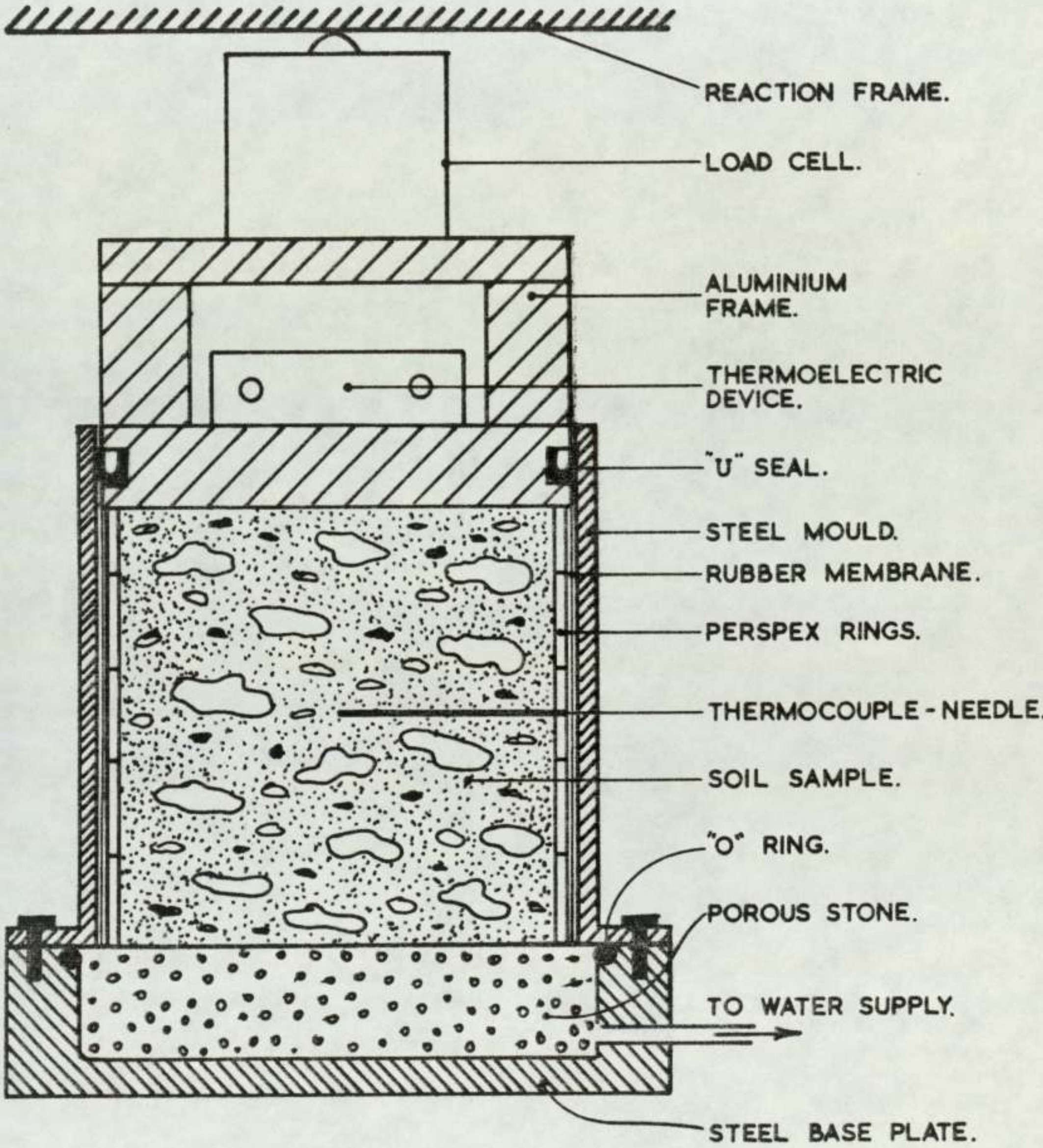


FIG. 7·2.

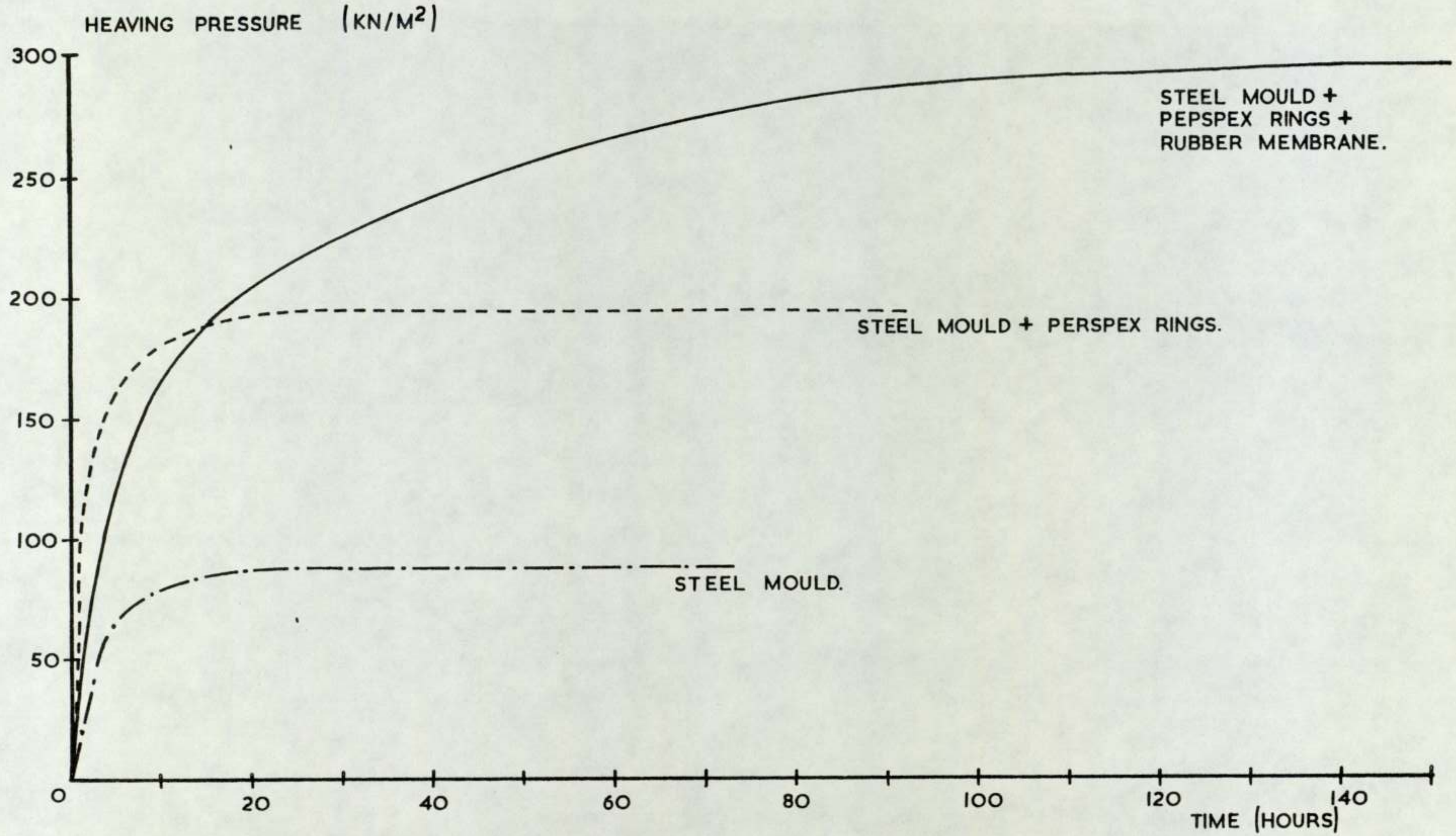


FIG. 7·3. Effect of modifications on measured heaving pressure.

TYPICAL TEMPERATURE GRADIENT FOR SAND/SNOWCAL SAMPLE.

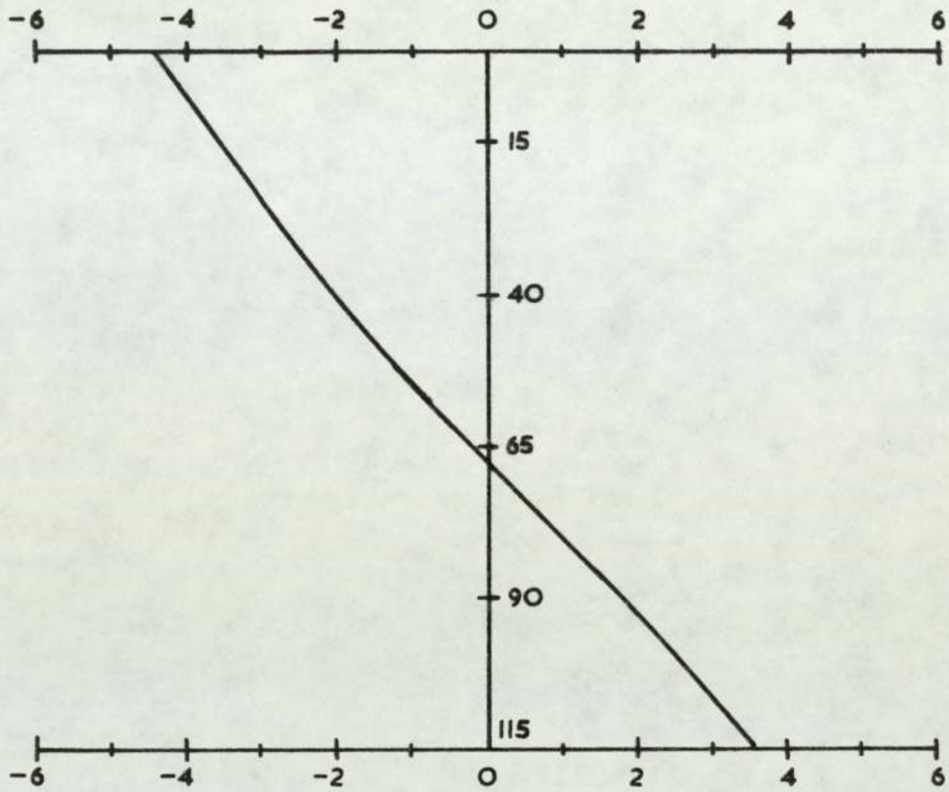


FIG. 7·4.

PENETRATION OF "O"- ISOTHERM INTO THE SAMPLE.

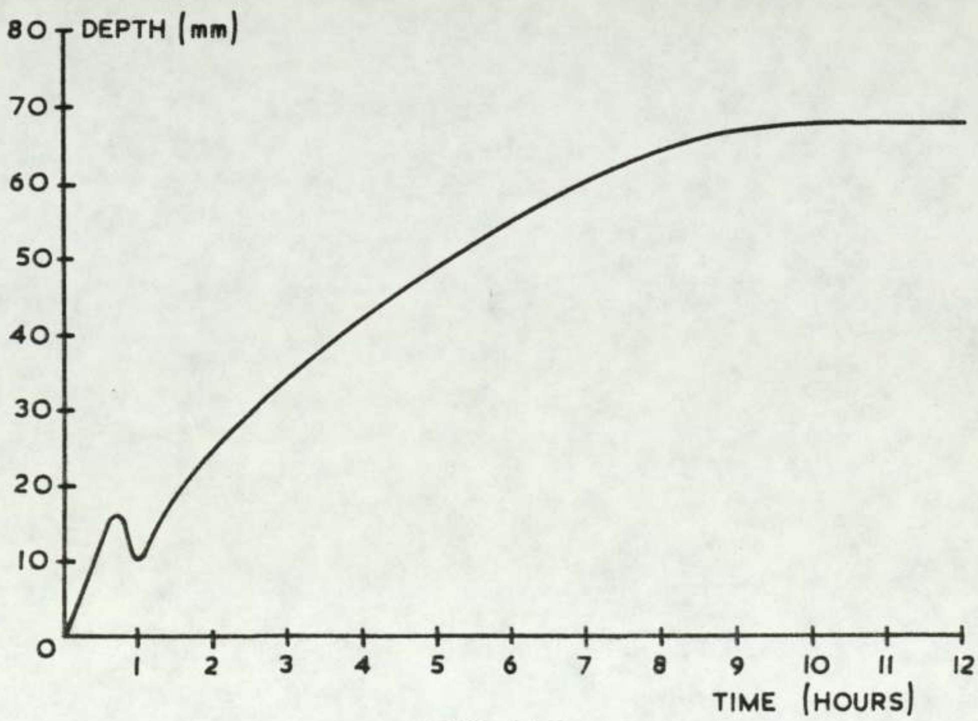


FIG. 7·5.

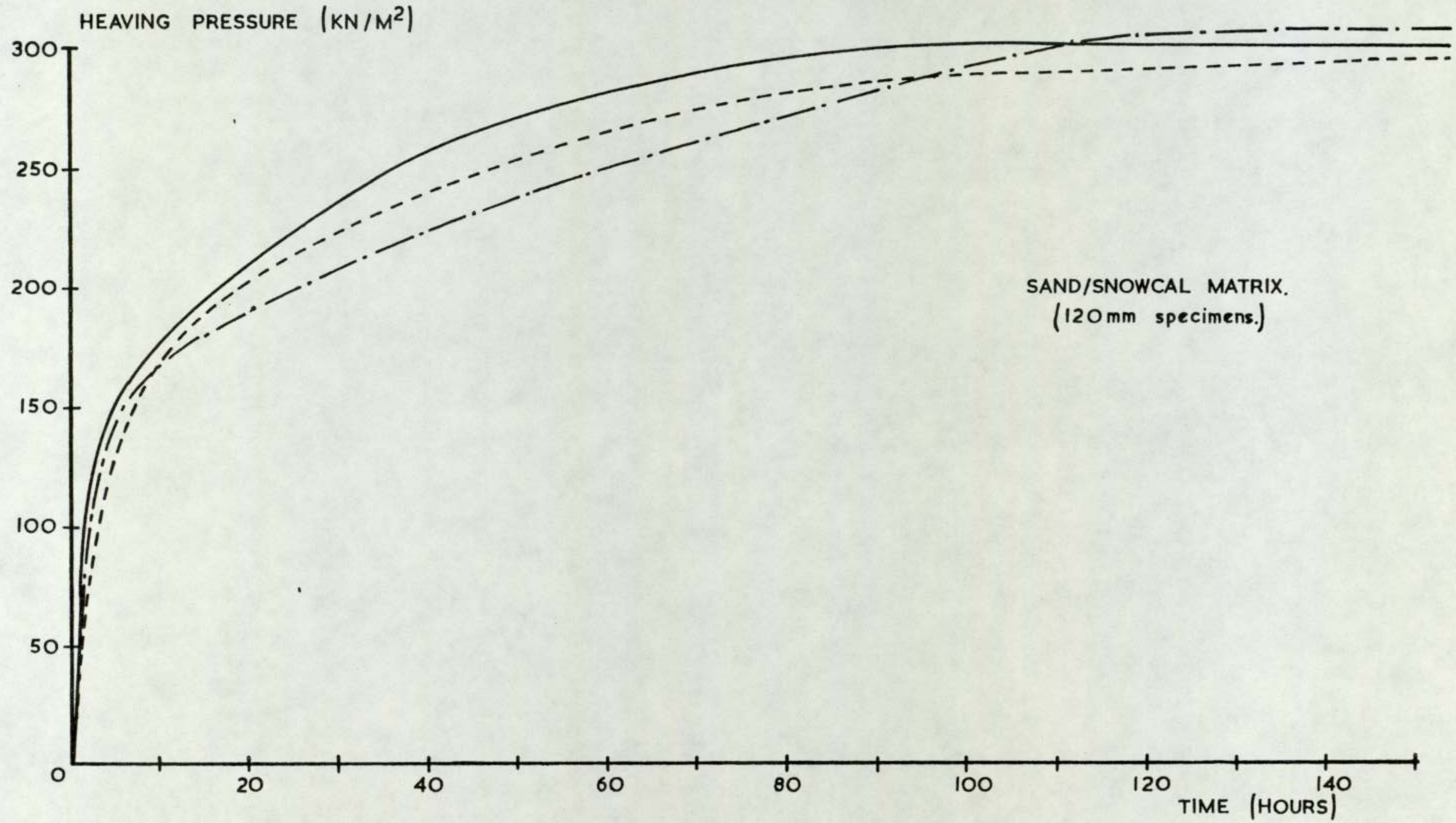


FIG. 7·6. Heaving pressure against time for some individual samples.

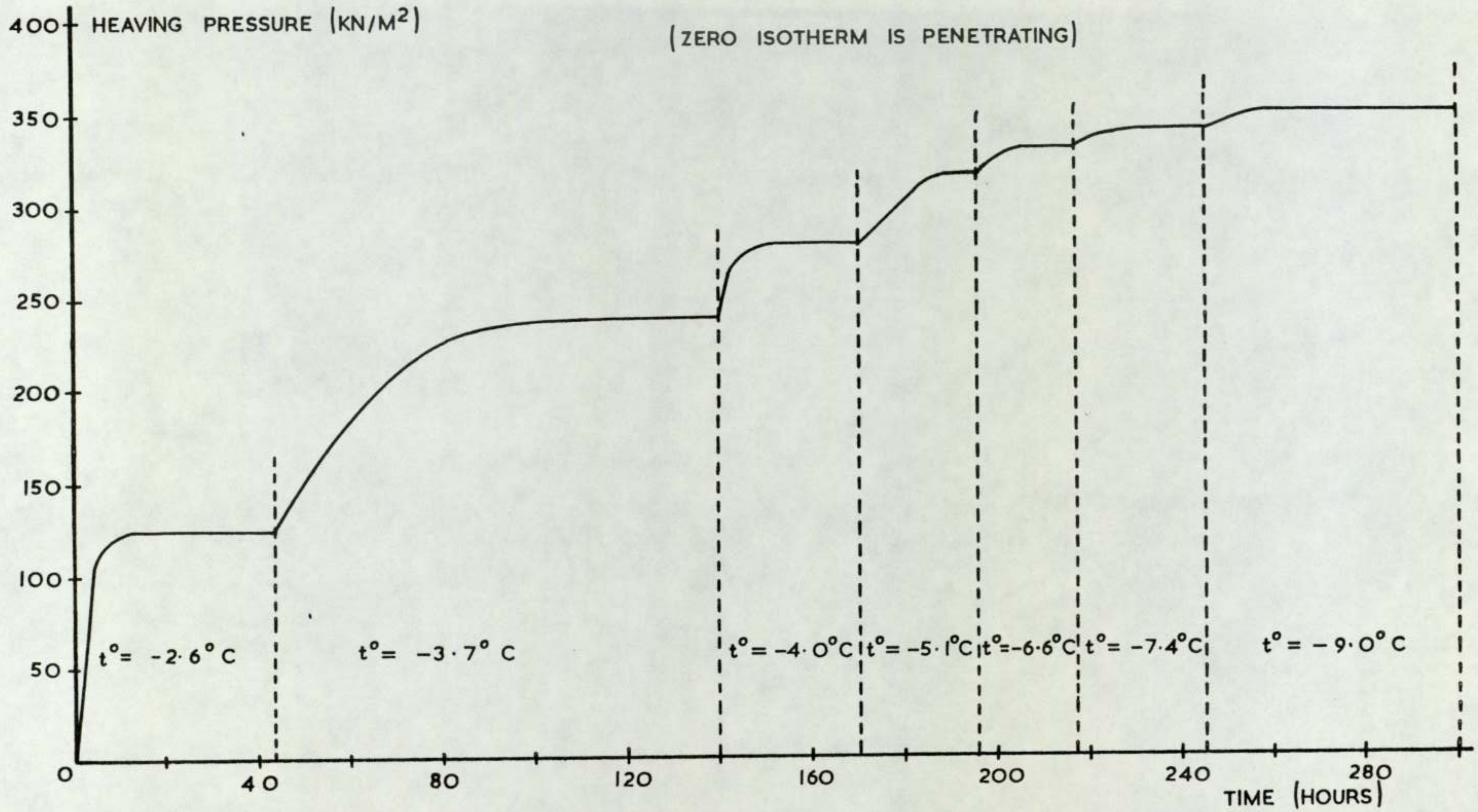


FIG. 7·7. Heaving pressure against time for different temperatures of the cooling plate.

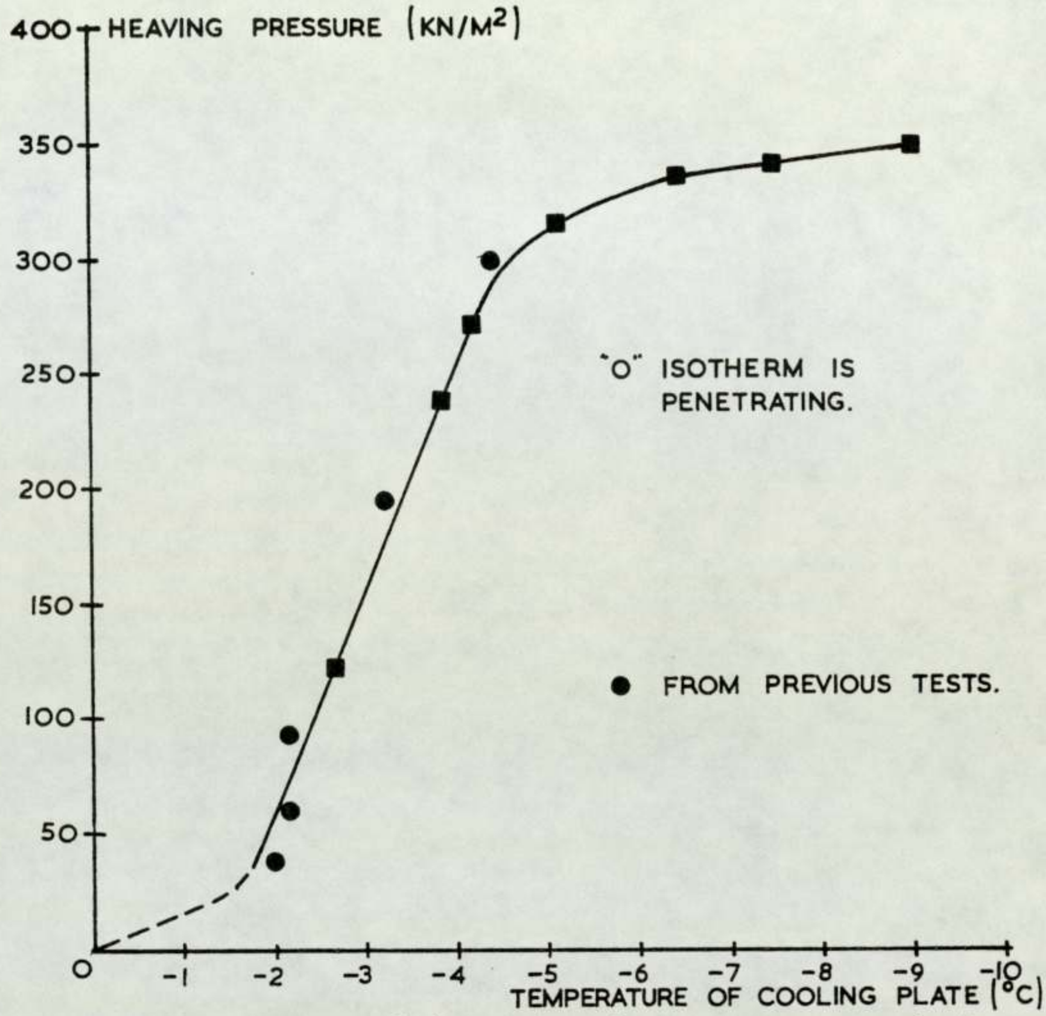


FIG. 7·8. Upper limit of heaving pressure against temperatures of the cooling plate.

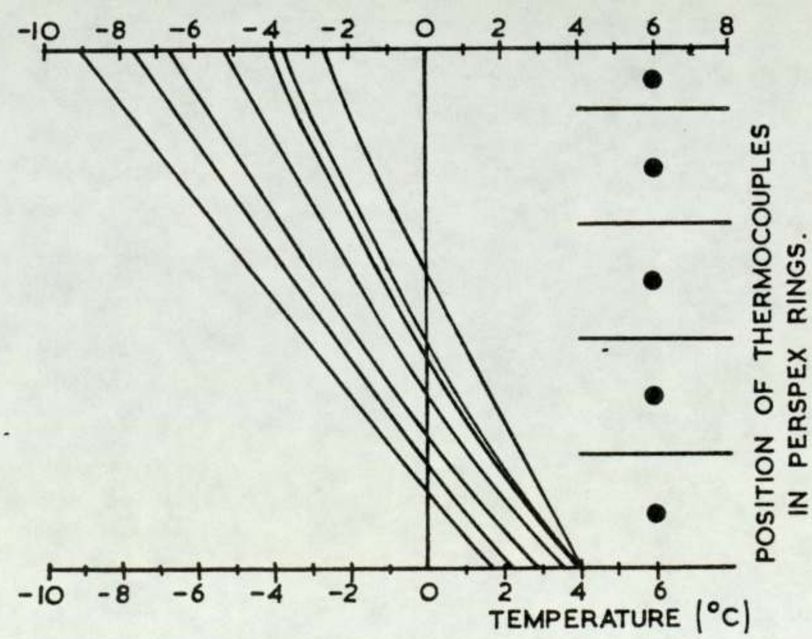


FIG. 7·9. Temperature gradient through the sample

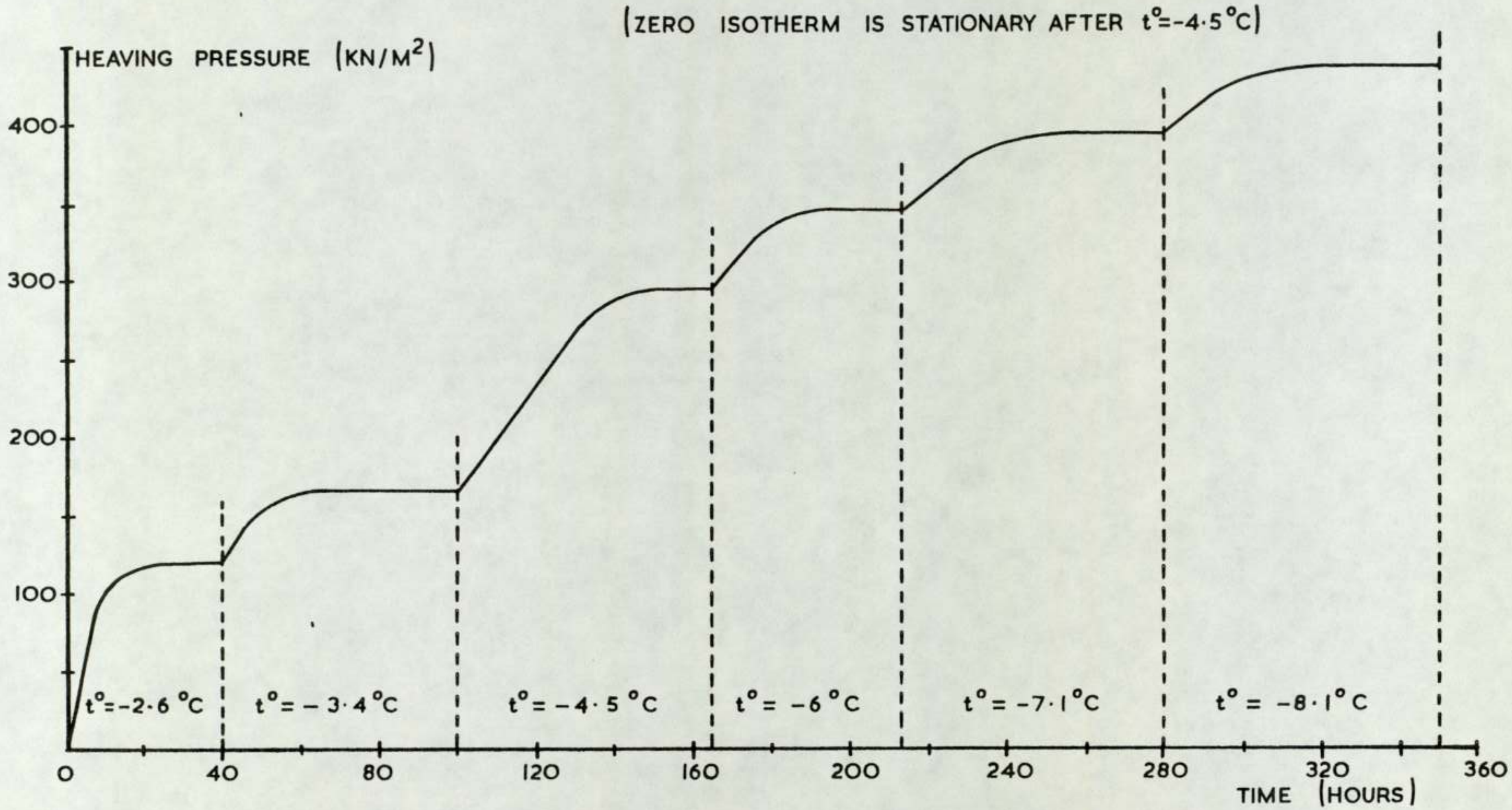


FIG. 7·10. Heaving pressure against time for different temperatures of the cooling plate.

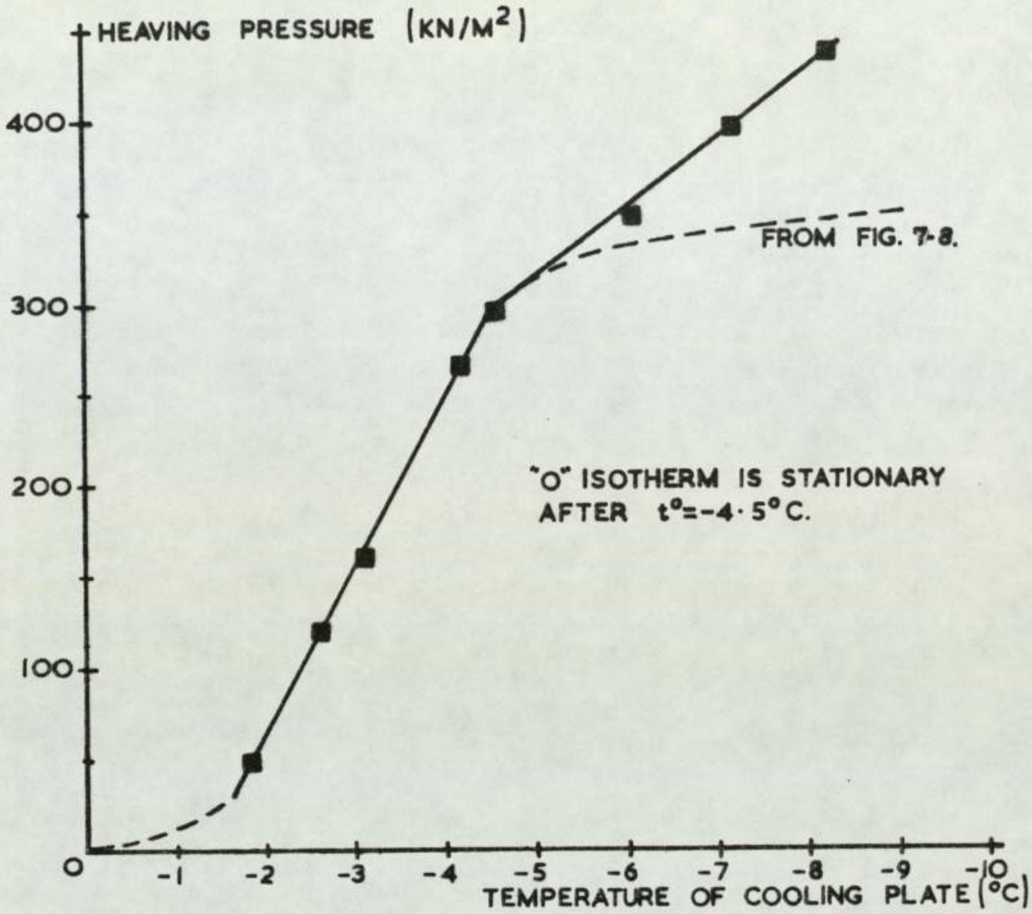


FIG. 7·11. Upper limit of heaving pressure against temperature of the cooling plate.

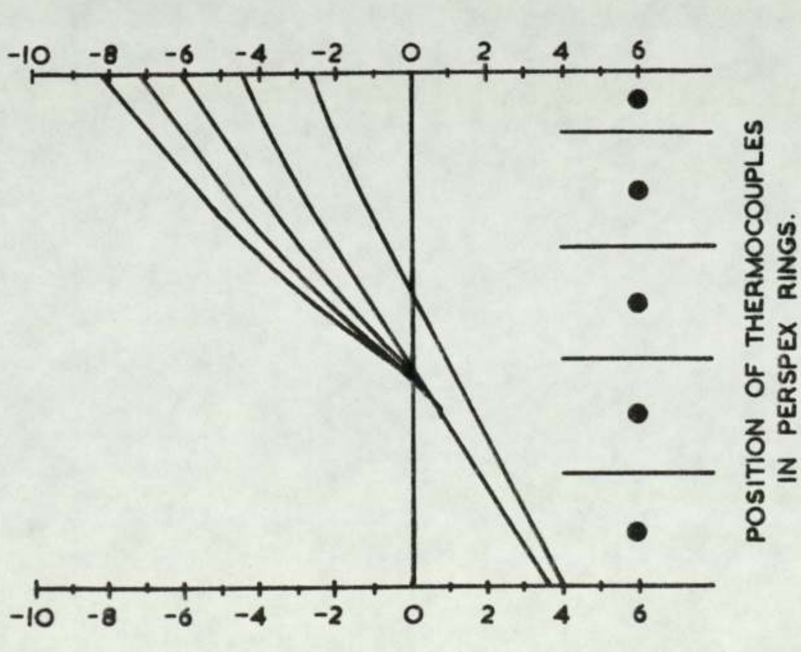


FIG. 7·12. Temperature gradient through the specimen.

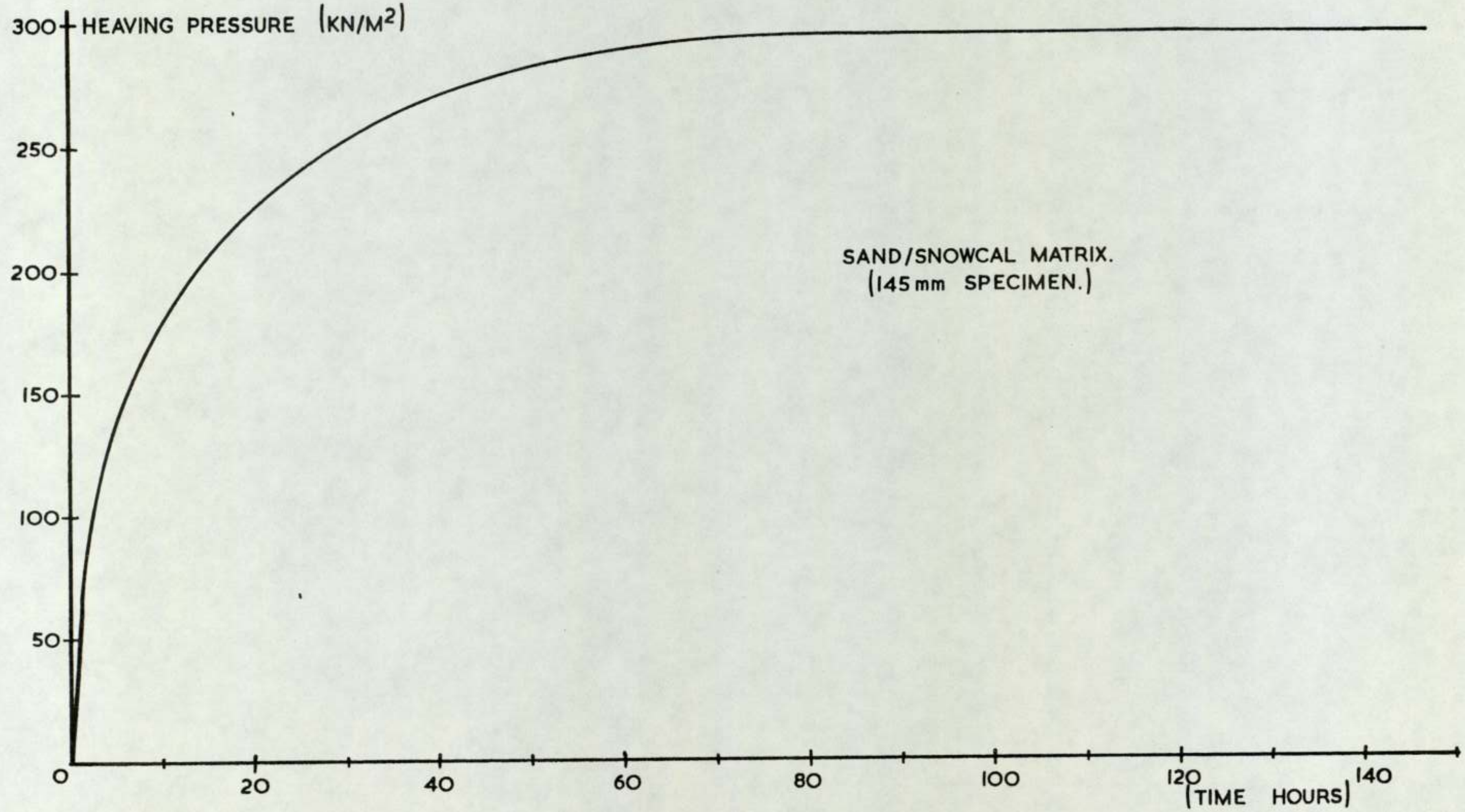


FIG. 7·13. Typical curve of heaving pressure against time.

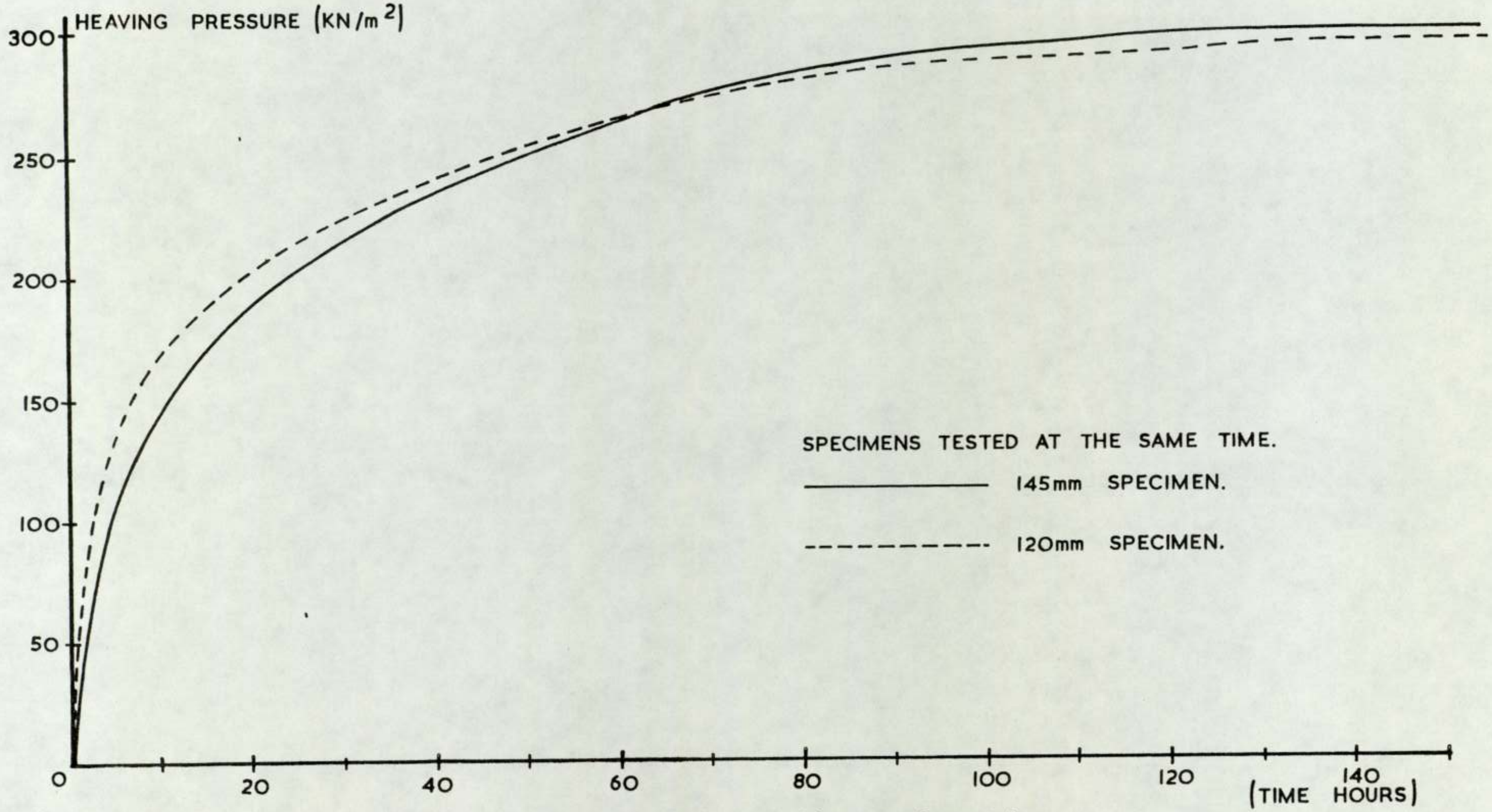


FIG. 7·14. Heaving pressure against time for sand/snowcal matrix.

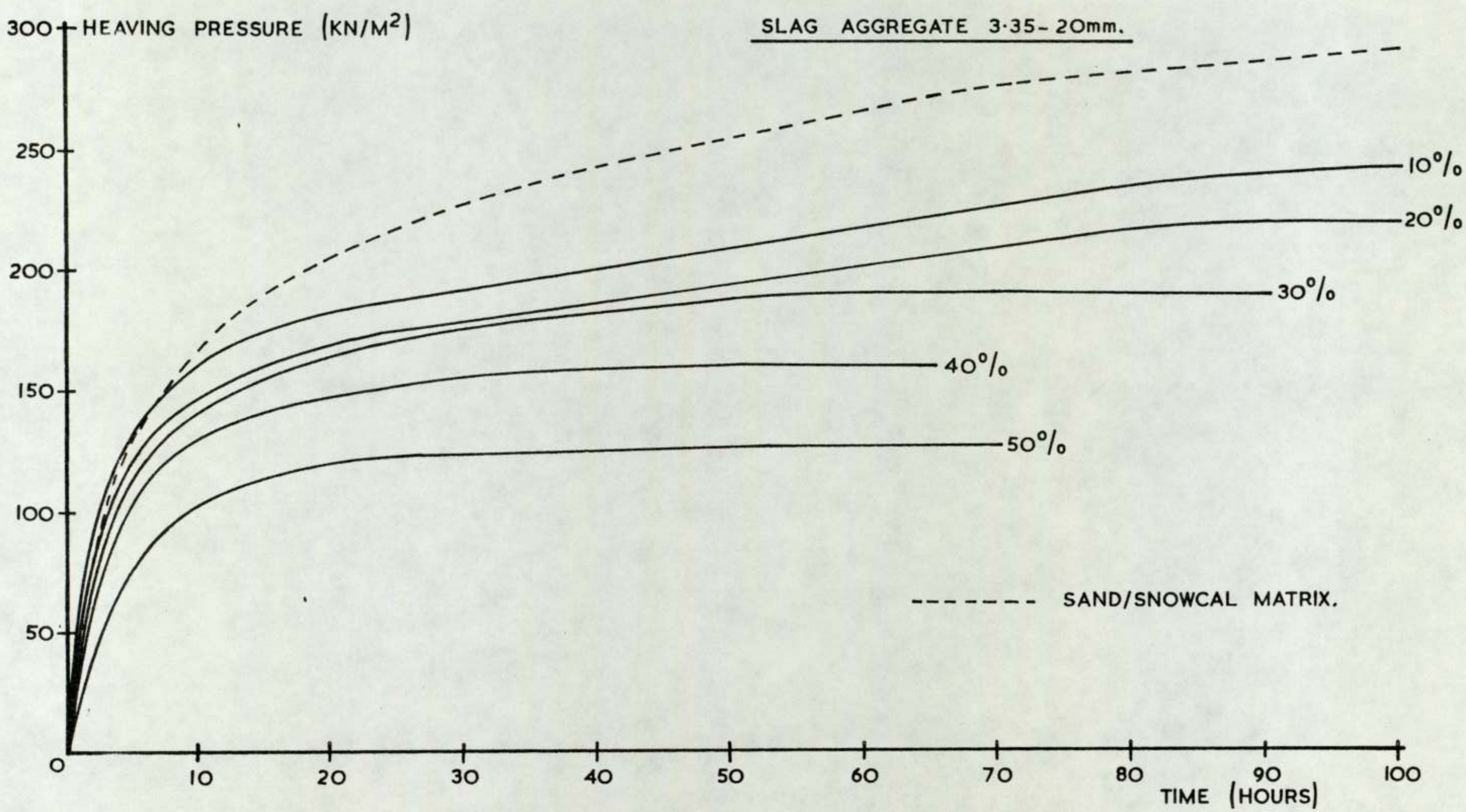


FIG. 7·15. Heaving pressure against time.

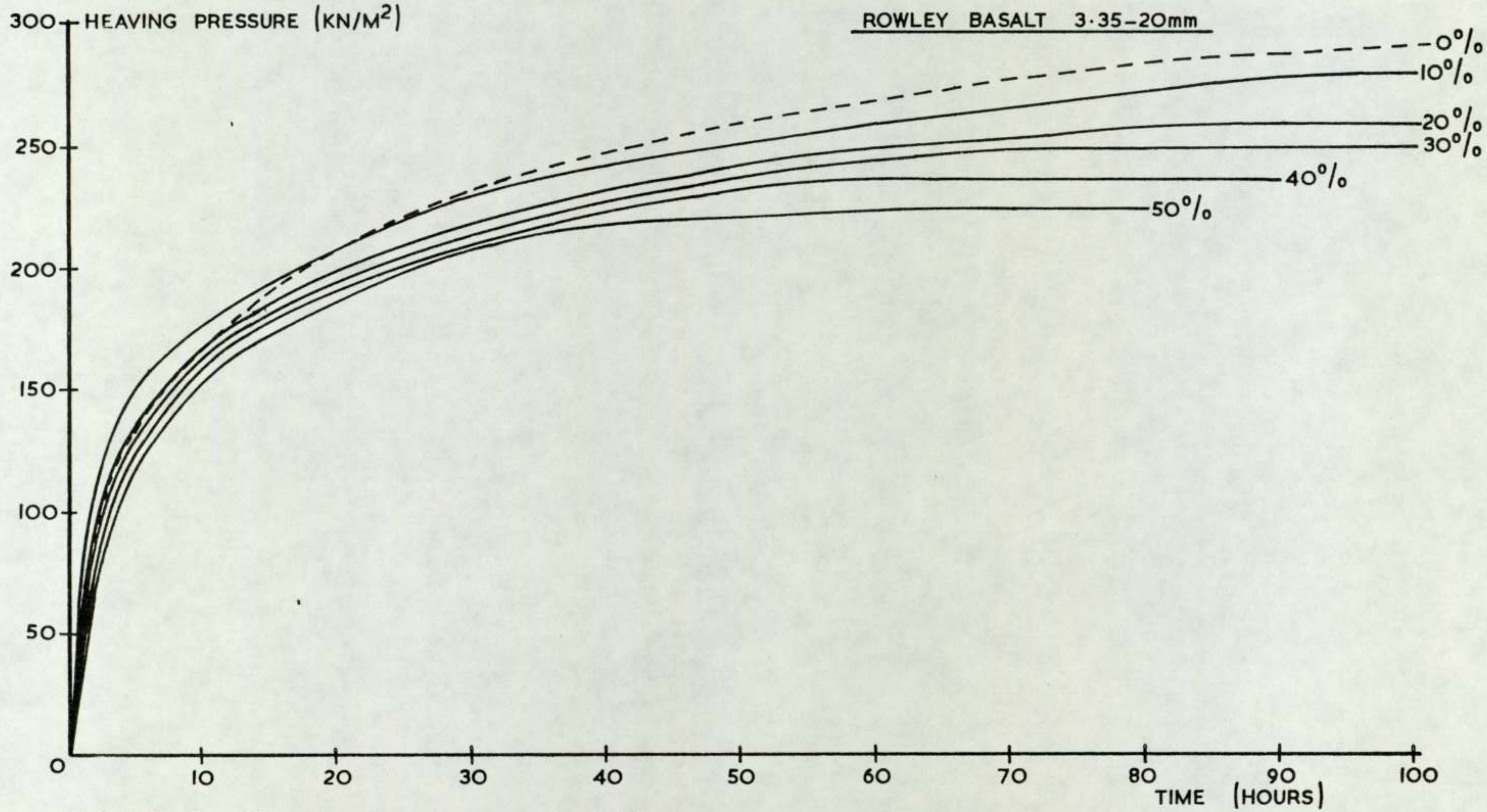


FIG. 7·16. Heaving pressure against time.

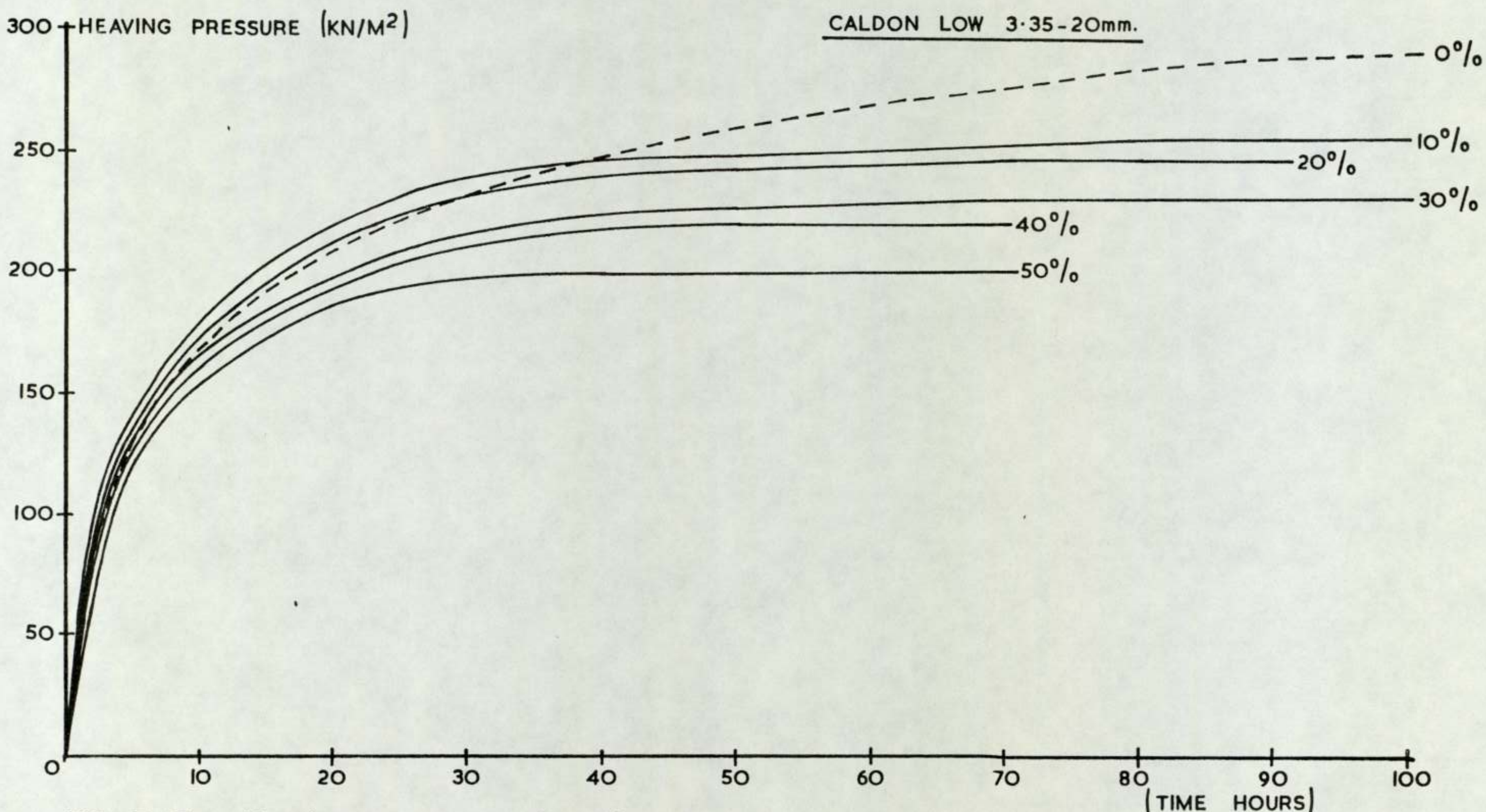


FIG. 7·17. Heaving pressure against time.

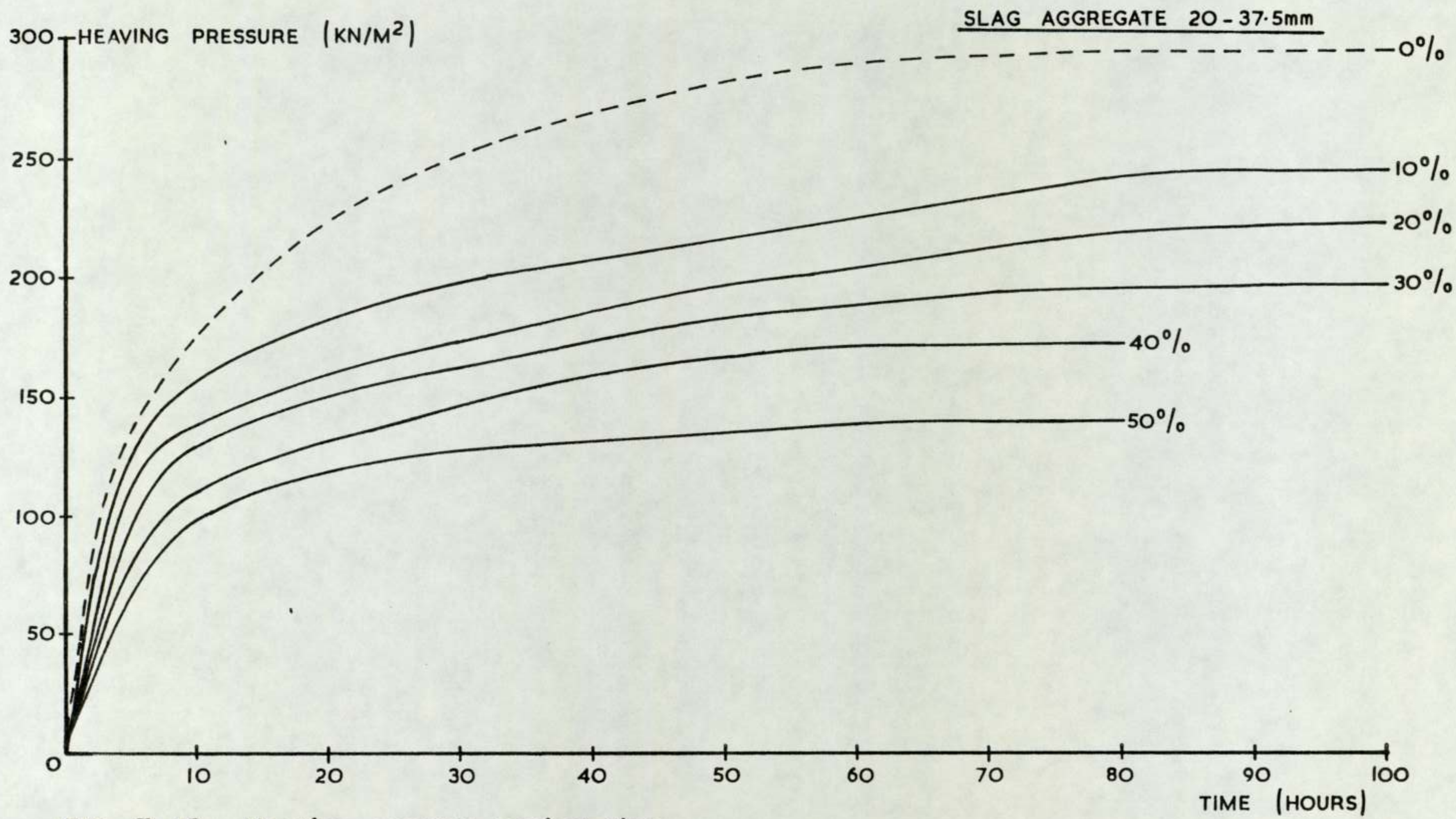


FIG. 7·18. Heaving pressure against time.

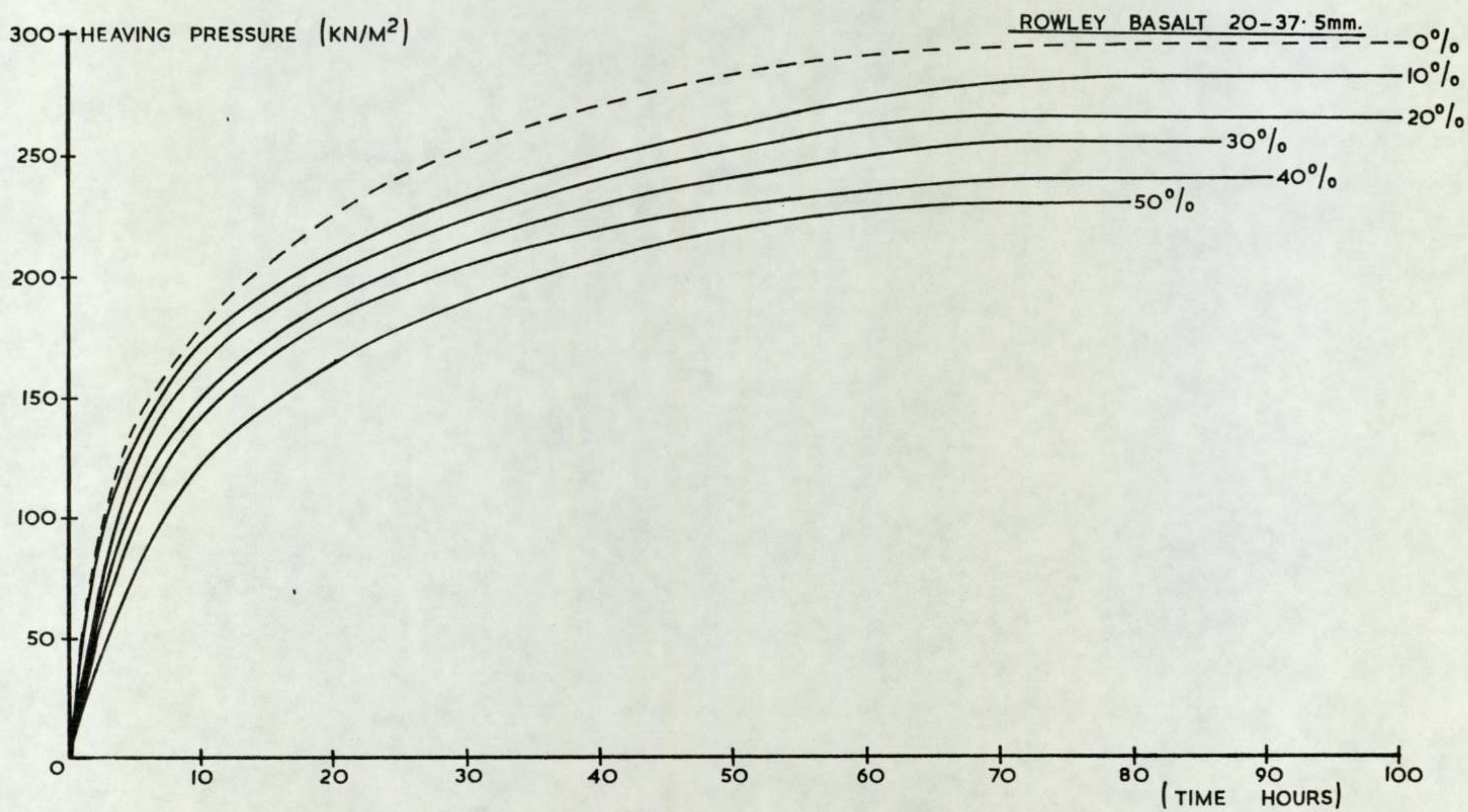


FIG. 7·19. Heaving pressure against time.

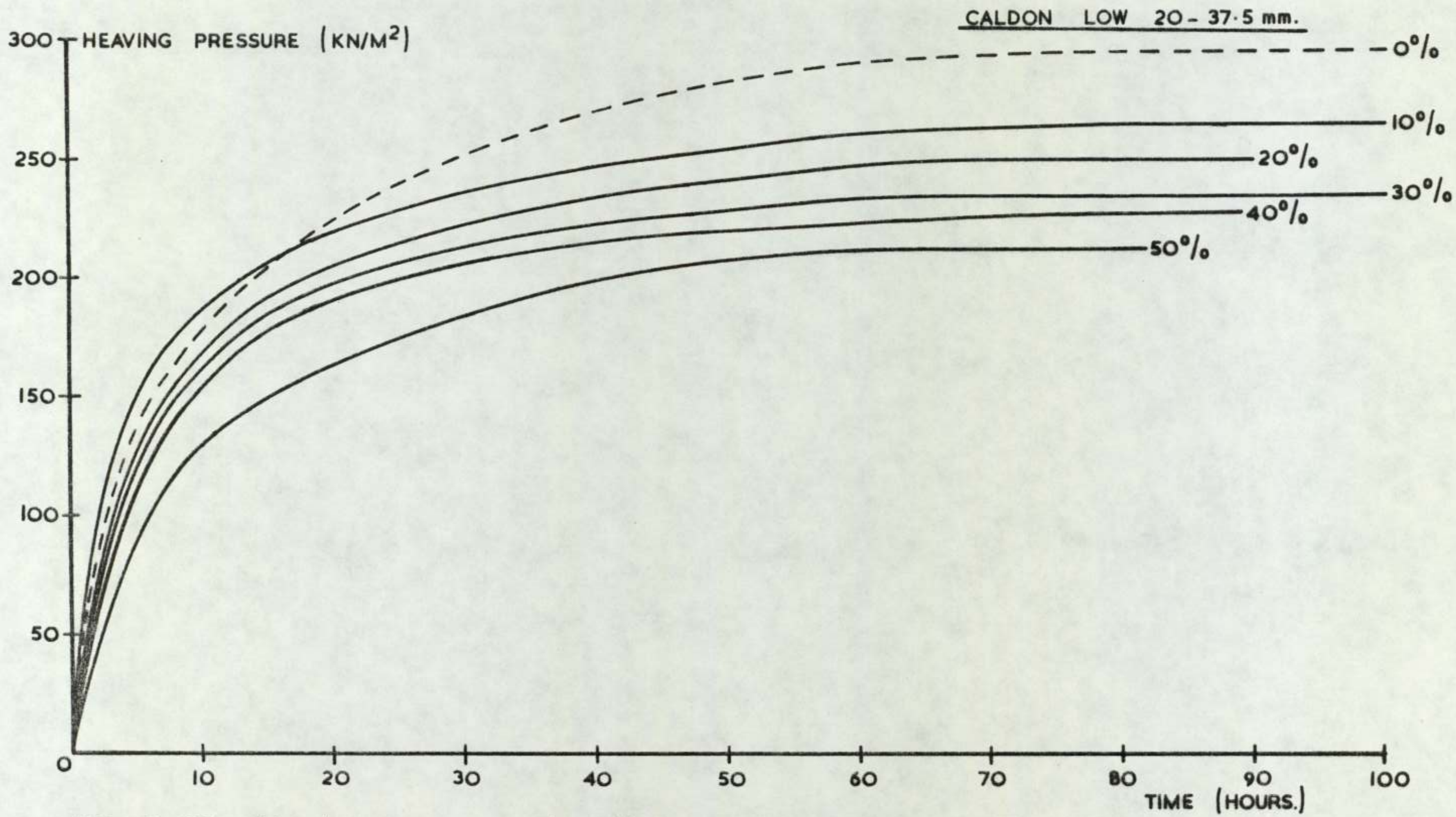


FIG. 7·20. Heaving pressure against time.

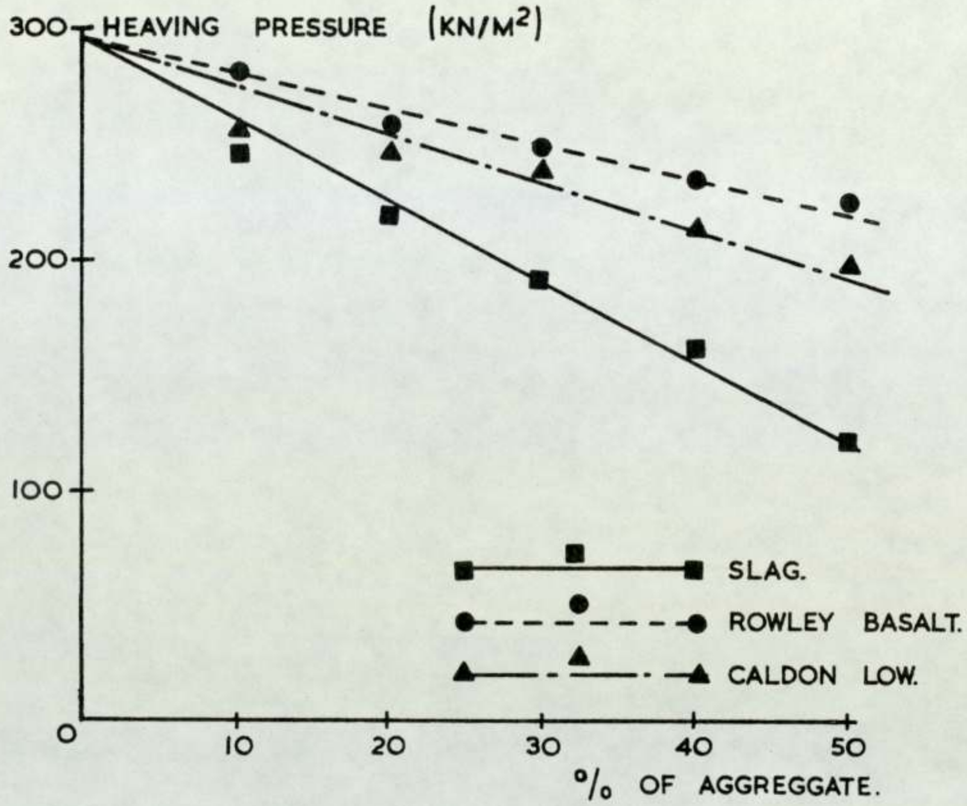


FIG. 7·21. Heaving pressure against percentage of aggregate 3·35–20mm.

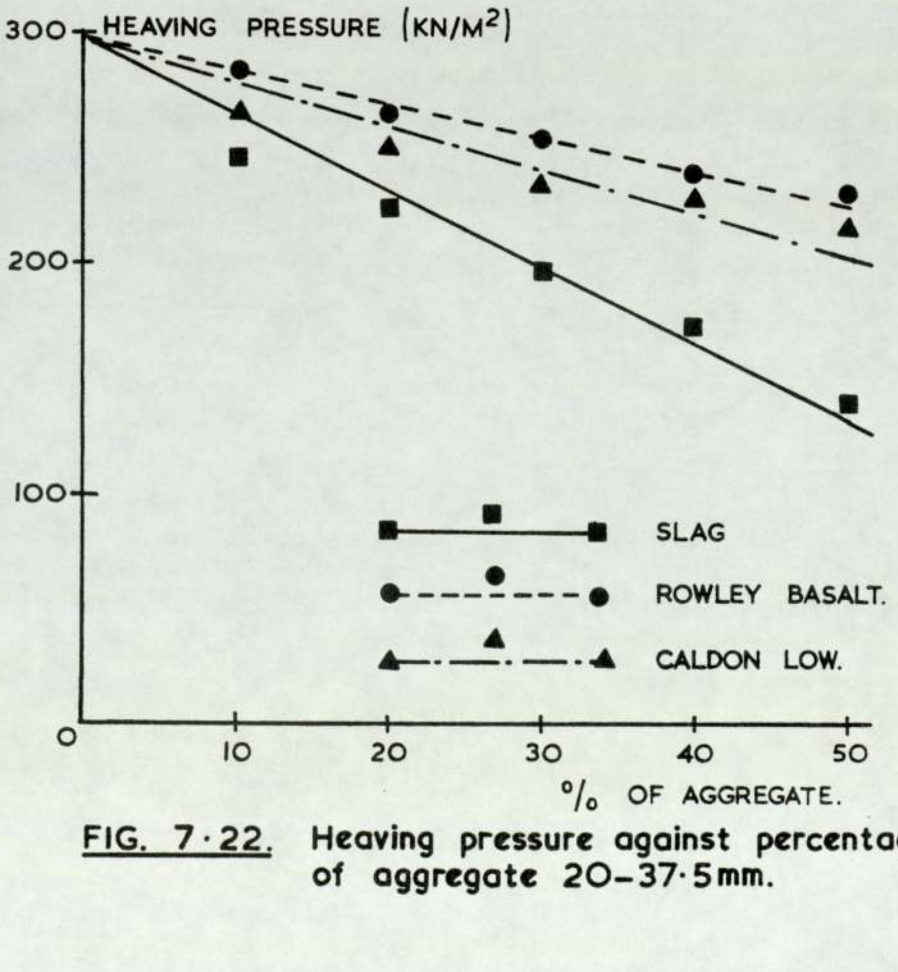


FIG. 7·22. Heaving pressure against percentage of aggregate 20–37·5mm.

CHAPTER VIII

CONTROLLED HEAVE TEST

8.1 Introduction

The frost susceptibility of a soil can be assessed either directly, by subjecting test samples to freezing, or indirectly, by considering other properties that are related to frost action, such as grain size etc. Although indirect methods have been used extensively, only freezing tests are currently considered to produce reliable assessments. Townsend and Csathy (63) found that grain size criteria were generally very successful in rejecting frost susceptible soils, but they frequently rejected non-frost susceptible soils, i.e. safe, but conservative. Unfortunately, many of the standard freezing tests (TRRL, CRREL etc) are time consuming with freezing periods in excess of 10 days. In addition, the reproductibility of the TRRL test is poor (81),(61). Therefore, the development of a rapid, accurate and economical method for assessing frost susceptibility has attracted a number of researchers, and some of these approaches, relating to heave tests, are reviewed in the following paragraphs. Other techniques have also been considered (58) as quick index tests for frost susceptibility and the measurement of heaving pressures have been considered in Chapter VII.

Considerable study (14),(111-115) was undertaken at University of New Hampshire during the period between 1965 and 1975. The object of the study was to develop a rapid freezing test that would produce data to correlate with the CRREL test, and so the work was very concentrated on the measurement of heaving rate rather than total heave. A block of rigid foamed plastic was used to insulate the specimen from room temperatures and it was frozen from the top using thermoelectric batteries. A multi-ring system was introduced (specimen mould consisted of seven rings) to reduce the effects of friction and adfreeze and higher heave rates were reported (111) with the multi-ring moulds than with tapered moulds. The testing time was reduced by adopting an increased rate of freezing. In addition, the specimen was frozen to a depth of 3 inches as compared with the 6 inches of frost penetration in specimens in the standard CRREL test (116). Although the heave rates measured in this rapid freezing test were much higher than those obtained from the CRREL standard test, the rapid freezing test was regarded as completely reliable for classification purposes.

The poor reproductivity of TRRL test has been of considerable concern for some time and, in order to achieve better control over the boundary conditions, a Precise Freezing Cell (PFC) was developed at the University of Nottingham (70),(117). The specimens were also frozen by means of Peltier battery but the preparation of the specimen and the test arrangement were close to that of the standard TRRL frost heave test (5).

The body of the cell was formed from thin PVC tubes with vermiculite insulation placed in the annulus between the tubes. The lower part of the inside tube was water tight and so provided a water bath. The specimen was positioned on a porous disc in a copper cup exactly as in TRRL test, and the porous stone was located in the surface of the water bath. The annular space between the specimen and the inner tube was filled with sand. A guard ring, containing a circulating refrigerant, was placed on top of the sand packing to prevent heat loss through the sand. The boundary conditions were similar to those in the TRRL test - +4.0^{o}C at bottom and -6^{o}C on the top of the specimen.

All heave was reported (70) to cease before 250 hours had elapsed. The tests were terminated when the heaving rate was less than 0.1mm/day and this resulted in test periods of less than 5 days for the tests reported by Dudek (70). The total heave was measured and much lower values were reported for tests in the PFC as compared with parallel tests undertaken in the SRU or cold room (70). It was suggested that such differences could be attributed to the faster rate of penetration of the zero isotherm in the PFC system, together with the manner in which the boundary conditions were applied. In the cold room and SRU, a high heaving specimen experiences considerable additional cooling through its side as it protrudes, but this is prevented in the PFC. Otherwise tight control was reported (70) over the specimen boundary conditions. The PFC was regarded as a reliable tool for modelling frost action but it was not studied as a system for assessing frost susceptibility.

8.2 Development of the equipment

8.2.1 Test rationale

The initial part of this project was concerned with standard frost heave testing, as reported in Chapter V and VI. It was, therefore, considered that the development of a rapid and controlled heave test would be useful for detailed study of the heave phenomena. Such a test could also be used to examine the possibility of assessing frost susceptibility in a shorter test period than that of the TRRL test. The following conditions were, therefore, considered as necessary so that the results could be related to the TRRL criteria (5):-

1) the specimens should be made in exactly the same way as for the TRRL test
2) the conditioning time should remain the same at 24 hours
3) the boundary conditions and the temperature gradient through the specimen should be as close as possible to those achieved in the TRRL test
4) the method of support for the specimen in the water bath

should be as in the TRRL test

5) the insulation around the specimen should be adequate to limit heat losses from the specimen sides and to produce unidirectional heat flow.

8.2.2 Test arrangement

The layout of the apparatus is shown in Figure 8.1 and various components are described in the following paragraphs. A standard frost heave specimen was produced as described in section 5.2.2. The specimen was wrapped in waterproof paper and placed on a 120mm diameter porous stone which was situated in a copper specimen carrier. This carrier is larger than that used in the standard frost heave test since it was decided to replace the waterproof wrapping paper with a multi-ring system. Zoller (114),(115) clearly demonstrated that such systems produce improved results in heaving tests and similar effects were observed in the heaving pressure tests reported in Chapter VII.

The waterproof paper was removed from the specimen and replaced by a system of seven Tufnol rings which were slid over the specimen. The internal diameter of the rings was 102.5mm so that there was a sliding fit with the specimen. The rings also provided limited insulation between the specimen and the copper carrier so that the radial heat flow at the base of the specimen was different (70) from that in the standard test.

The copper carrier, complete with specimen, was transferred to a water bath located in a refrigerator running at $+4.0\pm0.5^{\circ}C$. To minimise temperature variation the water bath was connected, via a circulating pump, with a relatively large reservoir which also served to maintain the water level in the water bath. The total volume of water was approximately 25 litres and the temperature was controlled by a mercury contact thermometer placed in the water bath which was preset to +4.0°C.

A 10cm thick block of expanded polystyrene was used to provide insulation around the specimen and it was protected from damage by a plywood casing. In the frost heave test the specimen, whether in a cold room trolley or an SRU, is situated in a regime cooled to -17°C, whereas, in this test, the temperature within the refrigerator is +4.0°C. In the cold room tests, reported in Chapter V, it was demonstrated that the normal gravel fill will conduct heat away from the specimen and so, to minimise the external heat losses, the expanded polystyrene was employed. In addition, the use of closely packed gravel in the relatively small annulus around the specimens could create side friction which would limit the recorded heave. The clearance between the polystyrene block and the specimen prevented direct contact across the interface and so the only support to the free-standing specimen was from the rings.

The specimen was left for 24 hours to condition as in the TRRL frost heave test. An aluminium plate, 10mm thick, was positioned on top of the specimen to provide a good thermal contact direct between the specimen and the cooling equipment. Two separate facilities were available to freeze the specimens and they were:-

a) thermoelectric device (TED)

b) cryostat.

The initial series of tests was undertaken using the TED but, in view of the unreliability of the associated temperature controller, it was replaced with the cryostat system. As previously described in Chapter VII, this had proved to be very reliable with temperature variations within ±0.1°C.

Throughout the freezing period, the heave was monitored using a linear potentiometer connected to a chart recorder. The test was generally continued until a maximum heave was obtained.

8.3 Influences on the test

It was considered that several experimental factors could influence the magnitude of the recorded heave and so, their effects were studied by a series of tests performed on specimens of the sand/snowcal matrix. The factors investigated were as follows:-

a) boundary conditions/temperatures

b) rate of freezing

c) duration of the test

d) friction and adfreeze.

8.3.1 Temperature of the cooling plate

This series of tests was undertaken with the cooling plate maintained at a different temperature for each test. The specimens were prepared and conditioned as described in 8.2.2. The cryostat was preset at the required temperature and, when it was switched on, the required top temperature was achieved within 30 minutes. Throughout all these tests the temperature of the water bath was kept at $+4.0^{o}C$. The results of these tests are summarised in Figure 8.2 and are referred to as line (a). It is clear that the frost heave, recorded in the CHU, is linearly related to the temperature of the cooling plate within the test range of $-1^{o}C$ to $-13^{o}C$. This is confirmed by a statistical analysis. This revealed a coefficient of correlation, $r = 0.999$ which demonstrates a highly significant relationship between heave and temperature of the cooling plate.

The temperature of the cooling plate largely dictates the rate at which heat is extracted from a soil. Experimental studies (107),(108) have demonstrated that the rate of heave of an unloaded soil depends on the net rate of heat extraction from the soil. Therefore, with a reducing top temperature and, hence, an increased rate of heat removal, the rate of heave and so total heave will increase. It was pointed out that a maximum heat rate existed at a particular value of heat extraction. These experiments were carried out on fine-grained soils with a wide range of values of heat extraction. In this study, a narrower range of heat extraction was investigated and so the optimum value was not achieved.

8.3.2 Temperature of the water bath

The test programme described in the previous section was repeated, but with the temperature of the water bath raised from $+4.0^{o}C$ to $+5.5^{o}C$. The temperatures of the cooling plate were kept as close as possible to those reported in 8.3.1 and the results are summarised in Figure 8.2 as line (b). The relationship between heave and temperature of the cooling plate is again linear with a coefficient of correlation $r = 0.92$. This again demonstrates a highly significant relationship between the two parameters.

A comparison, however, between the two sets of results in Figure 8.2, shows that, for a given top temperature, a lower heave is recorded at the higher water bath temperature. Similar behaviour was reported with the frost heave tests described in section 5.3.2 and it was attributed to a rise in the location of the zero isotherm and a decrease in the magnitude of the induced suction. It is apparent that, in order to maintain a constant heave, an increase in the water bath temperature would have to be accompanied by a decrease in the top temperature. This implies that as the heat input at the base of the specimen is increased, an increase must also be made in the rate of heat extraction to produce a constant heave. The relative changes in temperature could be indicative of the respective thermal conductivities through the unfrozen and frozen zones.

It was not possible to undertake similar tests at water bath temperatures below +4.0^{o}C since a suitable temperature control system was not available.

8.3.3 Temperature gradient

The tests reported in the previous sections clearly demonstrated the influence of the boundary temperatures on the heave. It was, therefore considered that it would be useful to study the relationship between heave and the temperature gradient, particularly with reference to the location of the zero isotherm.

Initially, the temperature gradient was determined through a specimen subjected to the same boundary conditions as a frost heave specimen (top, -6.2^{o}C, bottom, +4.0^{o}C). Thermocouples fixed in and around a specimen of cement stabilised matrix were used for this study. This specimen had previously been used, as described in Chapter V, to obtain the temperature distribution through specimens in the standard frost heave test. The temperature data is summarised in Figures 8.3 and 8.4. The corresponding values determined in the standard frost heave test are included for comparison.

It is clear from the temperature gradients, shown in Figure 8.3, that the position of the zero isotherm is higher in the specimen in the CHU than in the standard frost heave specimen. This is in spite of the fact that the boundary temperatures were identical for both arrangements. It is suggested that the difference in location of the zero isotherm may be due to additional heat extraction through the sides of the specimen in the standard frost heave test. As shown in Figure 8.4 the temperature recorded at the outer edge of the cold room specimen is lower than the corresponding temperature at the centre of the specimen. However, the position is reversed in the CHU specimen with the outer face being relatively warmer than the centre. Indeed the similarity of the centre and edge temperatures, in the CHU specimen, indicates that the test procedure more closely achieved unidirectional freezing than in the standard frost heave test.

The temperature distribution was also measured in the CHU with the sand/snowcal specimen. Thermocouples were inserted through the centre of each ring and the temperature readings were taken each day throughout the test period of 150 hours. The final position of temperature gradient is shown in Figure 8.3 and corresponds with a frost heave of about 20mm. This also shows that the position of the zero isotherm was higher in the CHU specimen than in the standard frost heave specimen.

It was reported (70),(117) in cold room test that, when a specimen is heaving and protruding through the packing the boundary conditions are changed as the temperature on the top of the specimen does not remain at $-6.2^{o}C$ throughout the test. During the cold room programme, the temperature at the top of the heaving specimens was observed to fall to $-7.0^{o}C/-7.8^{o}C$ after some 150 to 200 hours of the test. As the specimens heave and protrude through the insulation, additional heat will be extracted through the protruding sides. This is in addition to the cooling from the insulation which indicated by the temperature profiles shown in Figure 8.4 for the cold room specimens. In the cold room, the specimens experience much additional cooling, whereas the CHU specimen experiences only limited cooling from the sides whilst the top temperature is constant at $-6.2^{o}C$. These differences account for the reduced penetration of the zero isotherm in the CHU specimen.

An analysis of the data in Figure 8.2 indicated that similar frost heaves were recorded with different boundary temperatures, providing that the location of the zero isotherm was constant. This also demonstrated that as the location of the zero isotherm was lowered, there was an increase in heave. It, therefore, seemed appropriate that, for the assessment of frost susceptibility it is important to specify the position of the zero isotherm in the specimen as well as the boundary conditions.

The location of the zero isotherm in the CHU specimen depends on the top temperature. A series of tests was undertaken in which a different top temperature was selected for each test. Measurements were made of the top temperature, heave and depth of the unfrozen zone at the completion of the test. The results are given in Table 8.1.

Temperature of the cooling plate (^{o}C)	Heave (mm)	Unfrozen zone (mm)
-5.5	14.5	95
-6.2	17.0	75
-6.5	22.5	70
-7.0	24.6	62

TABLE 8.1 Frost heave at different temperatures of the cooling plate

It can be seen that, with a top temperature of $-7.0^{o}C$, the measured heave and the depth of the unfrozen zone (i.e. final location of zero isotherm) are very similar to those observed in the standard frost heave test. It was decided to adopt modified boundary conditions in the subsequent testing programme so that the location of the zero isotherm was similar to that in specimens in the cold room.

Accordingly, a top temperature of $-7.0^{o}C \pm 0.1^{o}C$ was selected with the temperature of the water bath remaining at $+4.0 \pm 0.5^{o}C$. The temperature gradient, determined through a cement stabilised specimen under these conditions is shown in Figure 8.5 and this compares closely with that obtained from cold room testing.

8.3.4 Friction and adfreeze

It is shown in Chapter VII that friction and adfreeze could significantly influence the measured heaving pressures, with the multi-ring system and rubber membrane producing an increase of some 200 percent in the measured pressures. In this testing programme with the CHU no adfreeze effect was observed, mainly due to the clearance between specimen and the insulation. At the completion of the test, the rings were uniformly spaced with clear gaps between each pair, again demonstrating the friction had largely been eliminated. As a further check, it was decided to perform some tests with the rings replaced by waterproof paper, as in the cold room tests. The results are given in Table 8.2 and they are very similar.

Means of specimen support	No tested	Heave (mm)	Standard deviation (mm)
Rings	5	25.14	1.2
Paper	4	24.80	0.9

TABLE 8.2 Frost heave for specimens tested in rings and paper

However, at the completion of the test, the situation of wrapping paper was of particular interest. The paper was not frozen to the CHU specimen and could be easily unwrapped and removed. On the contrary, with the cold room specimens the paper was solidly frozen to the sample and, usually, had to be torn away to permit removal of the specimen.

From Figure 8.4, it can be seen that the outer face of a cold room specimen is colder than the centre. This implies that a lateral heat flow occurs in these specimens, and this would be accompanied by lateral moisture movement and ice growth. Such movements would cause the specimen to swell laterally. This movement would be resisted by the wrapping paper and so adfreeze and frictional resistance would be developed at the interface between the specimen and the paper. Indeed, in some cold room specimens clear ice could be observed in the gap between the specimen and the paper.

With the CHU specimen, it is clear from Figure 8.4 that the outer face is slightly warmer than the centre. Thus, such lateral heat flow will be restricted. The specimen and paper did not become frozen together and so no adfreeze or frictional effects were developed between the specimen and the paper in the CHU system. Thus, the frost heave values obtained from the tests with paper and those with the multi-rings are very similar and were not found significantly different at the 5 percent level.

In view of the similarity between the two sets of results, it was decided to support the specimens with paper in the subsequent tests. Indeed, the frost heave of the specimens wrapped in paper is closer to the value obtained in the cold room, than the value obtained with the multi-ring support. Thus, the use of paper should give results that are likely to correlate with TRRL criteria for judging frost susceptibility.

8.3.5 Rate of freezing

In his work, Zoller noted (115) that the rate of frost penetration had a significant effect on the total frost heave. When the freezing front is penetrating at a slow rate, thicker lenses can be formed as more time is available for water to move to the ice lenses. The heave rate is influenced by the rate of heat removal (24) which is largely controlled by the surface temperature (118). When the surface temperature is lowered slowly and gradually over a considerable length of time, the total frost heave should be greater, than when the required surface temperature is attained rapidly at the beginning of the freezing period, always assuming that both final top temperatures are the same. The total heave will, therefore, depend on the rate of heave and the time during which heaving occurs.

In order to examine this behaviour, specimens of the sand/snowcal matrix were subjected to two different freezing regimes which would simulate rapid freezing and slow freezing. The rapid freezing followed the normal test procedure with the cooling plate operating at -7.0°C throughout the test. Slow freezing was achieved by initially operating the cooling plate at -1.0°C and, subsequently, reducing its temperature by 1°C every 24 hours until the normal testing temperature of -7.0°C was achieved, some 140 hours after the start of the test. The zero isotherm reached the same terminal location as in the normal test (i.e. rapid freezing). Freezing was continued for a further 200 hours, producing a total test period of up to 350 hours, compared with the 100 to 120 hours for normal testing in the CHU system. The results are shown in Figure 8.6 and clearly indicate the importance of the rate of freezing on the recorded heave. Very slow freezing produced a total heave of 45.8mm which is much higher than that determined in the cold room. The penetration of zero isotherm is shown in Figure 8.7. It can be seen that the zero isotherm with slow freezing reached its terminal position after some 140 hours of freezing compared with only 20 hours in rapid freezing and 70 hours in the cold room. On Plate 8.1 the specimen after slow freezing is shown at the end of the test compared with cement stabilised specimen and it is clear that slow freezing has produced thicker ice lenses throughout the frozen zone. Each lens corresponds to the daily change of $1^{o}C$ in the temperature of the cooling plate.

As the rate of frost penetration depends on the thermal characteristics of each soil (24), it was considered (107) appropriate to apply a single rate of heat extraction to all the soils tested. Thus, for all the future tests, a top temperature of $-7.0^{o}C$ was applied to the top of the specimen at the completion of the 24 hours conditioning period.

8.3.6 Duration of the test and definition of maximum frost heave

Each test was continued until a maximum frost heave was achieved. This maximum frost heave was regarded as the heave at which the rate of increase is less than 0.1mm in 24 hours. Some tests were performed for much longer periods to assess the reliability of this criterion for maximum heave. No significant change in heave value was noted even when freezing was continued for an additional 100-120 hours. This criteria was, therefore, regarded as reliable and, for the sand/snowcal matrix, the test was completed after 100-120 hours of testing.

8.4 Results of the tests

At the completion of the preliminary testing, the test requirements were adjusted to produce a standard and reliable procedure for subsequent testing. It was decided to perform the test in the following manner:-

1) Specimen prepared following procedure for the standard frost heave test.
2) Specimen wrapped in waterproof paper, placed in the copper carrier and transferred to the Controlled Heave Unit (CHU) located in a refrigerator running at $+4.0\pm0.5^{\circ}C$.
3) The water pump and contact thermometer are switched on and the specimen is left to condition for 24 hours.
4) At the completion of this period the cryostat cap is positioned on top of the specimen, and the potentiometer is adjusted.
5) The cryostat, potentiometer and chart recorder are switched.
6) Test continued until the maximum heave is obtained.

The scope of this study was limited by time and so it was decided to test only selected materials. These were the matrix and aggregate/ matrix mixtures containing 10, 30 and 50 percent of coarse aggregate. All three aggregate types - Slag, Basalt, Limestone - were used but only particles in the 20 - 3.35mm sub-group were tested. The large particles were not used, as they had not previously shown any unique influence on frost heave. In addition, such testing would have required extensive modifications to the CHU facilities to accomodate the larger specimens required for the 37.5 - 20mm particles.

The results are collected in Table 8.3 and typical heave-freezing time relationships are shown in Figures 8.8 to 8.10. All the values given in Table 8.3 are the mean of at least two individual determinations.

Material	Heave (mm)	
	CHU	Cold room
sand/snowcal	24.8	24.4
10% slag	18.2	18.9
30% slag	16.5	16.0
50% slag	8.3	9.0
10% basalt	19.0	19.5
30% basalt	17.2	16.4
50% basalt	12.5	11.6
10% limestone	19.5	18.4
30% limestone	16.3	15.2
50% limestone	14.3	13.6

TABLE 8.3 Frost heave values for selected materials tested in CHU, compared with cold room results.

The results in Table 8.3 clearly demonstrate that the frost heave values obtained in CHU are very close to those obtained in the cold room tests. However, overall they are slightly higher than the cold room results, but this is within experimental error acceptable for the test. It is, therefore, possible to conclude that the CHU test is reliable and shorter in testing time than the standard TRRL test. It provides data suitable for assessment of frost susceptibility of granular materials based on TRRL criteria.

CONTROLLED HEAVE UNIT (CHU)

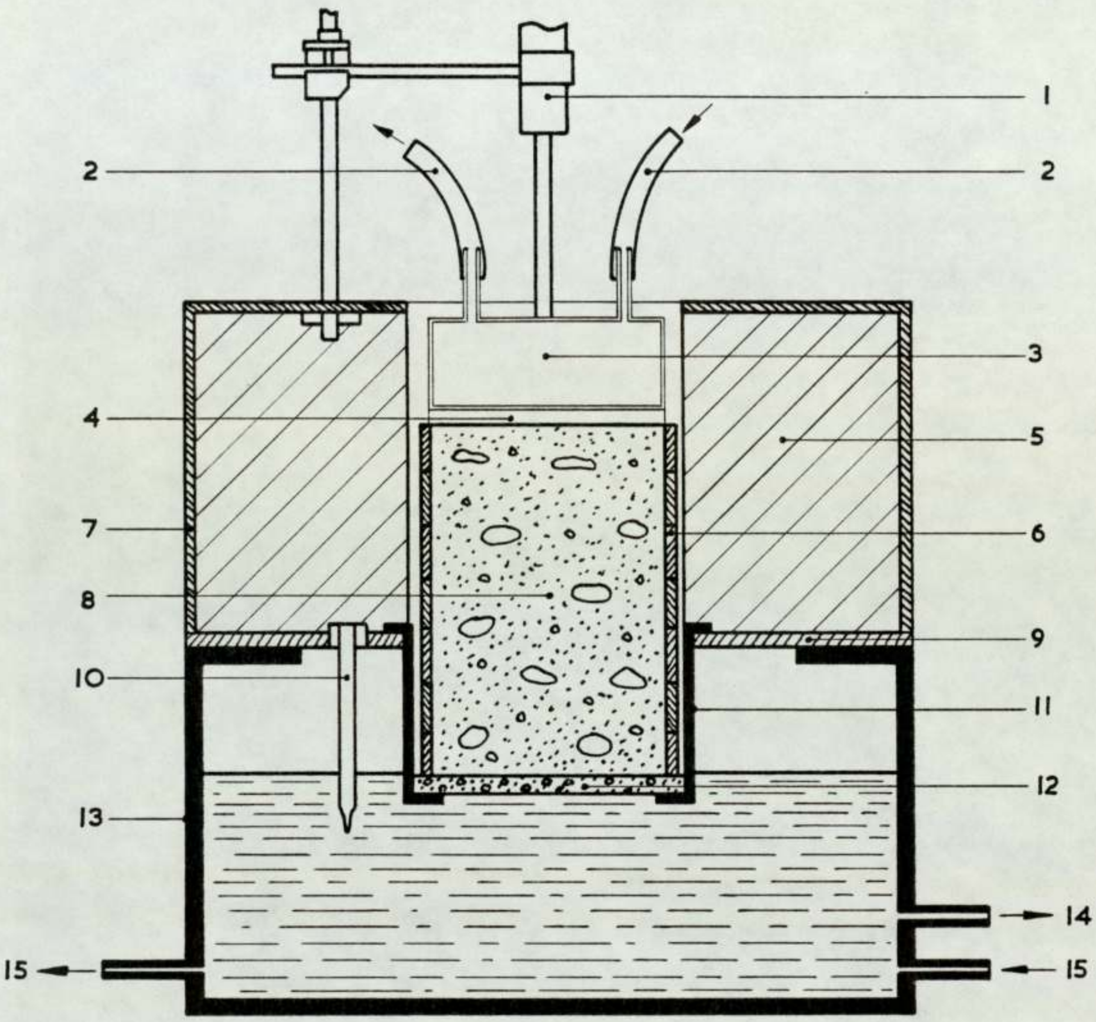


FIG. 8.1.

1 – POTENTIOMETER
2 – TO AND FROM CRYOSTAT
3 – COOLING PLATE
4 – HEUMINIUM PLATE
5 – EXPANDED POLYSTYRENE
6 – TUFNOL RINGS OR WATER-PROOF PAPER
7 – PLYWOOD CASING
8 – SOIL SAMPLE
9 – WOODEN PLATE
10 – CONTACT THERMOMETER
11 – COPPER CARRIER
12 – POROUS STONE
13 – WATER BATH
14 – WATER SUPPLY
15 – TO AND FROM CIRCULATING PUMP

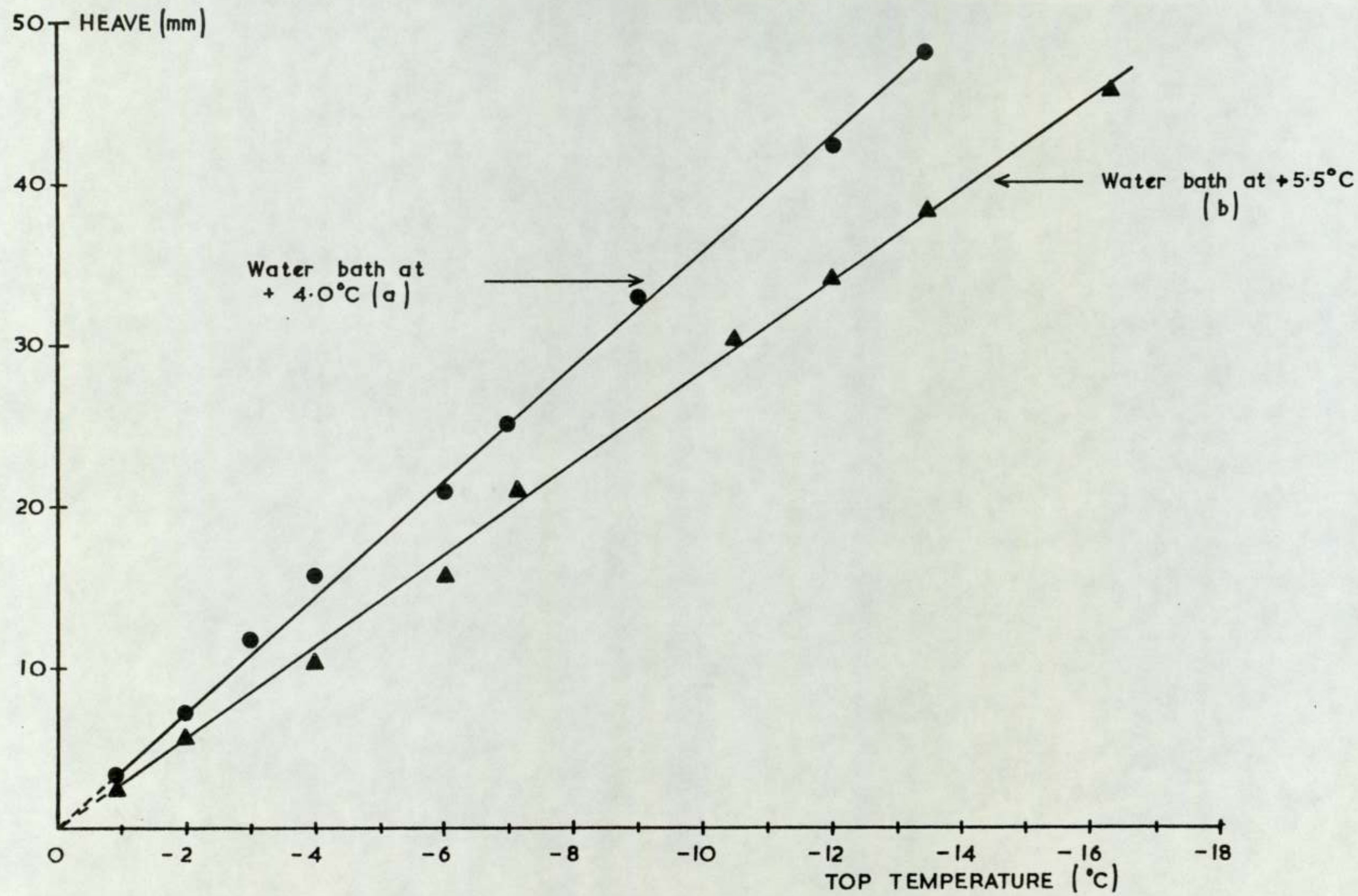


FIG. 8.2. FROST HEAVE AGAINST TEMPERATURE OF THE COOLING PLATE.

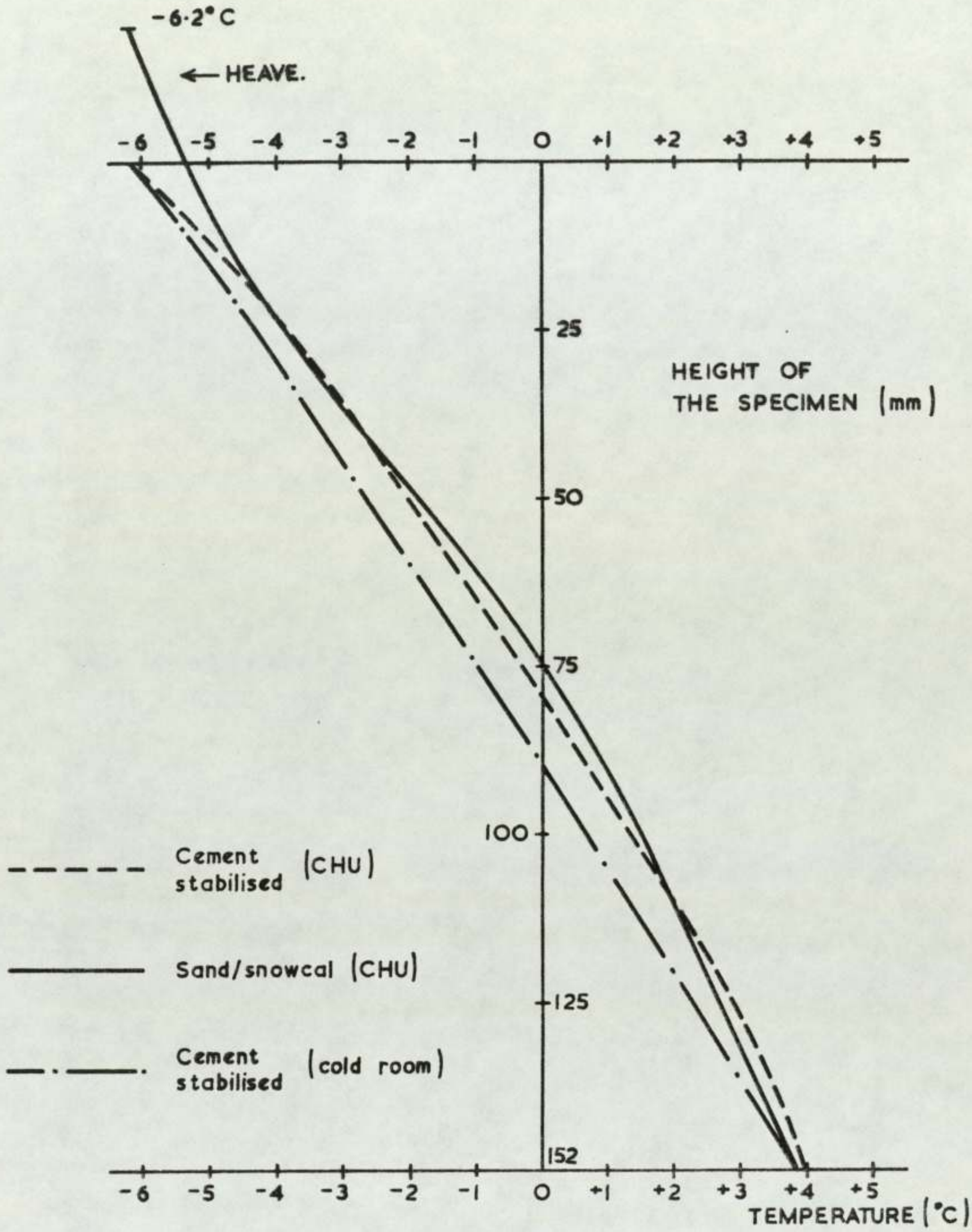
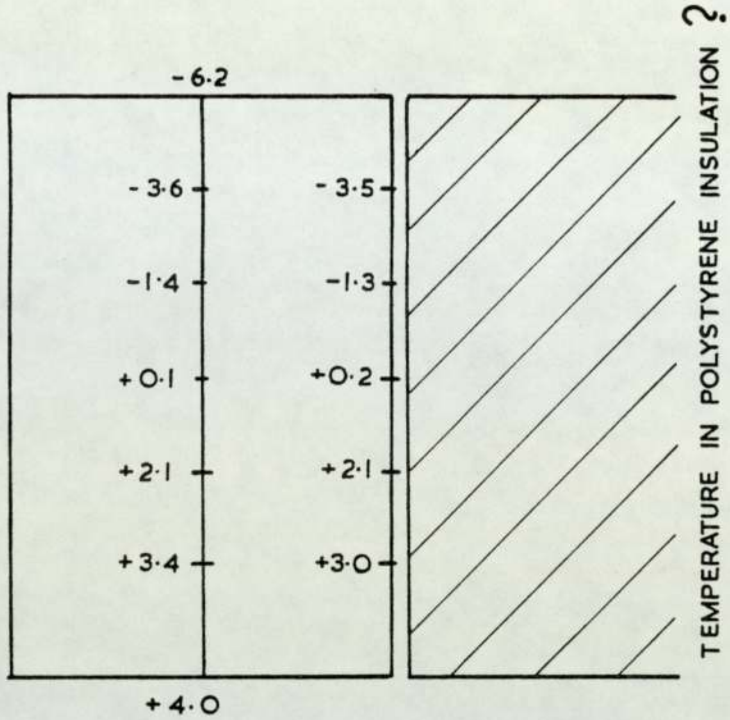


FIG. 8.3. TEMPERATURE GRADIENT THROUGH THE SPECIMEN

a) CHU



b) Cold room

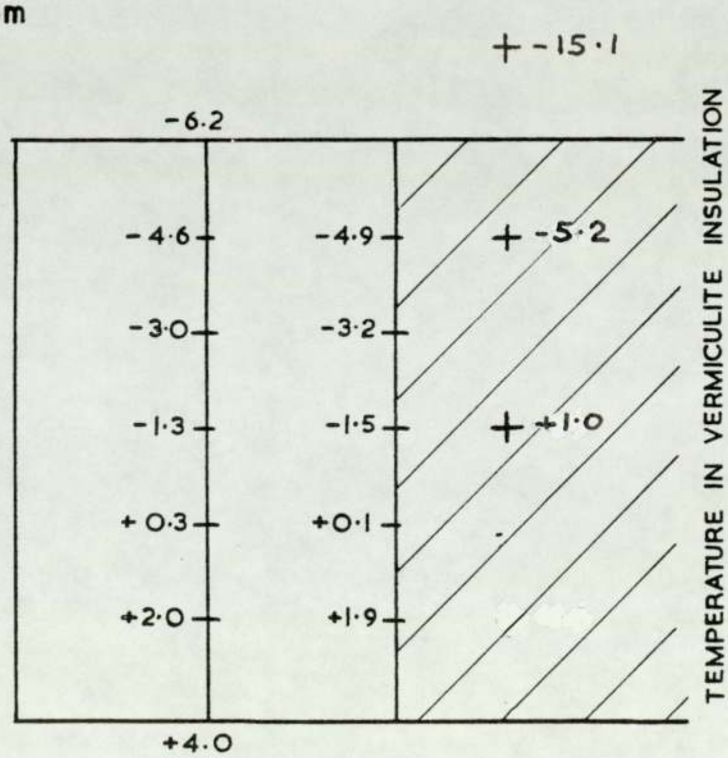


FIG. 8·4. TEMPERATURE READINGS THROUGH CEMENT STABILISED SPECIMENS.

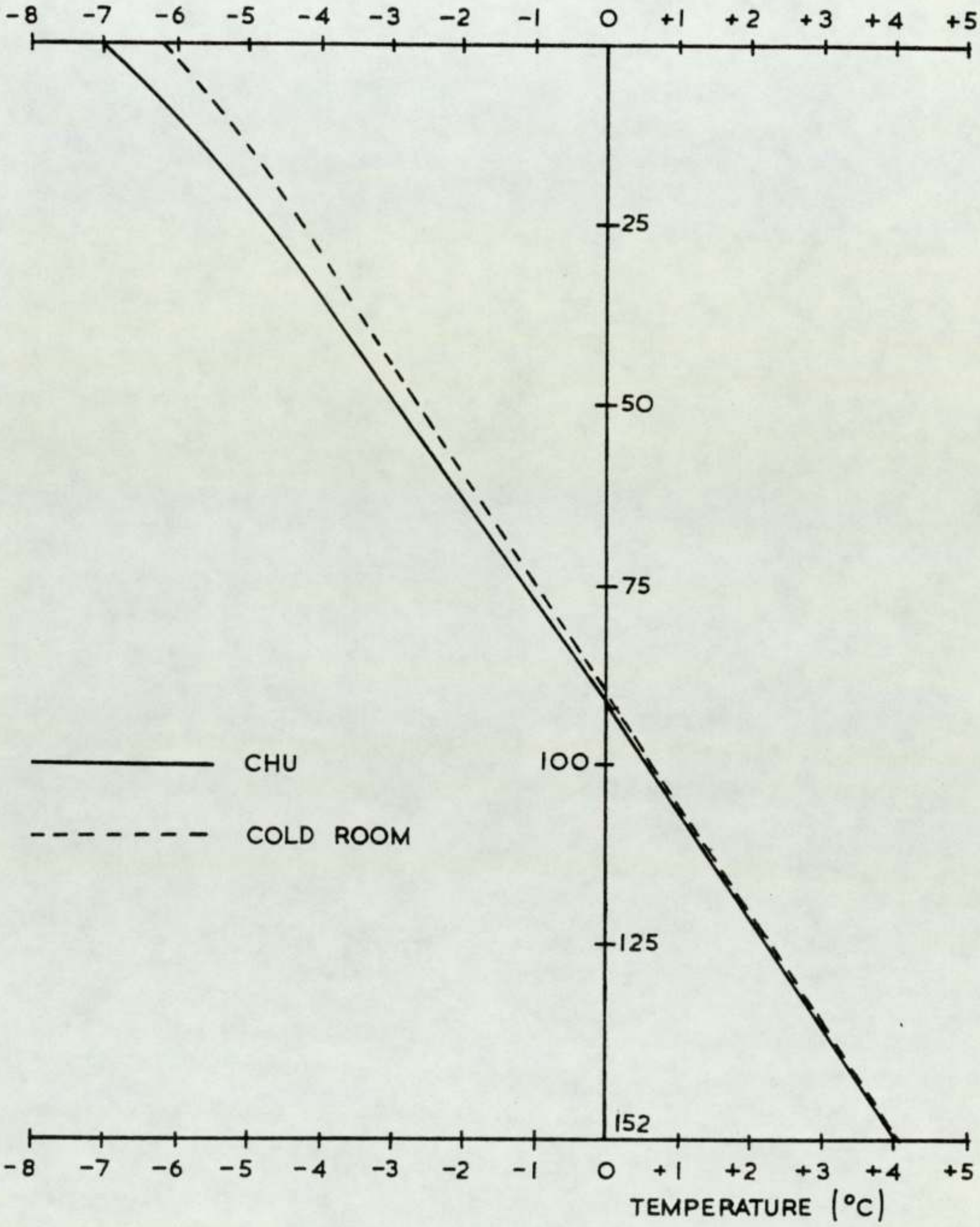


FIG. 8. 5. TEMPERATURE GRADIENT THROUGH CEMENT STABILISED SPECIMEN.

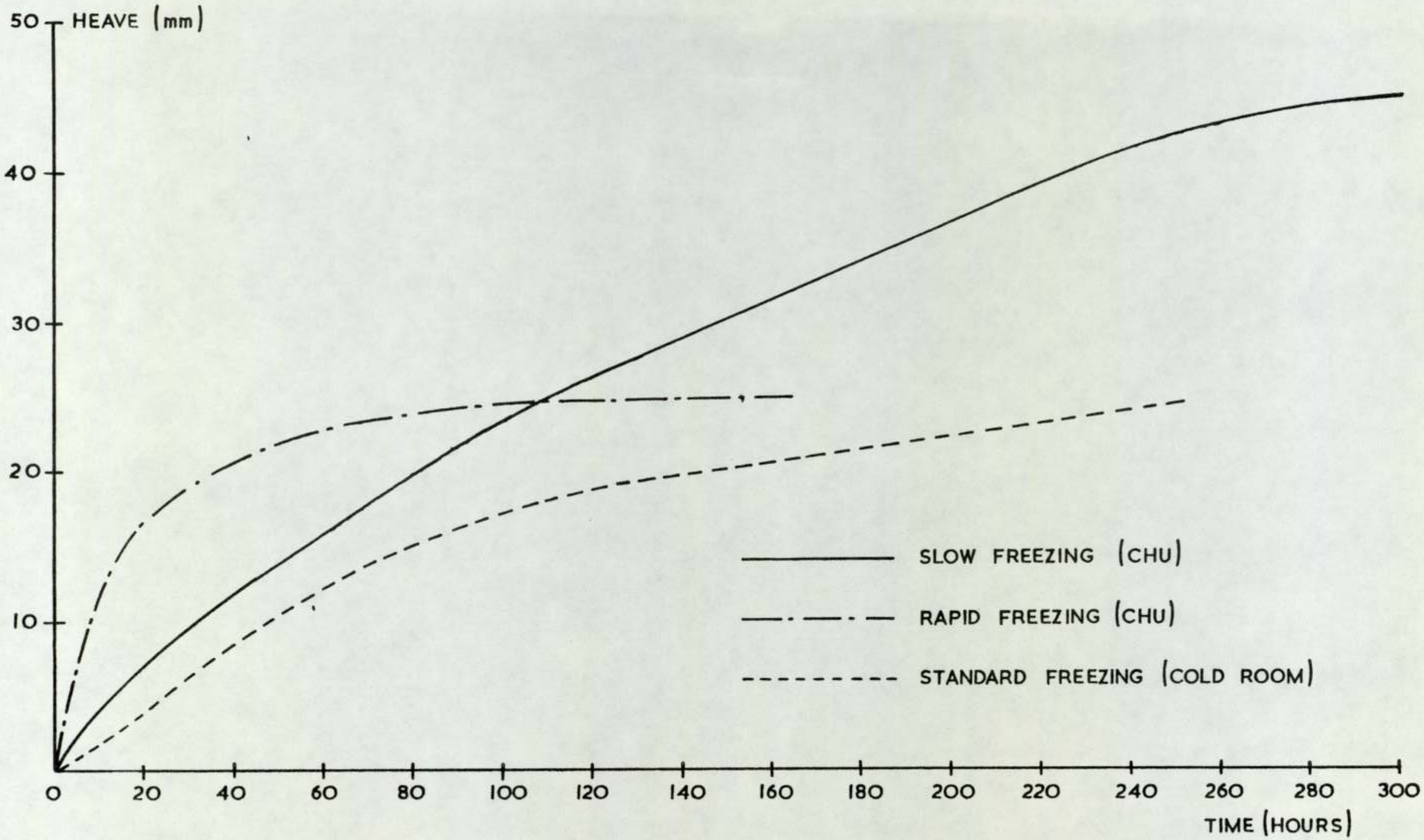


FIG. 8. 6. HEAVE AGAINST TIME FOR DIFFERENT RATE OF FREEZING.

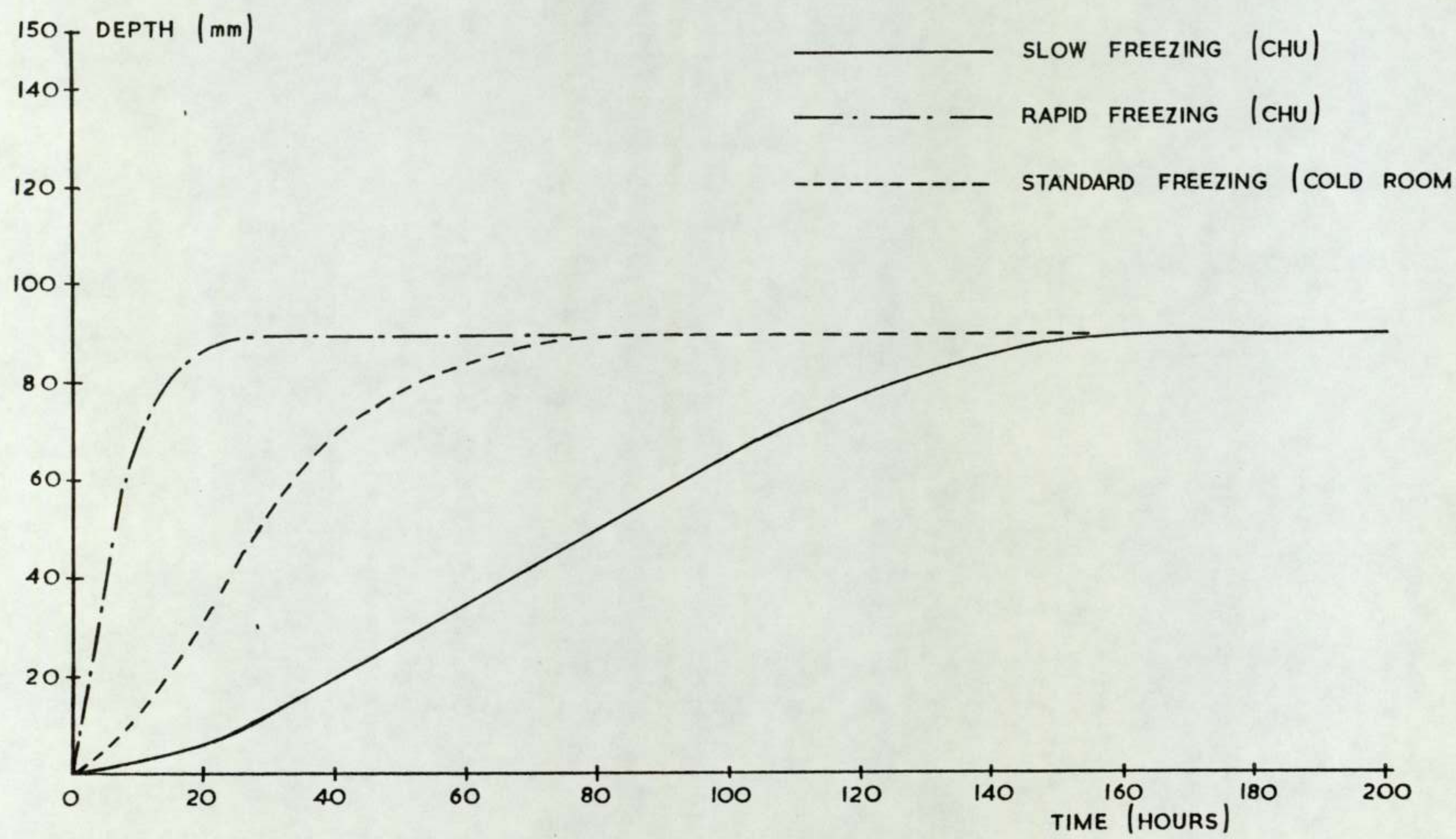


FIG. 8.7. PENETRATION OF ZERO ISOTHERM.

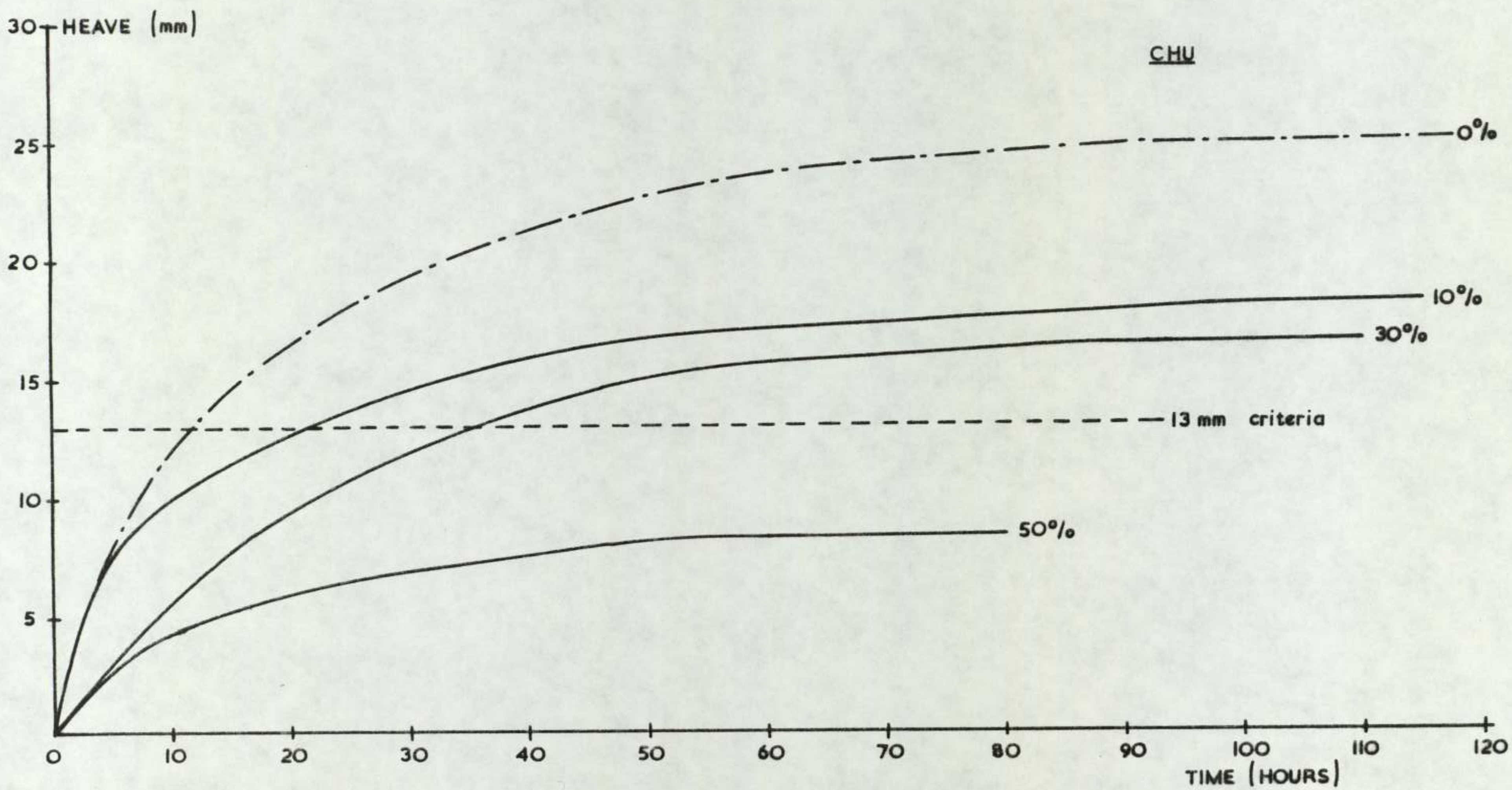


FIG. 8. 8. HEAVE AGAINST TIME FOR 20-3.35mm SLAG AGGREGATE.

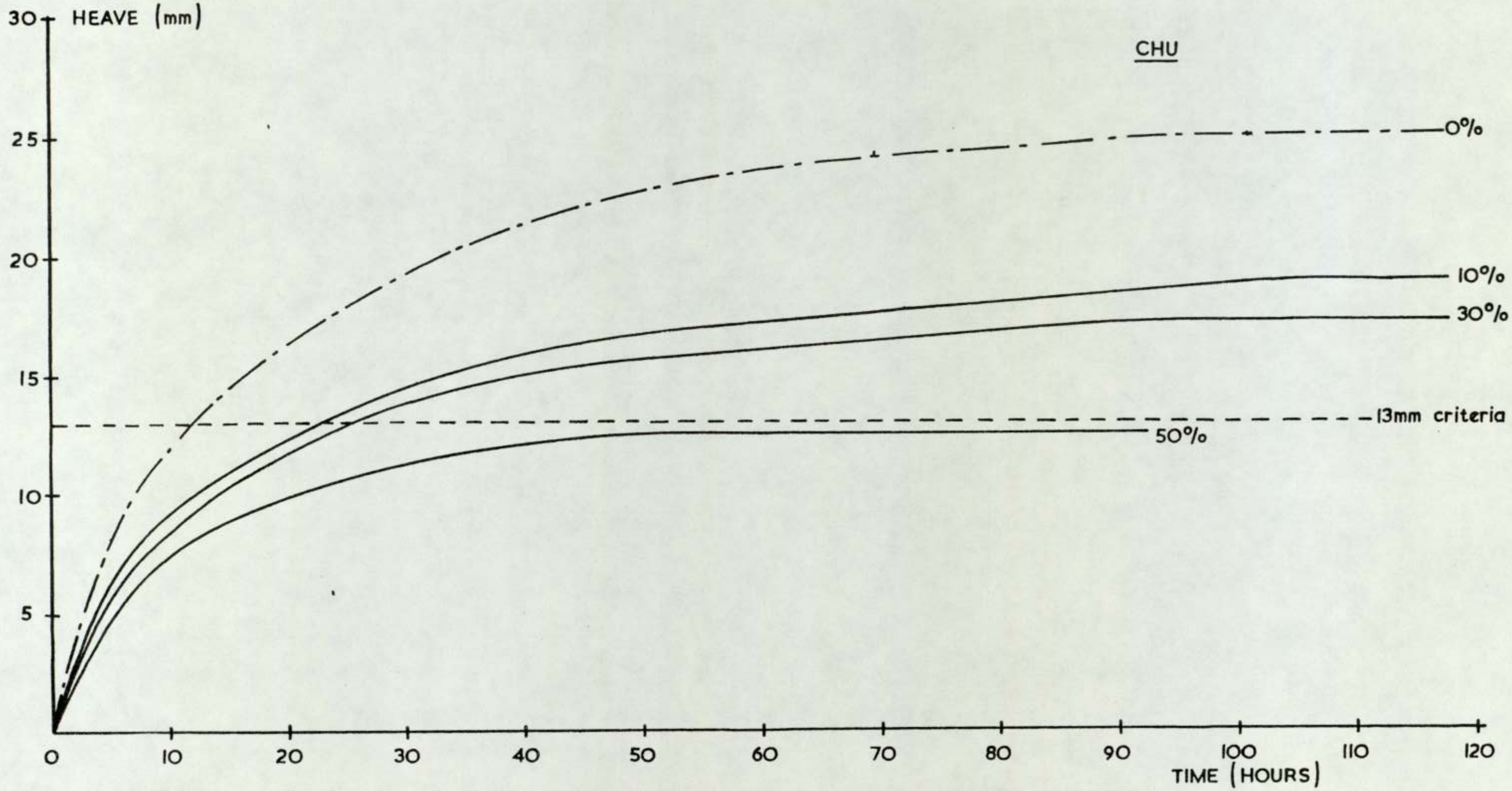


FIG. 8.9. HEAVE AGAINST TIME FOR 20–3.35mm ROWLEY BASALT.

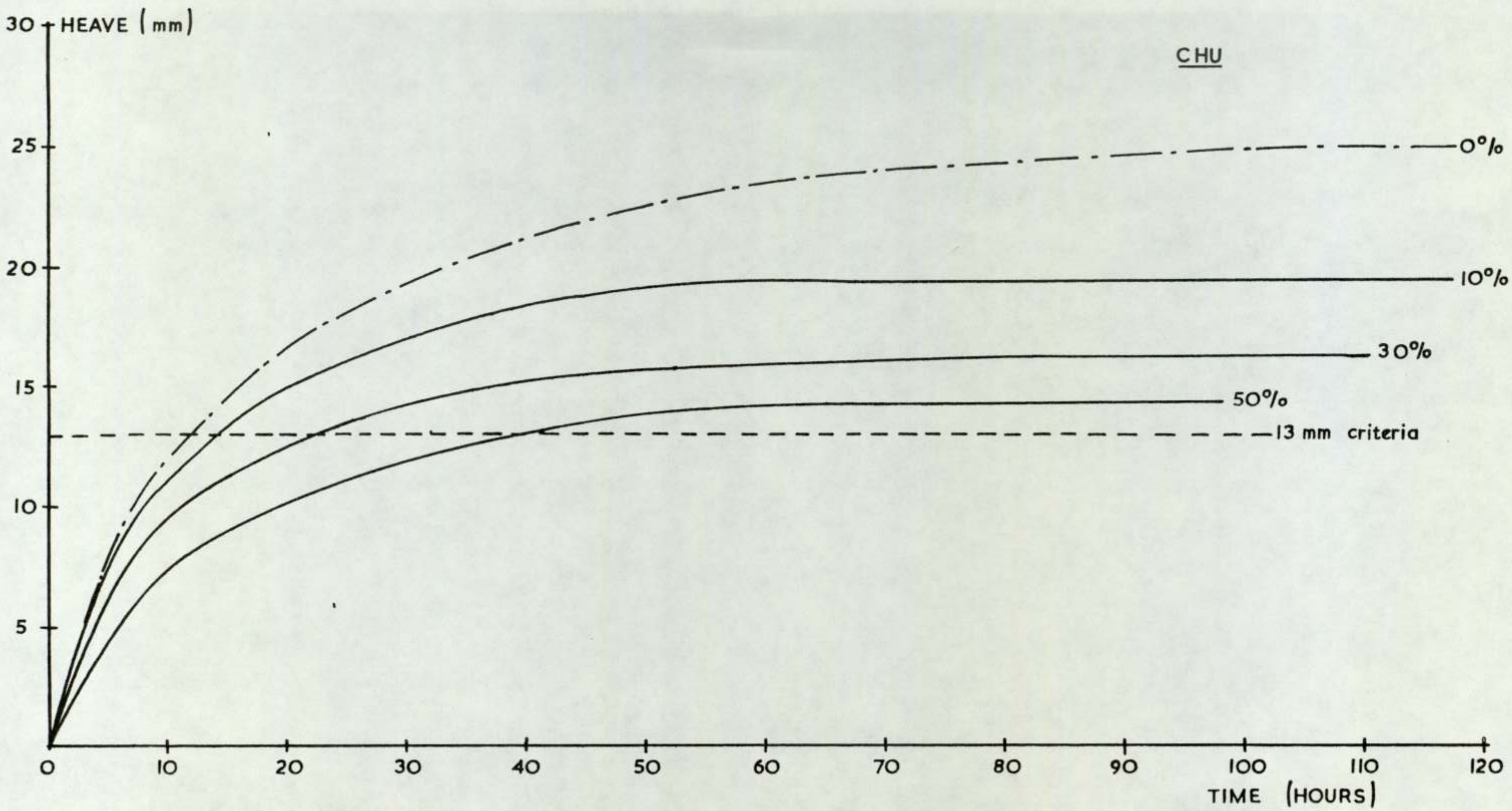


FIG. 8.10. HEAVE AGAINST TIME FOR 20–3.35 mm CALDON LOW LIMESTONE.

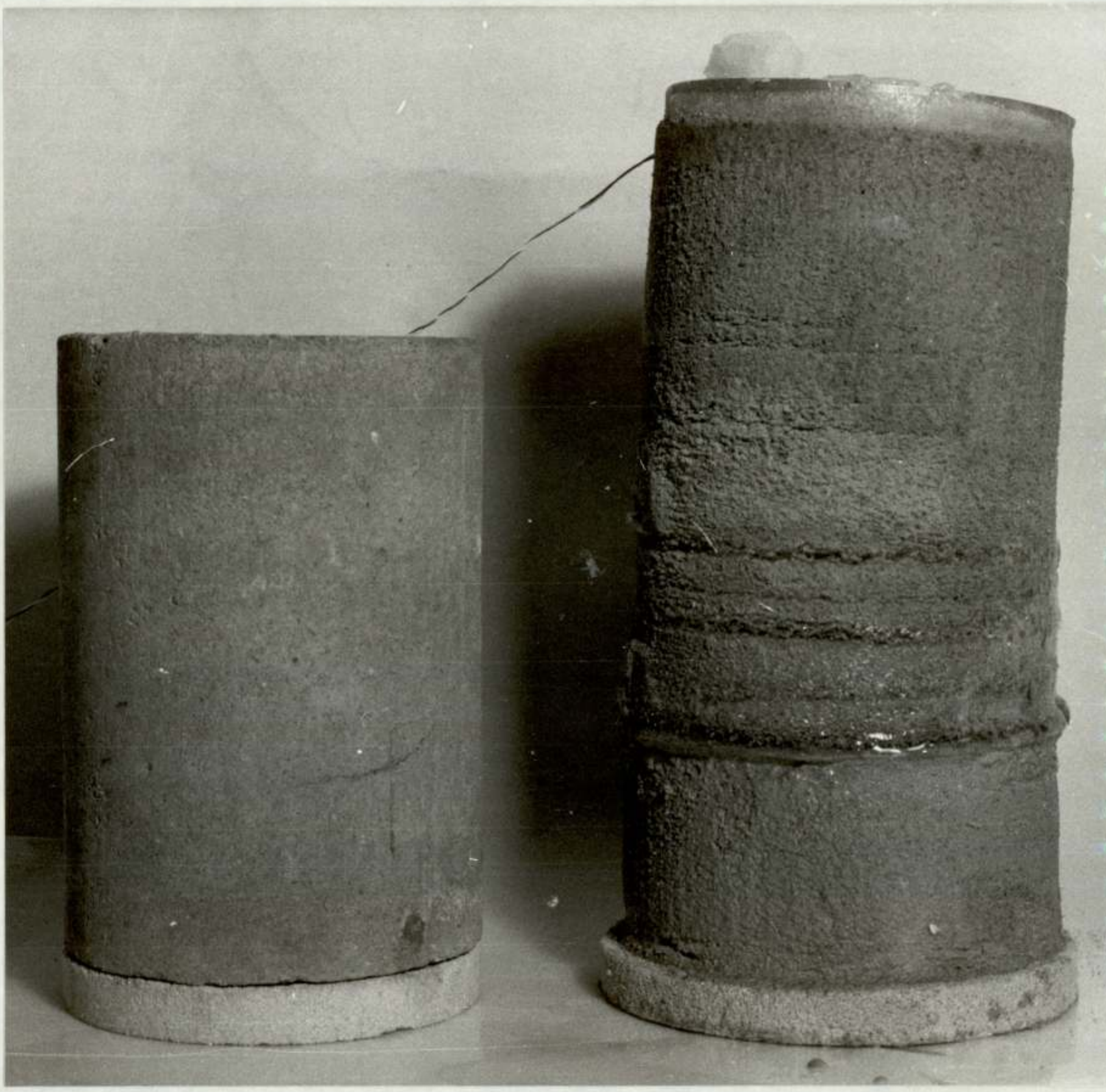


PLATE 8.1 Specimen after slow freezing.

CHAPTER IX

EFFECT OF SURCHARGE ON THE FROST HEAVE

9.1 Introduction

When a frost susceptible soil is frozen, frost heave will be produced. However, if this heave is restrained, either partially or completely, then heaving pressures will also be generated. In the case of partial restraint, both heave and heaving pressures will coexist. The relationship between these two parameters is especially important in the design of engineering structures subjected to ground freezing e.g. chilled gas pipelines, cold stores, LNG storage facilities, etc., thus the prediction of the heave and the heaving pressures, developed under different levels of restraint will aid the design of such structures.

Reductions in heave, following increases in the overburden pressure, have been widely reported and this approach has been suggested as one of the possible ways of controlling frost action in frost susceptible soils. It is unlikely that heave could be completely eliminated in many engineering locations, such as highways or airfield construction because of the high overburdens that could be required. However, with structures, such as cold-stores and LNG tanks, the weight and stiffness of the structure will provide significant restraint to the heave forces developed in the soil so that the frost heave will be reduced. The associated pressures will act on the structure and must be allowed for during design so that the inter-relation between heave and heaving pressure is of considerable interest.

In this Chapter, the relevant literature is reviewed, and this is followed by a description of an experimental study of the effects of surcharge on frost action in granular materials.

9.2 Theoretical aspects

Over fifty years ago, Taber (119) reported that a relatively small surface load entirely prevented frost heave if a soil was of such a texture that only a little segregated ice was formed under the most favourable conditions. He also suggested that the load necessary to reduce frost heave increased with decrease in the particle size of the soil.

In 1935 Beskow (16) independently demonstrated that increased surcharge pressures tended to decrease the heaving rate of a silty soil. In this study, he was able to vary the stress level by changing the surface load and/or the pore water pressure. The heaving rate remained the same when the difference between the applied stress and the pore water pressure was constant throughout the test, but with the increase of the difference between these two stresses, the rate of heave was reduced.

More recently, the effect of surcharge stress has been studies (120) under natural conditions on undisturbed subgrade soils. The freezing was promoted by normal frost action during a typical Alaskan winter. The data obtained suggested (120) that the surcharge load prohibited the migration of ground water to the freezing front. Seasonal frost heave of a silt was significantly reduced by a relatively small surcharge. The heave of the silt was reduced by some 30 percent with a surcharge equivalent to 15.8kN/m^2 (2.3 p.s.i.) and with the surcharge increased to 55.2kN/m^2 (8 p.s.i.) the heave was reduced by 75 percent. The surcharge also appeared to reduce the heave in the adjacent zones.

Attempts have been made to establish a critical external pressure at which frost heaving could be completely stopped. Currently there are two conflicting expositions concerning the concept of a shut-off pressure, and these are discussed in the following sections - 9.2.1 and 9.2.2. The one supports the concept of a shut-off pressure and suggests that the migration of water to the freezing front is prevented by the application of an external load. The other considers that such a critical pressure does not exist and, providing that freezing is continued for a sufficient time, heave will be produced. However, both suggest that frost heave will be reduced by an increase in the applied surcharge.

9.2.1 The shut-off pressure

The provision of a sufficient water supply to the freezing front is a necessary condition to sustain the growth of segregated ice to produce high frost heaves. When water moves away from freezing front, the growth of significant ice lenses is not possible, and so heave will only be caused by the in-situ freezing of the remaining porewater. The attraction of water corresponds to low effective stresses at the frost front, while expulsion conditions exist when the effective stresses are higher. Thus, a soil can attract or expel water at different level a surcharge. The shut-off pressure has been defined (45),(121) as the effective stress at the frost front which will induce neither flow of water into nor away from the freezing front. The existence of the shut-off pressure was explained (121) by use of the capillary model. In this model, the pressure difference across the curved ice-water interface is given by:-

$$\sigma_i - U = \frac{2\sigma_{iw}}{r} \tag{9.1}$$

where

σ_i = the stress in the ice

U = the pore water pressure

σ_{iw} = ice-water surface tension

r = the equivalent pore radius of the soil.

When the stress level on the freezing front is less than $(2\sigma_{iw}/r)$, water will tend to migrate to the interface and the ice lens grows. If the stress level is greater than $(2\sigma_{iw}/r)$, ice will propagate through the pores of the soil and water may be expelled. The stress $K = 2\sigma_{iw}/r$ was referred to (121) as the shut-off pressure.

It has been suggested (121) that the following equation can be written to describe the conditions obtaining at an advancing freezing front, where access of water is denied to the freezing front:-

$$\sigma - U = K \qquad (9.2)$$

where

σ = total stress at the freezing front

U = pore water pressure in the unfrozen soil immediately beneath the freezing front

K = shut-off pressure

Thus, when the total load on the soil (σ) is equal to K, the pore pressure, U, is zero, and there will be no tendency for water to move away from or towards the frost line. As supporting evidence it was observed (122) that fine grained soils expel water only at high overburden pressures, while coarse grained soils expel water at much lower pressures.

An alternative explanation of the shut-off pressure has been presented (49),(45),(60) in terms of the energy released during soil freezing. In the heaving process, the energy liberated at the freezing front will be used (60) to perform work:-

a) lifting the load above the freezing front

b) raising water up to the freezing front.

Thus, as the surcharge or overburden pressure is increased, a greater proportion of the available energy will be expended in lifting the load, so that less energy will be available to raise the water to the freezing front. Moisture transfer to the freezing front will, therefore, be reduced resulting in lower heaves. The rate of water migration will decrease until a pressure is applied at which there will be no flow into or out of the system, i.e. a shut-off pressure. Kaplar (60), in his model of heaving, has suggested that, although high pressures would be necessary to prevent heaving, the application of only quite low external pressures would be required to reduce the heave to tolerable levels.

It has been suggested that the shut-off pressure is a function of soil type, stress history and rate of freezing. Recent studies (46) in Canada have also indicated the duration of the freezing test may have an influence on the magnitude of this pressure.

9.2.2 Alternative theory of the overburden

Although considerable data has been documented to support the concept of shut-off pressure, Penner (46) has recently questioned this concept. It is suggested that it is not possible to control independently the two processes of frost heaving by loading the soil. In an experimental study he was unable to attain shut-off pressures for any of the soils studied, although the heave rates were near zero at the highest pressures. It was reported (46) that at high pressures, water initially was expelled from the samples, but in all cases this was followed by water intake after the rate of frost penetration had decreased. Thus, providing freezing was continued for a sufficient period shut-off pressures did not exist. Penner and Ueda (46) reported that the rate of heave was constant throughout the run for any particular pressure level.

As the pressure was increased, the zone of appreciable heaving was linked with a greater temperature range and so Penner and Walton (123) concluded that a heaving zone was involved in frost heaving rather than freezing plane. This heaving zone concept is otherwise called in literature as the frost fringe (28) or zone of segregated freezing (39). According to these thoughts (54) heaving pressures can build up indefinately as long as the process is given sufficient geological time. Thus, no surcharge or external pressure could totally eliminate heave.

In a related study (124), it was demonstrated that the amount of heave decreased with increase in the imposed pressure and this relationship was expressed as hyperbolic function. This again implies that the application of an external pressure will not totally eliminate heave, providing the freezing period is of sufficient length. It was also found that at a given cooling plate temperature a linear correlation existed between the total heave and the square root of elapsed time. This heave was attributed to water migration towards the freezing front. It occurred during the application of external pressures and, indeed, no shut-off pressures were established. It was concluded (124) that the ice lens segregation is a result of the hydraulic gradient through the unfrozen soil in the direction of the frost line, this gradient being attributed to the reduction in pore pressure at the frost line.

Takashi (125) derived an empirical equation connecting heave and surcharge load and again underlined that the complete elimination of heave would be difficult due to the freeze-expansion of the adsorbed water around soil particles behind the freezing front.

9.2.3 Soil type

Fine grained soils can withstand relatively high pressure and still exhibit significant heave (122). However, when quite low surcharge are imposed on coarse grained soils the heave can be considerably reduced and may be completely eliminated in short freezing exposures.

9.2.4 Rate of freezing

Hill and Morgenstern (45) suggested that, for a particular soil at a given applied load, suction is established at the freezing front and this suction can rise only to a limiting value with an increasing rate of heat extraction. This would control flow to the freezing front and, hence, the subsequent heave. It was also observed (30) that the greatest expulsion of water from the samples occurs when the freezing front is rapidly advancing. However, after the initial expulsion, the intake of water by ice lens growth became dominant. Therefore, the rate of heave increased with an increasing temperature gradient.

The cold side temperature had a significant influence on the heave rate, in the experimental study undertaken by Penner and Ueda (46), but this was only at low pressures. At high pressures when the heave rates were low, the confining pressure had a much greater influence on the heave rate.

Penner and Ueda (126) related the cold side temperature to the heave rate through the exponential function:-

$$dh/dt = a \exp (bP/T) \tag{9.3}$$

where

dh/dt = heave rate (mm/min)

h = heave (mm)

t = time (min)

P = overburden pressure (kg/cm^2)

T = cold side freezing temperature (^oC)

a and b = constants, dependent on soil type.

For small overburden pressures, the maximum heave rates were observed at cold side temperatures close to 0^oC, while at high overburden pressures the zone of significant heaving existed over a large temperature range (123). In addition with an increase in the overburden pressure, the temperature at which ice segregation commenced was lowered. It may be connected with the fact that the ice in the frozen soil is more easily melted by application of pressure (21) than is ice in bulk. Thus, the application of this pressure increased the thickness of the unfrozen water interface. Therefore, the higher the load that is applied, the lower will be freezing point depression.

9.3 Experimental study of low level surcharge

9.3.1 Development of the system

It was considered that low level surcharges could be produced by placing dead weights on top of the frost heave specimens. It was thought that a self refrigerated unit (SRU) would be the most suitable facility to adopt for studying the effects of such surcharges on frost heave. The arrangement of specimens in the SRU makes it easier to apply dead loads than in the more complex trolleys that are used in the cold room. It was, therefore, necessary to check that the results from SRU were compatible with those from the cold room when standard tests were performed without surcharge.

The SRU was based on a prototype developed at the University of Nottingham (70) and the freezing followed the procedure of the TRRL frost heave test (5),(8).

This preliminary study was undertaken on specimens of standard sand/snowcal matrix. These specimens were prepared and tested as described in Chapter V, with the exception that, after preparation, the specimens were positioned in the SRU, where they were left to condition for 24 hours at room temperature. Datum readings were taken on the brass rods and the SRU was switched on. The specimens were tested in a standard inner box in groups of nine in each trial. Two such trials were performed and the results are summarised in Table 9.1.

No of trial	Frost heave for individual specimens (mm)									Mean (mm)	St. dev. (mm)
	1	2	3	4	5	6	7	8	9		
I	23.48	28.58	23.60	27.79	21.71	25.23	24.62	25.12	23.80	24.88	2.16
II	24.42	24.06	27.28	25.30	21.73	23.38	25.16	26.02	22.20	24.17	1.90

TABLE 9.1 Frost heave values in SRU for sand/snowcal matrix

The results were compared statistically with those detailed in Table 5.3, for cold room tests on the sand/snowcal matrix. They were shown not to be significantly different at the 5 percent level and so the SRU was considered suitable for tests with surcharges.

In the standard frost heave test (8) the specimens are wrapped in waterproof paper before freezing. However, this paper is not sufficiently strong to withstand any loading and to provide adequate support for surcharged specimens. It was, therefore, decided to replace the paper with 25mm deep Tufnol rings. Due to the thickness of these rings, it was impossible to place the assembly in a standard specimen carrier which had been designed only to accomodate a 102mm specimen wrapped in paper. It was, therefore, necessary to use the larger carriers which had been produced for the 145mm specimens. Only four of these specimens could be accomodated in the modified inner box that was described in Section 5.4.2. A gap was created between the outer face of the rings and the edge of the carrier and this was filled with creased polythene to prevent gravel insulation coming into contact with the water. The initial results given in Table 9.2 clearly showed that the specimens tested only in the rings heaved considerably more than those previously tested in waterproof paper. It was decided to examine this behaviour to eliminate any possible variation in the recorded heaves due to the arrangment of the specimens in the SRU. The following frost heave tests were, therefore, performed:-

1) Four specimens wrapped in paper
2) Four specimens supported by multi-rings
3) Two specimens wrapped in paper and two specimens in multi-rings.

Test 3) was undertaken to eliminate the effects of any variations in the boundary conditions between separate tests. The results of these tests are summarised in Table 9.2.

No of trial	Means of specimen support	Frost heave (mm)				Mean (mm)	St. dev. (mm)
		1	2	3	4		
I	Tufnol rings	35.38	36.15	38.05	34.28	35.96	1.59
II	Paper	24.47	25.20	28.27	26.45	26.09	1.66
III	Tufnol rings	36.60	34.81	-	-	35.70	1.26
	Paper	-	-	24.86	26.57	25.70	1.19

TABLE 9.2 Frost heave values for different means of specimen support

It can be seen from Table 9.2 that the specimens in Tufnol rings consistently developed much greater heaves than those specimens wrapped in paper. Although the frost heave of specimens wrapped in paper, and tested in the 145mm carriers was greater than when tested in the standard arrangement, the two sets of results are not significantly different (similar behaviour was also indicated in section 5.4.2).

It was demonstrated in Chapter VII that friction and adfreeze significantly influenced heaving pressures. When a specimen was wrapped in paper, it was observed at the end of the heave tests, both in the SRU and the cold room, that the paper was frozen to the outside of the specimen. This indicated that besides frictional resistance between the paper and the surface of the specimen, adfreeze was also developed, and this may have a more significant effect on the heave value than the frictional effects. Both of these phenomena were almost eliminated when the specimens were tested in rings, and so such specimens develop considerably greater heaves. This implies that specimens tested under the standard conditions of the TRRL test (8) may not develop their maximum potential heaves, due to limitations imposed by sidewall resistance. For routine testing this would not have a significant effect, since all the specimens are tested in the same way and the criteria for assessing frost susceptibility were derived from testing under the specified conditions. All the frost heave tests, described in Chapter V and VI, had been performed under the standard conditions. It was intended to relate the study of the effects of the surcharges to these earlier tests, and so it was essential to produce boundary conditions in the surcharge programme that were the same as those of the standard tests. It was decided to test the specimens by wrapping them in paper and then sliding the slightly oversize rings over the paper to provide support. Two trials were performed under these conditions and the results are summarised in Table 9.3.

No of trial	Frost heave (mm)				Mean (mm)	St. dev. (mm)
	1	2	3	4		
I	24.53	24.22	26.01	25.12	24.97	0.79
II	23.19	25.55	27.49	24.01	25.06	1.89
Grand mean (mm)			25.01			

TABLE 9.3 Frost heave values for modified specimens arrangement in SRU

These results were compared with the results in Table 9.1, for the standard test conditions in the SRU, and they were found not to be significantly different at 5 percent level. The arrangement was, therefore, accepted for further testing.

Steel weights were used to provide the low level surcharges. It was decided to delay putting the weights on top of the specimen until the temperature in the SRU was $-17.0^{o}C$ and the top of the specimen had just frozen with a heave of less than 0.2mm which occured approximately 10 hours after the start of the test.

It was decided that the surcharge should only become effective once heaving had commenced and so it simulated heave against a structure. Application of the surcharge before frost action had commenced could produce significant consolidation in the materials, thereby altering the pore structure and so modifying the effects of freezing. In addition, if the steel weight was placed directly onto the Tufnol top cap, the boundary temperature conditions could be altered. The weights would rapidly cool to $-17.0^{o}C$ and this could produce additional cooling under the cap which would also modify the frost heave value (such behaviour was reported by Taber (119) during his early work on surcharge pressures). It was, therefore, decided to place the weights in a slightly elevated position, on a wooden support table, so that air could circulate above the specimen as in the standard test. The position of specimens in the SRU and the arrangement of the weights are shown in Figures 9.1 and 9.2. The remaining conditions of heave test followed the requirements of the standard test (5),(8).

9.3.2 Materials tested

Due to the time schedule it was impossible to examine the performance of all the materials described in the previous Chapters. It was decided, therefore, to initially study the effect of the surcharge on the highly frost susceptible sand/snowcal matrix. This was followed by tests on selected mixtures of the matrix and aggregates with 20 - 3.35mm particles. These mixtures were selected on the basis of the following conditions:-

1) Mixtures with similar heaves, but different heaving pressures. These materials were 30% Slag which had a heave of 16.0mm and a heaving pressure of $192kN/m^2$ and 30% Rowley Basalt with a heave of 16.4mm and a heaving pressure of $250kN/m^2$.
2) Materials with similar heaves and similar heaving pressures. These materials were the 30% Rowley Basalt, selected for 1), and 20% Caldon Low Limestone with a heave of 16.4mm and a heaving pressure of $246kN/m^2$.
3) Materials with similar heaving pressures but different frost heaves - 30% Rowley Basalt as for 1) and 10% Caldon Low with a heave of 18.4mm and a heaving pressure of $254kN/m^2$.

9.3.3 Preparation of the specimens

The specimens were prepared following the procedure described in Chapters V and VI for the standard testing. Four specimens were tested for each surcharge increment for each material.

9.3.4 Results of the tests

The results for the sand/snowcal matrix are collected in Table 9.4. It was decided not to use surcharges higher than 15.25kN/m^2 in this series, as arrangement became unstable with higher level of surcharge since the height of the weights would have exceeded the safe limit.

Surcharge (KN/m^2)	Heave (mm)	$\frac{\text{Surcharge}}{\text{heaving pressure}}$ (%)
0	25.01	0
3.25	20.79	1.1
7.86	18.23	2.6
12.48	13.91	4.6
15.25	12.25	5.1

TABLE 9.4 Frost heave values for sand/snowcal matrix under different levels of surcharge

The results for the selected mixtures are given in Table 9.5.

Surcharge KN/m^2	30% Slag		30% Basalt		20% Limestone		10% Limestone	
	Heave (mm)	$\frac{S(\%)}{h.p}$	Heave (mm)	$\frac{S(\%)}{h.p}$	Heave (mm)	$\frac{S(\%)}{h.p}$	Heave (mm)	$\frac{S(\%)}{h.p}$
0	16.0	0	16.4	0	16.4	0	18.4	0
3.25	13.10	1.7	14.62	1.3	15.20	1.3	-	-
4.80	11.37	2.5	-	-	-	-	-	-
7.86	9.60	4.1	12.90	3.1	12.10	3.2	12.64	3.1
9.35	-	-	10.50	3.7	10.80	3.8	11.60	3.7
11.90	-	-	9.75	4.8	9.97	4.8	10.50	4.7

TABLE 9.5 Heave values under surcharge

Note: $\frac{S}{h.p} = \frac{\text{Surcharge}}{\text{Heaving pressure}}$

The relationships between frost heave and the level of surcharge are plotted in Figures 9.3 and 9.4. It can be seen both from Table 9.5 and Figure 9.3 that, although the 30% Slag aggregate and 30% Basalt mixtures have similar frost heaves without surcharge, the Basalt mixture requires a much higher surcharge to reduce the heave to the non-frost susceptible value of 9.75mm. It is interesting to note that the Basalt mixture developed a higher maximum heaving pressure than the Slag mixture. The sand/snowcal matrix, with even higher values of frost heave and heaving pressure, also required significantly higher surcharges to reduce the heave to values below the 13mm criterion for frost susceptibility as is apparent from the results in Table 9.4.

The 30% Basalt and 20% Limestone mixtures, as indicated in Table 9.5 and Figure 9.4, required similar surcharges to reduce the frost heave to approximately the same value. However, the 10% Limestone mixture which initially had a higher frost heave, but a similar heaving pressure, to 30% Basalt and 20% Limestone mixtures required a similar level of surcharge to achieve similar heaves to those developed by the two other mixtures. It appears, therefore, from the above results that the heaving pressure dictates the behaviour of a particular material under surcharge. Those materials studies that had developed higher heaving pressures required greater surcharges to reduce the frost heave and, hence, the frost susceptibility.

In order to examine this influence the surcharges were expressed as proportions of the appropriate maximum heaving presure. These values are given, in percentage terms, in Table 9.4 and 9.5. It is clear that all the materials exhibited a reduction in frost heave as the surcharge ratio was increased. Of particular interest, it is apparent that with all the materials the frost susceptibility classification was reduced from highly frost susceptible to non frost susceptible (below 13mm), with comparatively low surcharges - equivalent to 4-5 percent of the maximum heaving pressure.

To investigate this relationship, the percentage reduction in heave was calculated and is plotted in Figure 9.5 against the level of surcharge, expressed as a percentage of the heaving pressure. A regression analysis was undertaken and this revealed that there is a linear relationship between the two parameters for above mentioned data, with a positive coefficient of correlation $r = 0.96$, which was found to be highly significant. The regression line can be expressed as:

$$Y = 8.81X \tag{9.3}$$

where

Y = reduction of heave (%)

X = surcharge/heaving pressure (%)

Thus, for all the materials tested only a relatively low surcharge is required to reduce frost susceptibility and this surcharge may be calculated if the heaving pressure and the frost heave are known.

9.4 Experimental study of high level of surcharge

9.4.1 Development of the facility

To investigate behaviour of materials under higher levels of surcharge the CHU, detailed in Chaper VIII was used. The specimen was supported in the multi-ring system to prevent collapse under the high surcharges. It was not possible to apply high surcharges via dead weights as the quantity required would not have remained stable at the top of the specimen. The load was, therefore, applied through a Bellofram air diaphragm, connected to a supply of compressed air, via a suitable regulator. The details of the arrangement are shown in Figure 9.6.

Specimen preparation followed the procedure described in Chapter VIII. It has been shown in Chapter VIII that the heave values of specimens in paper and specimens in rings were very similar in the CHU, unlike those from the SRU, and it was, therefore, considered appropriate to support the specimen with rings so as to provide lateral support against the surcharge load. The specimen was left to condition for 24 hours at a temperature of +4.0°C. The required surcharge was then applied and the specimen was immediately frozen from the top using the cryostat system. The frost heave was continuosly monitored on trace recorder. The test was stopped when the rate of increase in heave was less than 0.01mm/hour. However, some tests were performed for much longer periods of time in order to monitor any subsequent behaviour.

9.4.2 Materials tested

The materials were the same as those detailed in section 9.3.2 since the rationale used for selection in the low level study was also extended to this high level investigation. However, not all these materials were tested since, the low level work, had indicated that 10% and 20% Limestone mixtures had exhibited similar behaviour to the 30% Basalt mixture. The materials tested were, therefore, as follows:-

1) Sand/snowcal matrix
2) 30 percent Rowley Basalt mixture
3) 30 percent Slag mixture.

9.4.3 Results of the tests

All results are based on a minimum of two tests performed on each material at each particular level of surcharge and these results are summarised in Table 9.6.

Surcharge kN/m^2	Sand/snowcal		30% Slag		30% Basalt	
	Heave (mm)	S(%) h.p	Heave (mm)	S(%) h.p	Heave (mm)	S(%) h.p
0	25.01	0	16.0	0	16.4	0
24	10.5	8	5.2	12	-	-
48	6.7	16	-	-	4.2	19.0
72	4.5	24	1.1	38	2.5	29.0
97	1.7	32	-	-	1.0	38.0
120	1.0	40	-	-	-	-

TABLE 9.6 Heave values under surcharge

Note: $\dfrac{S}{h.p} = \dfrac{\text{Surcharge}}{\text{Heaving pressure}}$

The results are also presented in Figure 9.7 together with data from section 9.3.4 for the lower levels of surcharge. As the heaving pressure had been measured using a stiff load cell, the frost heave was not completely eliminated in such tests. The deflection of load cell was approximately 0.1mm. It can clearly be seen from Figure 9.7 that, in order to reduce the frost heave to below 10mm, only relatively low surcharges are necessary, although some limited movement is still apparent at high surcharges. It would, therefore, appear that for the materials tested shut-off pressures were not achieved. Thus, whilst it was not possible to completely eliminate heave, heave is reduced through an increase in the surcharge. The relationship between heave and surcharge is hyperbolic, which agrees with other experimental work (124) and with theoretical work (60).

The surcharge is not uniquely related to frost heave. It can be seen from Figure 9.7, that different surcharges are necessary for different materials to produce a given value of heave. Those materials with higher frost heaves and, especially, heaving pressures required higher surcharge for a given reduction in frost heave and, hence, frost susceptibility.

In Figure 9.8 the reduction in heave is plotted against the ratio of surcharge to heaving pressure, including data from Figure 9.5. It appears that there are two separate relationships between the reduction in heave and the surcharge ratio. At low levels of surcharge, up to 5 percent of the heaving pressure, there is a very clear relationship such that quite small changes in the surcharge produced marked differences in the reduction in heave. A surcharge ratio of approximately 5 percent is sufficient to reduce the heave by 50 percent. However, significantly higher levels of surcharge are required to achieve larger reductions in heave, so that for the complete elimination, if possible, of heave would require extremely high surcharges.

From these experimental results it seems that the magnitude of heaving pressure dictates the behaviour of a soil when frozen under surcharge loads. Typically, for two materials with similar frost heaves but different heaving pressures the material that developed the higher heaving pressure required a higher surcharge to achieve the same reduction in heave. Thus, the magnitude of any reduction in heave depends on the heaving pressure rather than the initial heave value.

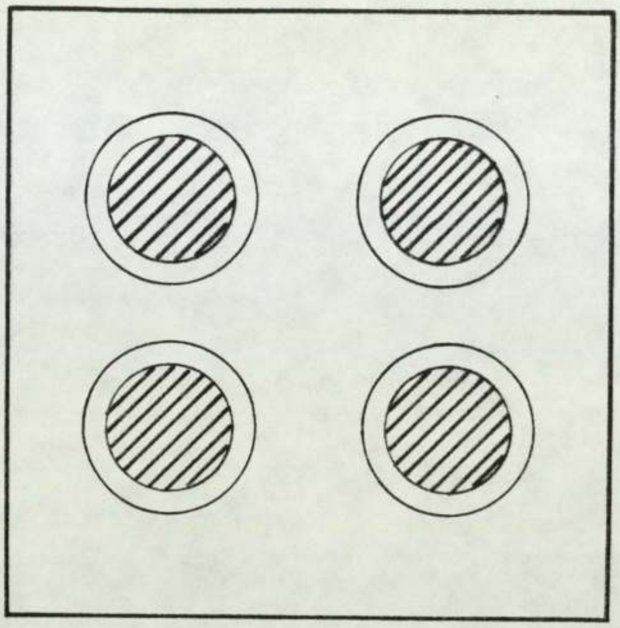


FIG. 9.1. POSITION OF SPECIMEMS IN SRU.

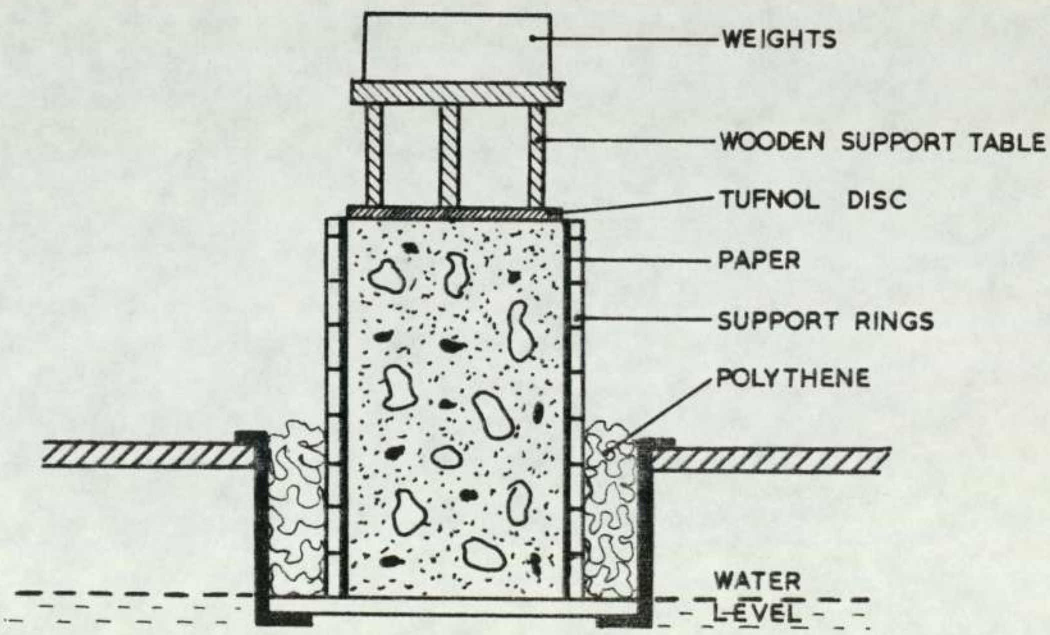


FIG. 9.2. ARRANGEMENT OF WEIGHTS ON TOP OF THE SPECIMEN.

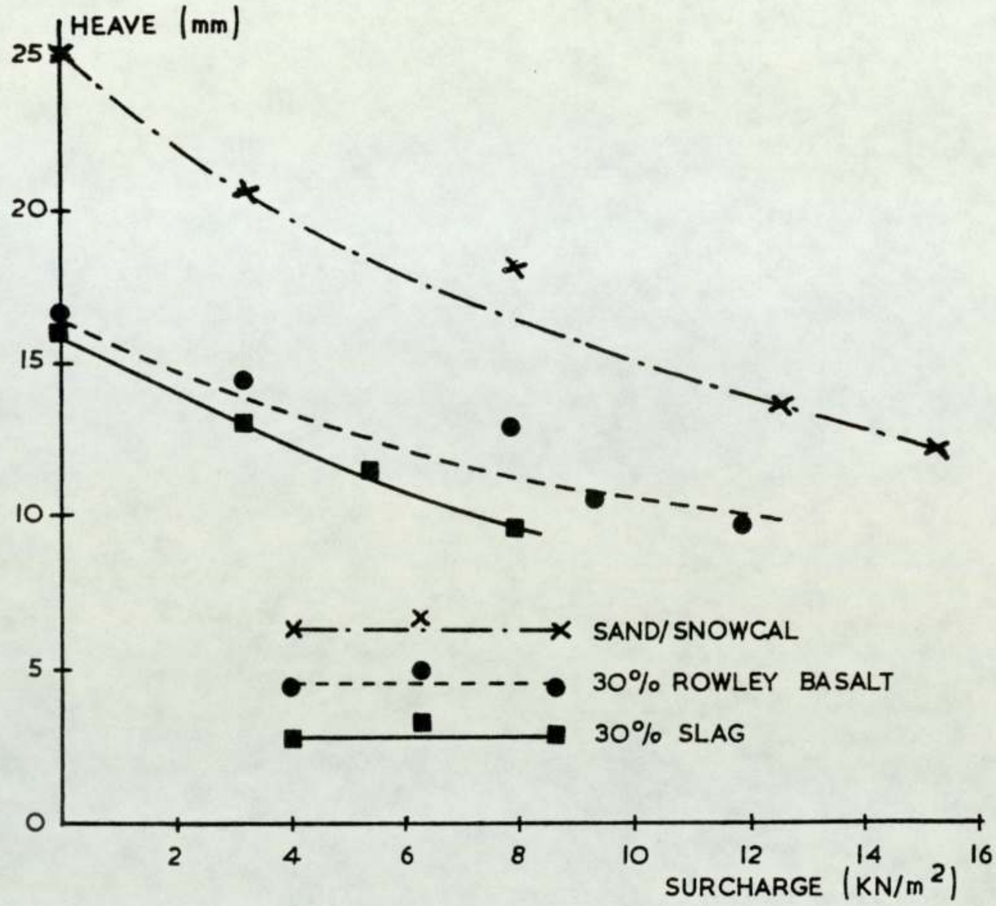


FIG. 9.3. FROST HEAVE AGAINST SURCHARGE.

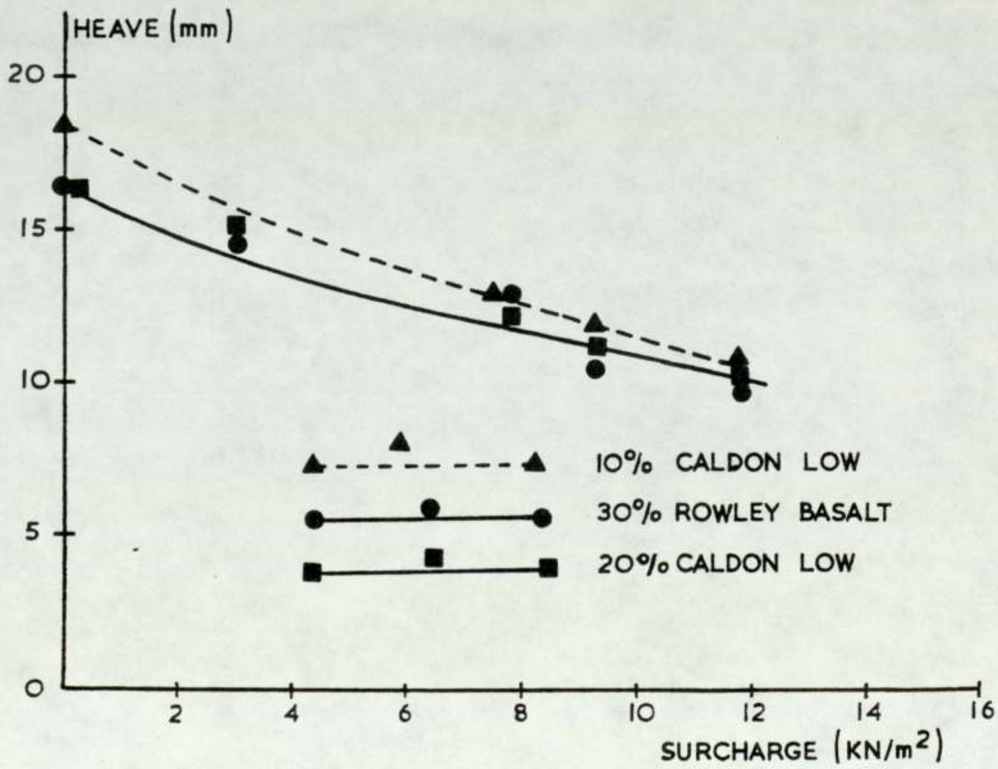


FIG. 9.4. FROST HEAVE AGAINST SURCHARGE.

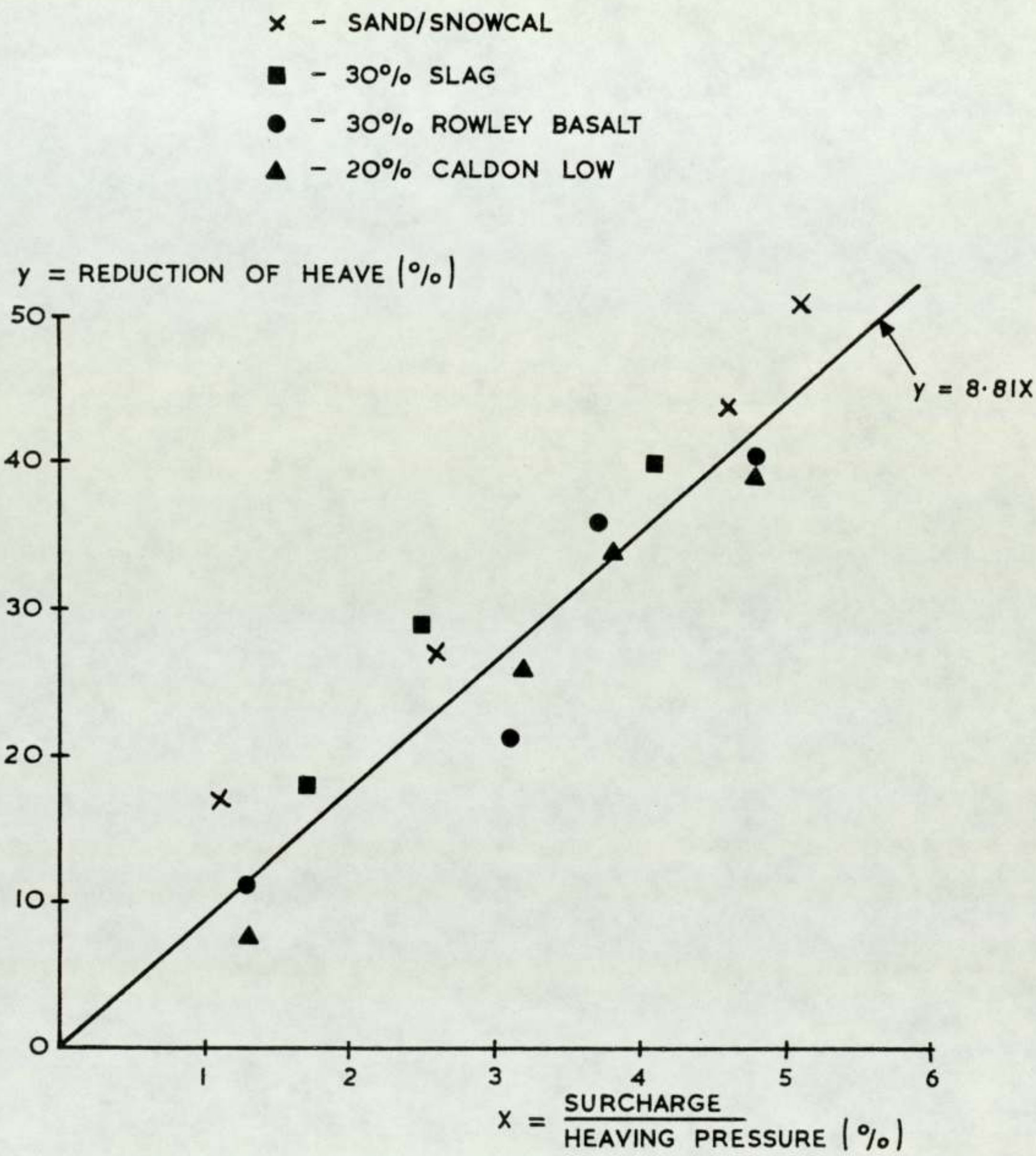


FIG. 9. 5. RELATIONSHIP BETWEEN REDUCTION OF HEAVE AND SURCHARGE RATIO.

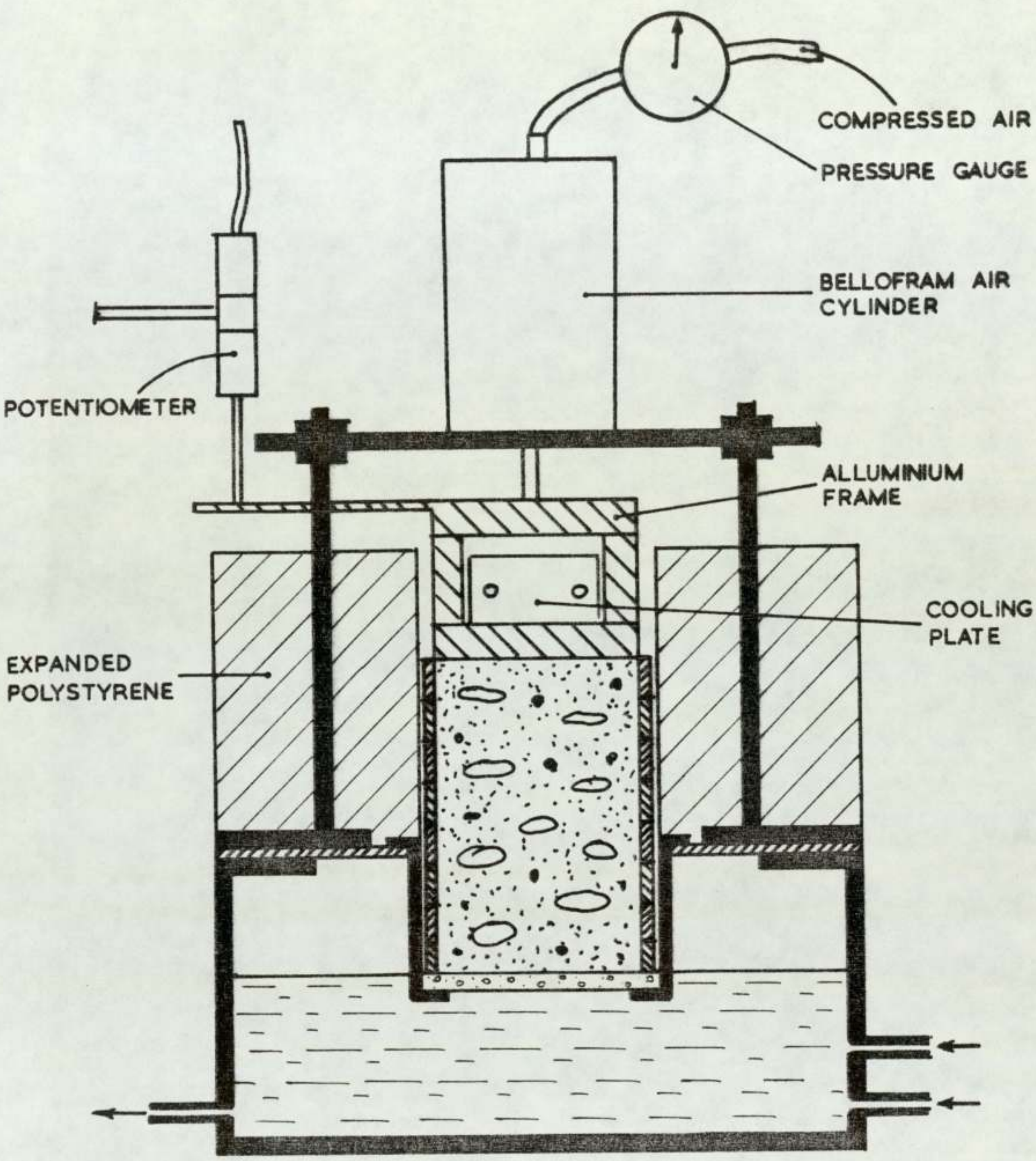


FIG. 9.6. MODIFIED CHU FOR FROST HEAVE TESTS WITH SURCHARGE.

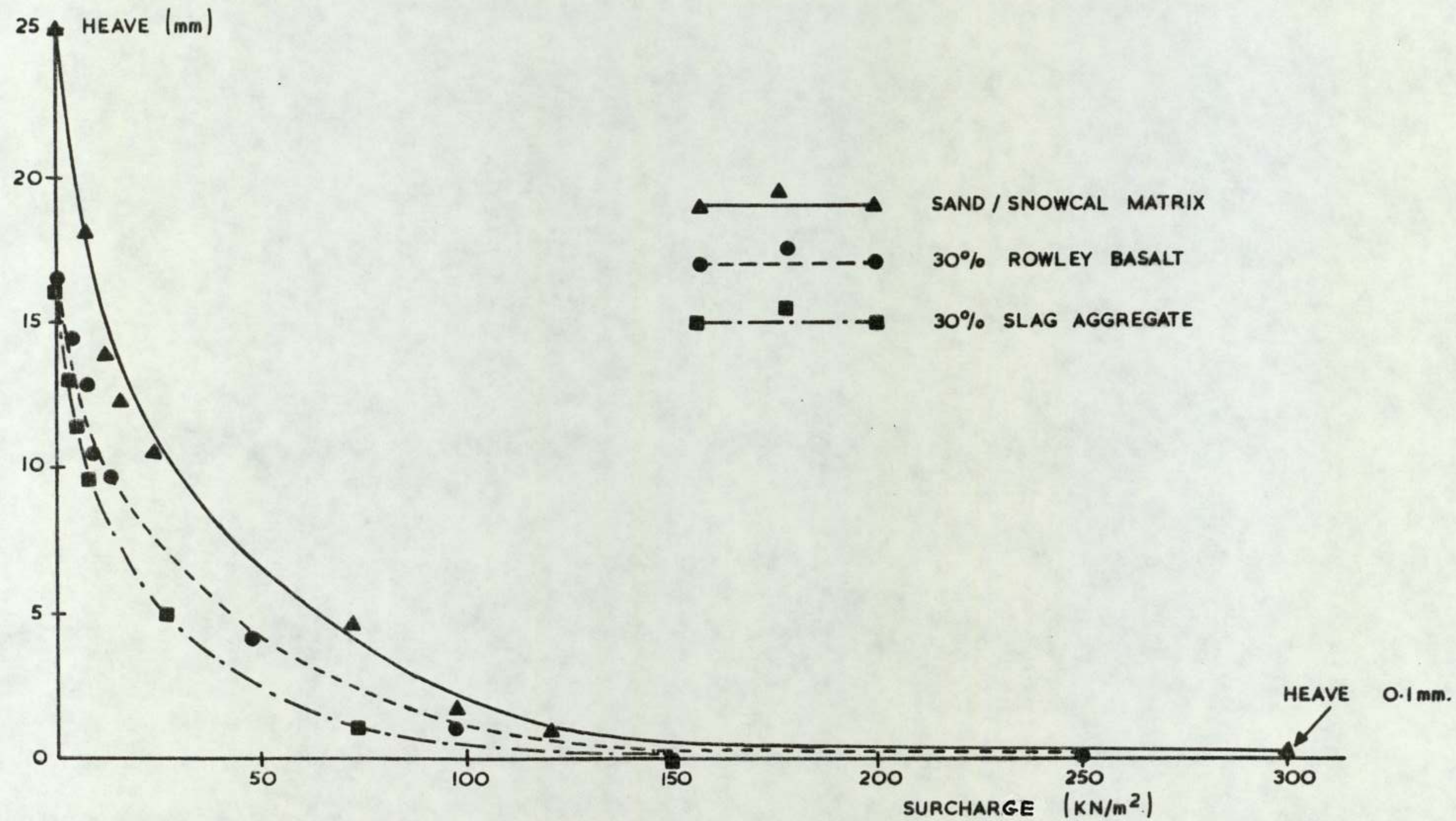


FIG. 9.7. FROST HEAVE AGAINST SURCHARGE.

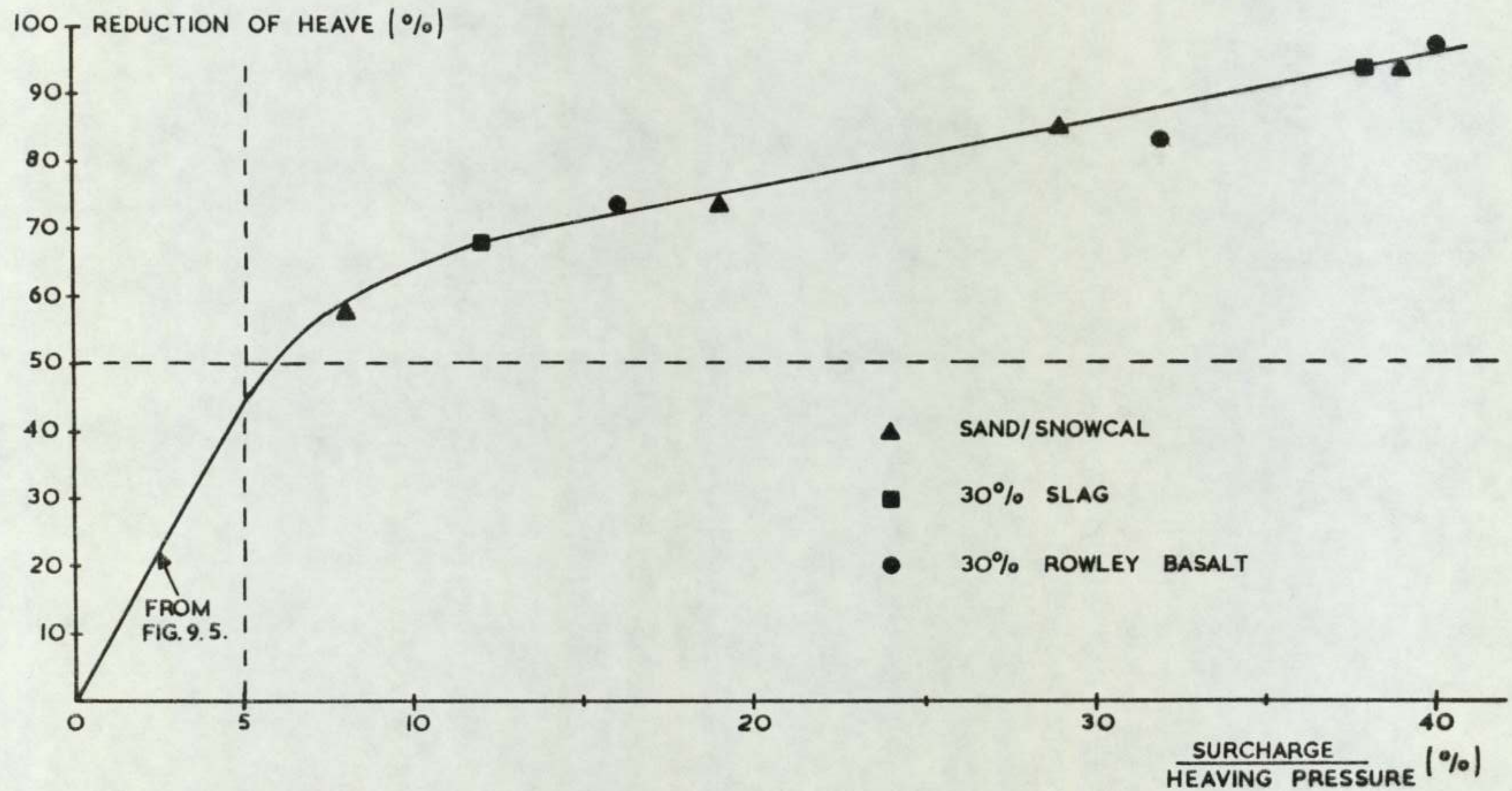


FIG. 9.8. REDUCTION OF HEAVE AGAINST SURCHARGE RATIO.

CHAPTER X

SOME ASPECTS OF FROST ACTION IN GRANULAR MATERIALS

10.1 Introduction

In the preceding Chapters frost action in granular soils has been discussed in terms of frost heave, heaving pressure and overburden or surcharge loads. It has been shown that the extent of frost action in the particular mixtures can be controlled by:-

1) the addition of coarse aggregate particles,
2) the application of surcharge loads.

The role of these factors has been discussed both separately and jointly. Most of the experimental results related to frost susceptibility have already been discussed and, so only the following key factors are considered in this Chapter:-

1) Mechanical stabilisation and the influence of aggregate type on frost action, including the interrelationship between frost heave and heaving pressure.
2) Influence of boundary conditions in freezing tests.
3) Consideration of the frost heave test and suggestions for improvements/modificatons in the assessment of frost susceptibility.
4) Relationship of the experimental observations to the various models of frost action described in Chapter II.

10.2 Introduction to mechanical stabilisation

The frost susceptibility of a soil may be reduced by stabilisation. This can be achieved through chemical or physical stabilisation - by bonding and/or waterproofing the soil particles or by mechanical stabilisation. This last technique involves mixing the frost susceptible soil with another material, so as to change the particle size distribution of the original soil. Although mechanical stabilisation is relatively easy to perform, it has not been extensively used for reduction of frost susceptibility. There is considerable published work available relating to the use of hydraulic binders, such as cement (61) and lime (127), to control frost action in soils. Many other chemical modifiers, including salt, lignosulphonates (128), have been suggested as possible additives that could reduce frost action. Whilst mechanical stabilisation has widely been accepted (89) as a technique for improving the bearing capacity of soil, it has not been considered for reducing frost action.

In Chapters VI and VII it was shown that, by mixing various aggregates with the frost susceptible matrix, its frost susceptibility was reduced both in terms of frost heave and heaving pressures. This modification of the matrix was effectively an illustration of possible benefits of mechanical stabilisation. The matrix was an artificial material consisting of sand and snowcal (4:1). To further examine the benefits of the technique, it was decided to select a highly frost susceptible natural soil, and to stabilise it with the same aggregates that were used to modify the matrix.

A waste sand, the by-product of Hilton quarry operated by Tarmac Ltd., was selected as the natural soil. The particle size distribution of the material is shown in Figure 10.1, together with that of the sand/snowcal matrix used in this investigation. It is clear that, overall, the waste sand is finer than the sand/snowcal matrix, with some 11 percent of clay sized particles compared with only 4.4 percent in the matrix.

The frost heave and heaving pressures were measured following the procedure described in Chapters V and VII. The waste sand was found to be highly frost susceptible with frost heave of 36.5mm, compared with a 24.4mm for the matrix. The heaving pressures were also higher, with a value of $460kN/m^2$ for the waste sand, compared with $300kN/m^2$

for the matrix. This behaviour was expected since the various theories and frost susceptibility criteria, that were reviewed in Chapter II, indicated that the increase in the content of fine articles would produce an increase in frost susceptibility. The higher content of these particles would be sufficient to modify the pore structure so as to produce increases both in heave and heaving pressure. Thus, this material, being highly frost susceptible was ideal for demonstrating the role of mechanical stabilisation.

It was decided to use only the 20-3.35mm particles, as the large particles had not shown any additional benefits as compared with the smaller, well graduated particles. Indeed, it was shown in Chapter VI, that the smaller particles had more influence on frost susceptibility than the larger particles. Following consideration of the appropriate results (Table 6.2) in Chapter VI, it was clear that such a highly frost susceptible soil would require a large addition of coarse particles to render it non-frost susceptible (5). It was, therefore, decided to add 50 percent of each type of aggregate to the waste sand. The frost heave and heaving pressures were measured and the results are collected in Table 10.1 and Figures 10.2 and 10.3.

Material	Heave (mm)	Reduction of heave (%)	Heaving pressure (kN/m^2)	Reduction of heaving pressure (%)
waste sand	36.5	0	460	0
50% Slag	8.8	76	218	53
50% Rowley Basalt	12.8	65	343	25
50% Caldon Low	15.0	59	308	33
sand/snowcal matrix	24.36	0	300	0
50% Slag	9.0	63	127	58
50% Rowley Basalt	11.6	52	225	25
50% Caldon Low	13.6	44	200	33

TABLE 10.1 Heave and heaving pressure for waste sand and sand/snowcal matrix mixed with 20-3.35mm aggregates

The results for the sand/snowcal matrix, from Chapters VI and VII, are also included in Table 10.1 for comparison and the frost heave of the matrix is also shown in Figure 10.4.

A comparison of the frost heave results in Table 10.1 shows that the influence of the aggregates on frost susceptibility is even more dramatic with the waste sand than with the matrix material. Indeed, the percentage reduction in heave is significantly greater with the waste sand. It can be seen, from Figures 10.2 and 10.4, that there is very clear similarity between the shape of the heave against freezing time curves, for both the matrix and the waste sand, when they are mixed with 50 percent of the coarse aggregates. Although the higher percentage of fine particles in the waste sand produced slightly higher heaves in these mixtures with 50 percent of aggregates, the shape of these curves is remarkably similar to those of the corresponding matrix-aggregate mixtures. This would imply that when a large percentage of coarse aggregate is introduced to a fine-grained soil, the properties of the aggregate itself will largely determine the behaviour of the composed mixture. It is, therefore, clear that not only the amount of fine particles, but also the amount of coarse particles will influence the freezing behaviour of the soil. The type of the aggregate is again shown to have a significant influence. It can be seen that 50 percent of Slag reduced the frost heave of the waste sand by 76 percent, whereas the same amount of the similarly sized Limestone particles only reduced the heave of the waste sand by 59 percent. Indeed, it is interesting to note that relative effects on heave, of the coarse particles, were the same in both the waste sand and the matrix. This again clearly demonstrates the importance of the type of coarse aggregate used to modify the frost susceptibility of a soil.

Whereas the reduction in frost heave, due to the addition of the aggregate, is larger with the waste sand than with the matrix, the reductions in heaving pressure are similar for both materials. The reduction is related to aggregate type, with the Slag aggregate again producing the largest reduction. It would appear, that for a given type of aggregate, the reduction in heaving pressure depends on aggregate content. Thus, providing that evidence is available of the effects of a particular aggregate on a given soil, it should be possible to predict the effects on heaving pressure when blending the same aggregate with other soils. It would only be necessary to establish the heaving pressure developed by the soil without aggregate.

It was shown in Chapter VI and Chapter VII, that frost heave and heaving pressure were, each, linearly related to the amount of aggregate added to the matrix. Separate relationships were apparent for each type of aggregate, both for frost heave and heaving pressure, and the differences between these relationships become more apparent as aggregate content increased. It was, therefore, considered appropriate to examine the possible relationships between frost heave and heaving pressure. Based on the data from Chapter VI and VII, the appropriate results are plotted in Figure 10.5 for the 20-3.35mm aggregates and in Figure 10.6 for the 37.5-20mm aggregates. It is clear that, for all the materials tested, the heaving pressure is linearly related to frost heave, but, again, the relationships depend on aggregate type with separate relationships for each aggregate. These differences become more apparent as the aggregate content increases. This provides further confirmation that the extent of frost action, in mixed soils, in terms of both frost heave and heaving pressure, depends not only on the fine fraction but also on the properties of the coarse aggregate. It should be noted, however, that both sizes of aggregate had a similar effect on heave and heaving pressure with the 20-3.35mm particles producing slightly larger reductions in frost heave than 37.5-20mm particles. The Slag aggregate was more effective than either of the other types and produced the largest reduction in both heave and heaving pressure.

Mechanical stabilisation could have some benefits compared with cement stabilisation, as no conditioning period is required and the materials could be mixed and laid on the site with a minimum of preparation. The removal of a frost susceptible soil, down to the required depth of frost penetration, and replacement of this soil with a clean gravel material is an alternative method of controlling the effects of frost action. However, as such replacement materials become more limited and, therefore more expensive, mechanical stabilisation could become a viable alternative. Indeed, instead of replacing the entire frost susceptible soil, it could be mixed with the clean gravel and relaid. As a further extension of this method artificial or waste materials such a crushed concrete or bricks could possibly be used to modify the pore or particle structure of the soil, although further investigation would be required before definite guidelines could be produced.

This study of mechanical stabilisation has shown that the Slag was more effective in reducing frost heave and heaving pressure, than the other types of aggregate. This observation has also been reported in the earlier Chapters and so consideration should be given to some of the factors that could account for this behaviour.

10.2.1 Internal boundaries

The extent of frost action in a soil, whether expressed in terms of frost heave or heaving pressure, greatly depends on the pore size distribution, providing that water is freely available at the freezing front. The pore structure of a mixed soil will be largely dictated by the coarse aggregate content, and by the relationship between the pore structure within the particle and that of the surrounding matrix. With an increase in the content of coarse particles a mixed soil will contain considerably fewer fines per unit volume (also per unit cross-section in a given plane) of material. Additionally, a limited number of large pores will be expected to form (89) between the large particles as they begin to form a continuous skeleton.

Similar behaviour would be exhibited by all the mixed materials at a given particle content, irrespective of particle type. Thus, whilst such behaviour accounts for some of the changes due to the incorporation of coarse particles, it does not adequately differentiate between the role of the different types of coarse aggregate.

In section 4.7, it was shown that the pores in the Slag particles are, generally, larger than those of the Basalt and Limestone particles although many are "ink-bottle" in shape and there are, usually, additional closed pores within the particles. It was also demonstrated that the pores, particularly in the Limestone, were small and very uniformly distributed. The interface between the matrix and the Limestone particles would, therefore, be expected to contain a large number of small pores formed between the conjunction of the open surface pores and the adjacent matrix. However, only a limited number of such small pores would occur at the Slag-matrix interface due to the coarser texture of the Slag particles. Thus, it could be expected from capillary theory model, described in Chapter II, that the frost heave or heaving pressures should be higher for the Limestone mixtures than for the Slag mixtures. This is supported by the experimental observations, with the intermediate behaviour occurring with the Basalt mixtures. The pore structure of the Basalt was between the extremes represented by the Slag and Limestone particles.

Another important consideration is the role of large particles lying across the freezing plane, with a portion of the particle above and a portion below, for they will offer frictional and displacement resistance to the heave forces located in the plane of freezing (60). Particles with a coarse surface texture are likely to develop greater interfacial resistance to displacement than smooth textured particles. In addition, large surface pores will rapidly fill with ice which will act like internal anchors and again would be expected to develop higher frictional resistance than smooth particles. The Slag particles have a significant amount of deep surface pores, the Basalt particles have some surface cracks, whereas the Limestone particles contain almost no large pores. Thus, mixtures containing large amounts of Slag aggregate would be expected to develop greater internal resistance to the freezing forces, than mixtures containing the other aggregates, and so they could be expected to develop lower values of frost heave and heaving pressure.

10.2.2 Thermal parameters

It has been demonstrated (107),(108) that the rate of heave is very dependent on the rate of heat extraction. With constant boundary conditions, for all the materials considered, the thermal conductivity of the soil - the rate at which heat energy flows across a unit area of the soil due to a temperature gradient - will depend on the thermal conductivity of both the matrix and the aggregates. For a given aggregate content, it is reasonable to assume that the thermal conductivity of the matrix is constant and so, the thermal conductivity of the mixture will largely depend on that of the aggregate. The rate of heat extraction will, therefore, depend both on aggregate content and aggregate type.

The matrix consists of 4 parts of sand to one part of crushed chalk and so its thermal conductivity will largely be controlled by the sand, or quartz, fraction. Of the major rock forming minerals present in the selected aggregates, quartz clearly (129) has the highest thermal conductivity as is shown in Table 10.2 using values abstracted from Horai (130). Thus, the addition of aggregate particles is likely to produce a mixture of lower thermal conductivity, since the various rocks contain minerals of lower thermal conductivity than quartz.

Mineral type	Thermal Conductivity (W/m^{o}C)	
	Mean	Variation
Quartz	7.7	
Feldspars		
Orthoclase	2.0	1.7 - 2.3
Plagioclase	2.1	1.9 - 2.3
Micas		
Muscovite	2.3	2.2 - 2.5
Phlogopite	2.1	1.9 - 2.3
Calcite	4.2	3.5 - 4.7

TABLE 10.2 Thermal conductivity of some rock-forming minerals (130)

The Limestone consists of some 99% calcite, calcium carbonate. It is apparent from the values in Table 10.2 that although calcite has a lower thermal conductivity than quartz, it is higher than those of the other listed materials. Basalts (131) generally contain plagioclase and augite minerals together with various accessories. The particular Rowley material is largely plagioclase with calcite accessories. Thus, from the data in Table 10.2, it is clear that these particles will have a lower conductivity than the Limestone particles and so would produce composite materials of lower thermal conductivity.

It is difficult to obtain precise data on the thermal properties of the Slag particles, particularly as the chemical, and physical, structure is greatly dependent on the source of supply, manufacturing process and subsequent treatment. Basically slags are complex mixtures of calcium silicates and aluminates. Although it is difficult to predict their mineralogy, it is likely to be closely related to that of the igneous rocks than to that of the limestone, or basic quartz. The thermal conductivity of the Slag is, therefore, likely to be low.

Additional support for these suggested levels of thermal conductivity can be gained from consideration of the particle density and porosity. The thermal conductivity of rock-forming minerals has been shown (130) to increase with increases in their density. The investigation of the aggregate properties, described in section 4.7, revealed that the Slag aggregate, is a dense material, with a considerable content of large pores. However, these pores are either closed or "ink-bottle" shaped and so are free from water and contain only air. The Basalt also had a number of internal cracks, breaking the structure of the mineral, while the Limestone was a porous material with small, evenly distributed pores. The water absorption values of the aggregates given in Table 4.7 in Section 4.5 showed that under vacuum, the Slag absorbed approximately three times as much water as the Limestone and twice as much as the Basalt. The Limestone appears to be denser in terms of the proportion of mineral matter to the total pore space, than either the Slag or the Basalt. Thus, with constant test conditions, the Limestone particles would be able to conduct more heat, than the other particles and with the increase in heat transfer would be expected (107) to increase the frost heave. This is also supported by the earlier comments regarding the thermal conductivity of the rock minerals.

When heat is conducted through soil, it will be transmitted through the contacting solid grains and so with an increase in the coarse aggregate content, the conduction of heat through the particles will become more important. This will be particularly influenced when the aggregate content approaches 50 percent and the aggregate - matrix mixture forms a skeleton - type soil. The Slag aggregate, with large pores in the particles will transmit less heat than the Basalt or Limestone. Thus, mixtures containing large amounts of Slag would develop the lowest heaves. The highest heaves, from the mixed soil, would develop by the Limestone mixtures with the heaves of the Basalt mixtures being between these limits. This behaviour is supported by the experimental results in Tables 6.2 of Chapter VI and by the more limited data in Table 10.1. At low aggregate contents this effect will be less pronounced and the heaves for all the aggregate types do not differ considerably at contents below 30 percent.

Another important consideration is the total porosity of the material, which reflects its dry density. It has been reported (132) that a decrease in porosity leads to more contact points and, hence, to a better heat transfer. In section 4.6 the total porosity was calculated for all the mixtures. It can be seen from the results in Table 4.8 that the total porosity is similar for all mixtures with only low percentages of aggregate in the matrix. However, as the aggregate content is increased more differences become apparent between the values for mixtures containing different aggregates. For mixtures containing 50 percent of the aggregate, the Slag mixture has a porosity of 0.23, compared with 0.20 and 0.17 for the respective Basalt and Limestone mixtures. The Limestone mixture will, therefore, be able to effectively transfer more heat than the other mixtures and this will also lead to the development of higher heaves.

The low porosity of the mixture, coupled with the good conductivity through the aggregate particles, will allow more heat to be extracted through, say the 50 percent Limestone mixture, than through the corresponding Slag mixture. Hence, higher frost heaves are developed by the Limestone mixtures than by the Slag mixtures.

10.2.3 Combined effects

From the discussion in the preceding sections, it is suggested that the introduction of coarse particles into the matrix produces reductions in frost heave and heaving pressure through several, interrelated mechanisms:-

(i) mobilisation of internal friction at the particle/matrix interface.

(ii) changes in pore structure both within the mixed material and localised at the particle/matrix interface.

(iii) reductions in thermal conductivity.

The reductions observed with the selected matrix have been discussed earlier and, in Table 10.1, the effects produced in two different matrices are summarised. Although the particular reductions are unique for each combination of matrix-coarse particle, it is clear that with both matrices, for a given particle content, the reduction in heave is greater than that in heaving pressure.

When the freezing soil is allowed to heave freely, all the proposed mechanisms would be involved. However, in a heaving pressure test, the movement of the sample is very low (less than 0.05mm) and so the full effects of the frictional resistance are unlikely to be mobilised. Thus the heaving pressure test provides an indication of the relative changes in thermal conductivity and pore structure, whereas heave tests also involve the internal resistance to displacement. The relative influence of the various factors would depend on the characteristics of the matrix and, particularly in view of its high thermal conductivity, on the quartz content.

10.3 Influence of Boundary conditions

10.3.1 Temperature of the cooling plate

In the cold room and SRU, variations in the air temperature, within the specified tolerances, did not significantly influence the temperature at the top of the test specimens, since the Tufnol caps on top of the specimens have a very high thermal resistance. However, with heaving pressure and CHU equipment, the temperature of the cooling plate could be adjusted and controlled over a wide range of values. It was shown in Chapters VII and VIII that the top temperature had a significant influence on heaving pressure and frost heave, although these relationships took different forms. Frost heave was linearly related to the cooling plate temperature down to $-13^{o}C$, but the heaving pressure was only linearly related to this temperature down to $-4.5^{o}C$. At lower temperatures the relationship deviated from the linear form so that although heaving pressure continued to increase, the rate of increase was much lower. This may be attributed to the comparatively narrow range of temperatures that were applied. These were limited by the performance of the experimental equipment.

With the temperature of the cooling plate being reduced, the net rate of heat removal is increased. It is recognised by the various theories and supported by experimental studies (107),(108), that the rate of heave of an unloaded soil depends on the net rate of heat extraction from the soil. Therefore, the frost heave is directly related to the temperature of the cooling plate and, at least within the experimental range of temperatures, this relationship is linear. It is suggested (107) that the flow of water to the freezing front is controlled by the temperature gradient in the frozen soil. Thus as the temperature of the cooling plate is lowered, water intake will be promoted leading to an increase in heave rate, as was observed with the CHU tests.

At very high rates of heat extraction, however, the rate of frost penetration is very rapid. Thus, the heat production due to frost penetration takes an increasingly larger part of the total heat extraction, while the ice lens growth rate becomes constant or decreases. Under such conditions the rate of water intake becomes dependent on the hydraulic conductivity rather than the temperature gradient (107),(133). This was not observed in the particular tests as the range of heat extraction rates was not large. However, such observations have given rise to the concept of an optimum heat extraction rate (107) for each soil. This has lead to the suggestion (126) that standard frost heave tests should be undertaken at two rates of heat extraction whilst Loch (134) has suggested a suitable rate to applied to Norwegian soils in frost susceptibility tests.

Heaving pressure is linearly related to the temperature of the cooling plate over a narrower temperature range than the frost heave. This relationship deviates from the straight line for cooling plate temperatures below $-4.5^{\circ}C$, with the rate of increase in heaving pressure decreasing as the temperature of the cooling plate is further reduced. Similar behaviour has been reported by Takashi (26) and he has suggested that the dependence of the maximum heaving on the temperature of the cooling plate is not compatible with the capillary theory.

As the temperature of the cooling plate is reduced the flow network, through the frozen soil, becomes interrupted so that ice lens growth is restricted at the cooling plate. At such temperatures ice lenses grow between the cooling plate and the freezing front (26) and so the heaving pressure is no longer linearly related to the temperature of this plate. It depends on the temperature of the particular growing lenses. The temperature at which the network becomes interrupted depends on soil texture so that with fine grained soils such linear behaviour is observed (26) down to $-20^{\circ}C$.

In section 10.2 it has been shown that, with certain boundary conditions, the frost heave is linearly related to heaving pressure, with separate relationships for each type of aggregate. The particular boundary conditions were designed to produce a temperature gradient through the specimens similar to that produced in the standard frost heave specimens. It was, therefore, decided to examine whether the frost heave and heaving pressure could be related over a range of cooling plate temperatures for the sand/snowcal matrix. Experimental data, presented in Chapters VII and VIII have been used to plot the relationship in Figure 10.7. All this data was obtained from tests with a constant bottom temperature of $+4.0^{\circ}C$ and so, the zero isotherm was penetrating through the specimen following each step reduction in the top temperature. It can be seen from Figure 10.7 that there is a relationship between frost heave and heaving pressure although it is not linear. After a rapid increase in both the frost heave and the heaving pressure down to approximately $-7.0^{\circ}C$, the rate of increase in heaving pressure is much less than that in heave and it appears that the heaving pressure may be approaching a limiting value. Heave tests were not performed at temperatures below $-9^{\circ}C$ but it is probable that at lower temperatures the heave behaviour would also change (108).

10.3.2 Temperature of the water bath

In both the cold room and the CHU the temperature of the water bath significantly influenced the measured frost heave. The lower heaves were recorded at the higher water bath temperature, for a constant cooling plate temperature, and this was observed for all such temperatures between -1 and -15°C. The decrease in heave was attributed to a rise in the location of the zero isotherm when the temperature of the water bath is increased and to a decrease in the magnitude of the induced suction. It is important to note that in order to maintain a constant heave, when the temperature of the water bath was increased, it was necessary to reduce the top temperature of the CHU specimen as was shown in Figure 8.2.

It was also noticed that heave tests, both in the CHU and the cold room, with different boundary conditions, but with the zero isotherm in a similar location, produced comparable results. It is, therefore, suggested that the temperature gradient and the position of zero isotherm should be specified for experimental purposes, particularly where the testing is being undertaken to assess frost susceptibility.

10.3.3 Friction and adfreeze

It was clearly demonstated in Chapters VII and IX that friction and adfreeze have a significant effect on heaving pressures and frost heave. Considerable development work was reported in these chapters to eliminate such effects from the heaving pressure and CHU equipment. The final modication to these facilities, which included a multi-ring system together with a greased rubber membrane, produced a 200 percent increase in the heaving pressure compared with that measured with the original system.

When a multi-ring system was used in the SRU, in Chapter IX, an increase in frost heave of about 150% was noted. But in the CHU the introduction of a multi-ring system did not produce a significant difference in the recorded heave compared with that of a standard, paper wrapped specimen. In the CHU, due to different lateral temperature conditions from those in the cold room and SRU, the adfreeze effect was not apparent. This was clearly illustrated at the end of the CHU test as the specimens could be easily unwrapped. In comparison, the specimens from the cold room and the SRU were frozen to the paper at the completion of the tests and this would act as a restraint to the frost heave. It is, therefore, essential to assess the effects of adfreeze and friction on the exhibited front action when commencing a series of freezing tests or developing a new equipment.

It is possible to conclude that boundary conditions such as:-

1) temperature of the cooling plate,

2) temperature of the water bath,

3) adfreeze and friction,

have a significant effect on both frost heave and heaving pressure and so should be clearly specified.

10.4 The Assessment of Frost Susceptibility

In the United Kingdom, frost susceptibility is assessed by subjecting laboratory specimens to the TRRL frost heave test. This section is concerned with relating the experience gained with the test to that reported by other workers, and comments are presented on several aspects of the test. In addition, the measurement of heaving pressure is considered as an alternative technique for assessing frost susceptibility.

10.4.1 Specimen Size

The presence of large particles in excess of 37.5mm, in 102mm diameter specimens was recognised (61),(82),(135) to be one of the probable causes of the experimental variability. It was suggested (135) that the use of 152mm specimens would simplify the testing of such materials since it would increase the ratio between the size of the particles and the diameter of the specimen. In the present investigation, specimens of 145mm diameter were used but it was considered that this did not represent a significant departure from the alternative diameter of 152mm.

In Table 10.3, experimental results obtained elsewhere (82),(135) are summarised together with the results obtained with the 145mm specimens.

Material	MEAN HEAVE $\frac{102MM}{152MM}$
After R. Jones (135)	
Whin 1	0.64
Cal 2	0.50
Carb 2	0.62
After P. Sherwood (82)	
Sand/Limestone filler	0.62
Limestone Gravel	1.15
Granite	0.77
Whinstone	0.62
Calcitic Dolomite	0.61
Carboniferous Limestone	0.60
Chapter VI	
Present investigation *	0.92

TABLE 10.3 Ratio of the mean heaves obtained with 102mm specimens and 152mm specimens

* Note diameter of the large mould is 145mm, not 152mm as employed elsewhere.

In the present investigation, the 145mm specimens produced consistently higher values of heave than those obtained with the 102mm specimens. This is in agreement with the work at Nottingham University (135) and the TRRL (82). Jones (135) indicated that the ratio between the heaves of the two sizes of specimens ranged from 0.50 to 0.64 whilst, at the TRRL (82), the range was 0.60 to 0.77 with one material producing a value of 1.15. In view of the considerable variation in this ratio it was concluded (135) that the introduction of 152mm specimens would not produce a simple solution for testing such coarse, granular materials.

For the particular materials tested in this investigation, the ratio varied from 0.91 to 0.94, as detailed in Chapter VI, thus producing a reasonably consistent correlation between the heave results from the two sizes of specimen. This good correlation has been attributed to the nature of the materials that were tested, since all the mixed materials consisted of a closely graduated, standard matrix into which prescribed quantities of selected aggregates were introduced. This produced a more uniform and consistent distribution of both fines and large particles as compared with the the various crushed aggregates and fines that were used in the other investigations (82),(135). In particular, the fine matrix was consistent throughout this investigation. It is, therefore, suggested that the ratio of 0.92, established in this study, should only be regarded as applicable to the particular materials and should not be used for the interpretation of experimental results obtained with other mixtures.

10.4.2 Comparison between CHU and PFC

In order to provide better control over the boundary conditions in a heave test, the Controlled Heave Unit (CHU), described in Chapter IX, was developed. A similar facility, known as Precise Freezing Cell

(PFC), has been developed and described by Dudek (70) and Jones (117). This was also designed to give precise control over the boundary conditions in frost heave tests (70). Both techniques appear to give repeatable heave results, although there appears to be significant differences in the absolute values.

The total heave measured with the PFC, was much lower than that from corresponding tests undertaken in the SRU or cold room (70). For instance, a reference mixture consisting of four parts sand to one part limestone filler, similar to the standard matrix used in the present investigation, produced a mean heave in the PFC of 6.7mm and in the cold room/SRU of 20.1mm (117). In comparison, as reported in section 8.4, the standard matrix produced a mean heave of 24.8mm in the CHU compared with 24.4mm in the cold room. It was, therefore, necessary to consider any factors which could account for the lower heave values reported with the PFC. Of particular note are:-

a) adfreeze effects,

b) boundary conditions with respect to the location of the zero isotherm,

and these will be considered separately in the following paragraphs.

It was shown in Chapters VII and IX that surface friction and, especially, adfreeze could significantly influence the measurement of heaving pressures and of frost heave. This was emphasised in Chapter IX where the introduction of a multi-ring system to the CHU, produced an increase in frost heave of about 150%, and suggested, therefore, that the results in the SRU and cold room are affected by adfreeze between the paper and the side of the specimen. It was reported by Dudek (70) that at the end of a test in the PFC, the paper was frozen to the specimen and, therefore produced a significant adfreeze and frictional resistance. This did not happen in the CHU for, at the end of the test, the paper could be easily removed from the specimen.

This difference may be attributed to the manner in which the boundary conditions were applied in the PFC and the CHU.

In the PFC the annular space between the specimen and the inner tube was filled with sand, with a guard ring being placed on top of the sand. Lateral pressures would, therefore, be applied to both the wax paper and the surface of the specimen. This produced additional surface friction which would be effective throughout the test. In the CHU the specimen is wrapped in paper, but it is free standing with a clearance between the specimen and the insulation. Thus, no additional restraint or friction was developed at the paper-specimen interface.

With the PFC the guard ring placed on top of the sand packing contains a circulating refrigerant maintained at $-6^{\circ}C$. This was introduced to maintain temperature stability at the cold face of the specimen. However, as the specimen starts to heave and enters the annulus of the guard ring, it is very likely that the vertical surface of the specimen will experience additional cooling. This will stimulate some lateral water movement towards the outside of the specimen. Such a phenomenon was discussed in detail in section 8.3.7. As a result of these effects, adfreeze will be developed between the paper and the surface of the specimen.

In the CHU the outer face of the specimen is slightly warmer than the centre since the heaving specimen is not exposed to a guard ring, but is merely enclosed in a polystyrene block with the entire assembly in a cold cabinet operating at $+4^{\circ}C$. Thus, no adfreeze was apparent between the specimen and the paper. The adfreeze of the paper to the specimen surface is, therefore, caused by the temperature distribution through the sand packing. This is enhanced by the lateral pressures from sand packing and guard ring which will cause a closer contact between the paper and the specimen, so that adfreeze is quickly produced under favourable temperature conditions. Such adfreeze will significantly reduce the total heave exhibited by a specimen in the PFC.

It was discussed in section 8.3.3 that the location of the zero isotherm in the CHU depended on the top temperature. With a top temperature of $-6.2^{\circ}C$, a typical value measured with a cement stabilised specimen in the cold room, the final location of the zero isotherm in a specimen of the sand:filler matrix was somewhat higher than that observed with similar specimens in the cold room. It was underlined in the cold room/SRU that, when the specimen was heaving and protruded through the sand packing, it experienced not only additional lateral cooling, but the top temperature was also lowered. In the CHU this top temperature remained constant throughout the test. It was, therefore, decided to adjust the top temperature so as to obtain a similar position of the zero isotherm in the CHU specimen to that achieved with the cold room specimens. This resulted in an increased value of the total heave as the top temperature was lowered from $-6.2^{\circ}C$ to $-7.0^{\circ}C$, the top temperature in the PFC being $-6.0^{\circ}C$. With the CHU specimen the unfrozen zone for a top temperature of $-6.2^{\circ}C$ was 75mm while with $-7.0^{\circ}C$ it was 62mm, which is similar to that observed in the cold room specimens.

Jones and Dudek (117) include details of the temperature gradient through a PFC specimen (Figure 5 in (117)). It appears that the unfrozen zone is also about 75mm in the PFC specimen with a top temperature of $-6.0^{\circ}C$, and this would be expected to produce a lower value of total heave compared with cold room/SRU tests.

It is, therefore, possible to conclude that the effects of adfreeze, together with the different top temperature/position of the zero isotherm in the specimens tested in PFC, are likely reasons for difference in the results obtained in PFC and CHU.

In addition, it is important to note that the total heave measured in the CHU is lower than the "absolute" heave measured in the SRU with a multi-ring system, which virtually eliminated the effects of sidewall friction and adfreeze. These differences in heave values were also attributed to the different rates of freezing imposed in the two tests, as was discussed in section 8.3.5. However, comparisons of the heave results from the standard tests and from the CHU tests given in Table 8.3, indicated that they are quite similar. This may imply that the elimination of adfreeze in the CHU compensated for the faster rate of freezing and, by coincidence, these values were of the same magnitude. It is, therefore, possible to use the standard criteria, developed for the TRRL frost heave test, with the CHU test, for the particular materials investigated, providing that all the boundary conditions remain as described in the preceding paragraphs. With other materials, where changes in the rate of freezing and the elimination of adfreeze have yet to be assessed, this may not be possible.

10.4.3 Use of the Cold room and the SRU

Several comparative studies (61),(136) have been undertaken to assess the influence of the test facility - cold room or SRU - on the results of the frost heave test. Although different forms of SRU were adopted, it was concluded (61),(134) that tests could satisfactorily be undertaken in the SRU. Indeed, although the test was originally specified (5) in terms of a cold room, it is clear that the SRU will become the preferred facility for future testing (82). There was, however, a tendency for the two facilities to produce different heave values for those materials with high heaves. Whilst Kettle (61) found that the SRU produced a lower heave value for such materials, Jones (137) suggests that there was a tendency for the SRU to give higher heave values than the cold room for very frost susceptible materials. As these differences were only apparent with materials that exhibited heaves greater than 15-20mm, they are not likely to influence the classification of frost susceptibility.

In the present investigation, only a limited number of tests were undertaken in SRU and care was taken to calibrate the boundary conditions, using cement stabilised specimens, with those achieved in the cold room. It was underlined, in Chapter V, that changes in the boundary conditions could cause considerable variations in the heave results from the cold room. A preliminary study in the SRU using sand/snowcal specimens produced the results reported in Table 9.1. These revealed that the results obtained in SRU were not significantly different from those obtained in the cold room. This is largely attributed to the high degree of control over the boundary conditions in the two facilities. However, the use of well-graduated, standard matrix also reduced the variability in the results and, with natural materials, a larger variation may be expected.

10.4.4 Improvements to the TRRL frost heave test

Specimen preparation was not studied in this investigation, as static compaction was used throughout for the preparation of frost heave specimens. However, a comparative study between the hydraulic conductivity values of specimens of 102mm and 145mm diameter indicated that zones of undercompacted material and overcompacted material were present in statically compacted specimens. Thus, the use of a vibrating hammer as has been recommended (67),(82) should represent an improvement in the production of uniform specimens.

It is believed that one of the major factors causing great scatter in heave results is variation in the boundary conditions. This is especially significant when the temperature of the water bath is considered. Even variation within the permissable range of $+4.0 \pm 0.5^{o}C$ can produce a difference of $1^{o}C$ in the limiting values. The cold room is more vulnerable to such variations, as the water bath is topped up daily, and it is difficult to employ a reliable source of water circulating. A circulating pump in the water bath did not completely eliminate localised cold regions. Although similar cold zones were noticed in the SRU, they were much less pronounced. It is possible that further modifications of the heating system (location of the heating tape) and circulating system could produce even smaller variations in the temperature of the water wash. Since the SRU was only used for a small part of the total study, such modifications were not pursued as the heave results from the SRU were in agreement with those from the cold-room.

The sand filling appeared to conduct more heat than the vermiculite and so with vermiculite, it was clear that lateral heat flow was reduced. This was especially noticeable when testing 145mm diameter specimens. A study of the type of insulating material and the selection of a matching insulating material, with similar thermal characteristics to the test material could limit lateral heat losses and probably, also, minimise the adfreeze effects. However, such modifications should not complicate the test procedure or raise the cost of the test.

In order to check the boundary conditions, it is suggested that use should be made of cement stabilised specimens, with the thermocouples permanently incorporated both inside and outside the specimen. This gives an easy and reliable comparison between successive test trials and facilities, as thermocouples are positioned in predetermined locations and the cement stabilised specimen does not experience frost heave.

Variations in the air temperature both in the cold room and the SRU, within the permissible range of $-17^{\circ}C \pm 1^{\circ}C$ did not have a significant influence on the top temperature under the Tufnol cap of the cement stabilised specimens. When a specimen heaves and protrudes through the sand filling, the top temperature is lowered. Thus, specimens with higher initial heave will have their top temperature lowered and so, have a stimulus for even greater heave, compared with the low heaving specimens in a particular test run. It is impossible to control this fluctuation in the cold room or SRU, but in the CHU, with a constant top temperature, a more rigid control is possible over the boundary conditions. The variations in the heave results were observed to be less than those from the other facilities. It may be more beneficial, for a standard test, to adopt a cryostat cooling plate system as a means of freezing the specimen instead of freezing in the cold-rooms or SRU's. This would provide an improved control over the boundary temperature but could be expected to complicate the test procedure (96).

Although a direct study was not undertaken of the length of the test period, it is clear from the detailed heave results that it could be reduced from 250 hours to 100 - 120 hours. At the completion of this period of time, the specimens generally exhibited some 80% of the 250 hour heave. Similar behaviour has been reported by other workers (61),(67),(82) and it is recommended that such a change should be adopted with the test period of 100 hours. This has recently been proposed (66),(82) with appropriate criteria and appears to offer considerable benefits to those undertaking the test.

10.4.5 Frost susceptibility and heaving pressures

The measurements of heaving pressures has been suggested (52),(137),(138) as an alternative for assessing frost susceptibility. However, appropriate frost susceptibility criteria have yet to be developed. Such an approach will require future correlations between laboratory data and field observations. Considerable data has been obtained, during this study, related to heave and heaving pressure. Present frost susceptibility criteria (5) are based solely on frost heave and so it was considered appropriate to apply these criteria to the heaving pressure data.

The appropriate results are given in Chapters VI and VII and a comparison of the frost heave and the corresponding heaving pressures indicates that materials which develop pressures of less than 150kN/m^2 were non-frost susceptible. This can also be seen from the frost heave/heaving pressure relationships given in Figures 10.5 and 10.6. However, such a criterion could be rather conservative, as some materials (50 percent Basalt mixture) which developed heaving pressure in excess of 150kN/m^2 were also classified as non-frost susceptible through its frost heave. It is, therefore, suggested that heaving pressure could be an additional and useful aid in assessing frost susceptibility, but it should be related to a particular structural design, rather than to an unrestrained frost heave.

The TRRL frost susceptibility criteria (5) were specifically developed for roadworks and so they may not be appropriate for structural applications such as pipelines. In these locations the heaving pressures could produce critical stresses in the structure leading, ultimately, to catastrophic failure, and so, the tentative criterion, based on heave/heaving pressure relationship, may not be suitable. Indeed, when the weight of the structure contributes to a reduction in the surface heave, without producing structural distress, this criterion would need to be revised.

For the future development of criteria based on heaving pressures, it will be necessary to undertake correlations between laboratory studies and field observation. The acceptable heaving pressures may also have to be related to a particular application and even to particular structural forms.

10.5 Consideration of the Theoretical Models

The freezing behaviour of mixed granular materials has been studied in the present investigation. Although the materials were initially classified as granular, some 8 percent of fine silt was present in the matrix, and so the materials should be treated as mixed soils rather than as ideal, granular mixtures. In Chapter II three theoretical models were considered, namely:-

1) capillary,
2) secondary heaving,
3) adsorption force.

Although the derivation of the absorption theory is different from that of the secondary heaving model, they have some common phenomenological aspects. The absortion theory involves a partially frozen zone, referred to as a zone of diffused freezing, which resembles the frozen fringe in secondary heaving. However, the formulation of the adsorption theory is more complicated than that of secondary heaving and the controlling factor, for determining the freezing point depression, is the surface area between the ice and the soil which will be much greater in clayey soils than in mixed, granular materials. This consideration has, therefore, been confined to only the capillary theory and the secondary heaving theory.

The secondary heaving theory, however, incorporates both "primary" and "secondary" heaving, with primary heaving effectively representing the capillary theory. It may, therefore, be possible to combine the two phenomena into a single explanation. It is suggested that the primary heave/capillary model is responsible for the beginning of the process, with the extent of the frost action being largely dictated by the soil data, such as pore size, and by the rate of heat extraction. The extent of secondary heaving will, however, determine the magnitude of the heaving pressures and the effects of prolonged freezing. The controlling factors will then become the temperature gradient in the frozen zone and the extent of the frozen fringe. This explanation assumes that water is freely available to the growing lenses.

As coarse aggregate is introduced to the matrix, the pore size of the mixed soil will increase due to the development of large pores between the interacting aggregates and there being an insufficient amount of fines to fill these spaces. In addition there is a reduction in the amount of small pores contained in any freezing plane through the material.

From the capillary the pressure difference across the curved interface is given by:-

$$p_i - p_w = \frac{2\sigma_{iw}}{r_p} \qquad (10.1)$$

where

p_i = ice pressure

p_w = liquid pressure

σ_{iw} = interfacial tension of the ice/water interface

r_p = effective pore radius of the soil

It is clear that, with an increase in the pore radius, r_p, the pressure difference across ice-water interface will be reduced. This will reduce the induced suction and so the flow of water, and hence the frost heave, will be reduced.

This capillary model represents the primary element in heaving. In a mixed, granular soil containing some colloidal or fine material, a partially frozen zone - "frozen fringe" - is expected to exist. It will be very small in comparison to that present in clay soils. In this study, with the aggregates being added to a standard matrix, the thickness will largely be dictated by the amount of coarse aggregate. The study of heaving pressure, reported in Chapter VII, illustrated that the magnitude of the heaving pressures was dependent on the temperature of the cooling plate (rate of heat extraction) and, particularly, on the temperature gradient under the ice front. This suggests that the magnitude of the heaving pressure was dependent on the extent of secondary heaving rather than, solely, on the extent of capillary freezing.

It is difficult to be precise as to the extent of secondary heaving in the soils studied and it is expected that with large amounts of coarse aggregate, the capillary model will be more dominant. However, for future mathematical modelling of soil heaving, it will be more appropriate to consider frost action in mixed granular soils in terms of secondary heaving rather than attempting to attribute all the observations to the capillary model.

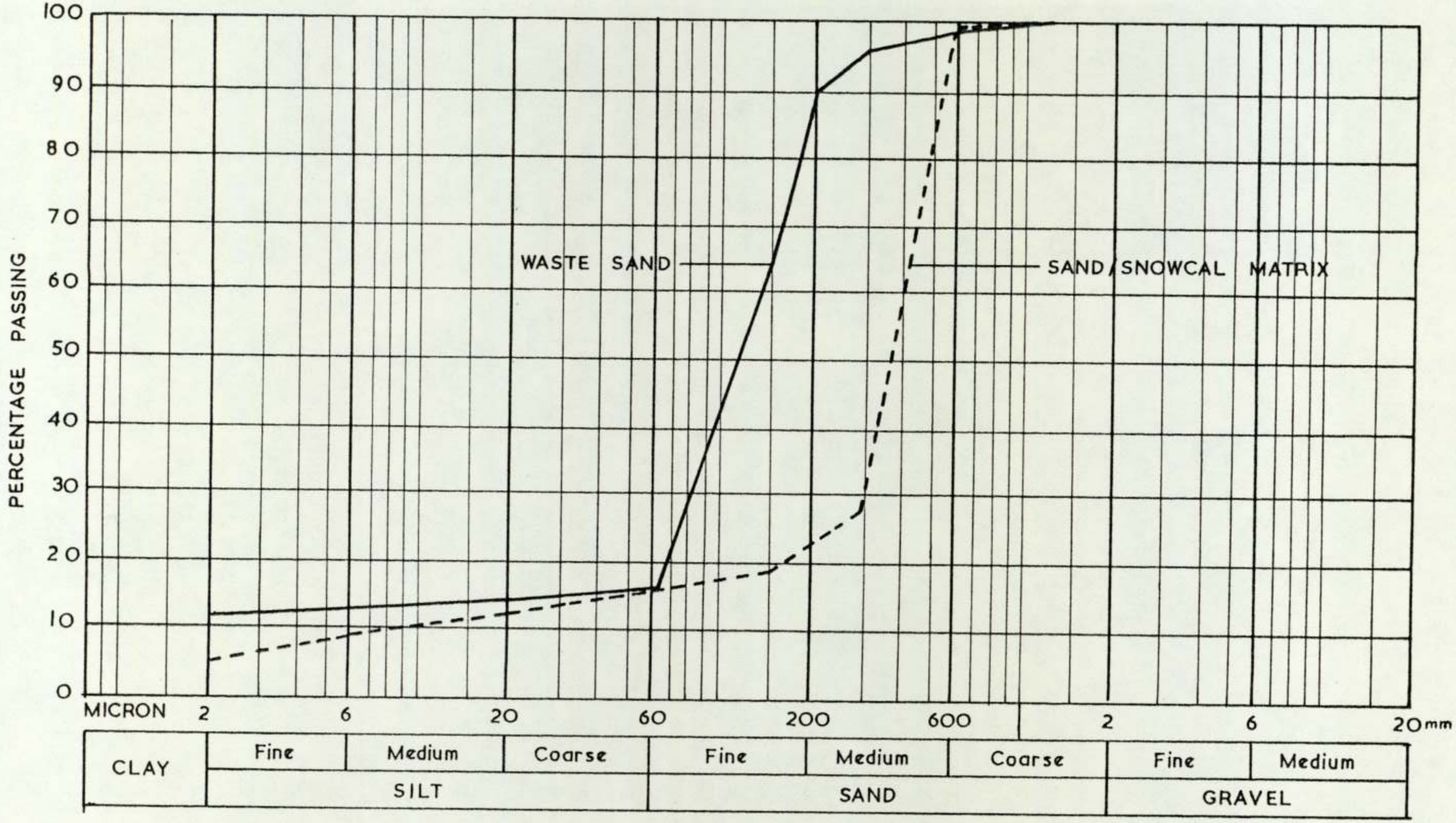


FIG. 10.1. PARTICLE SIZE DISTRIBUTION FOR WASTE SAND AND SAND/SNOWCAL MATRIX.

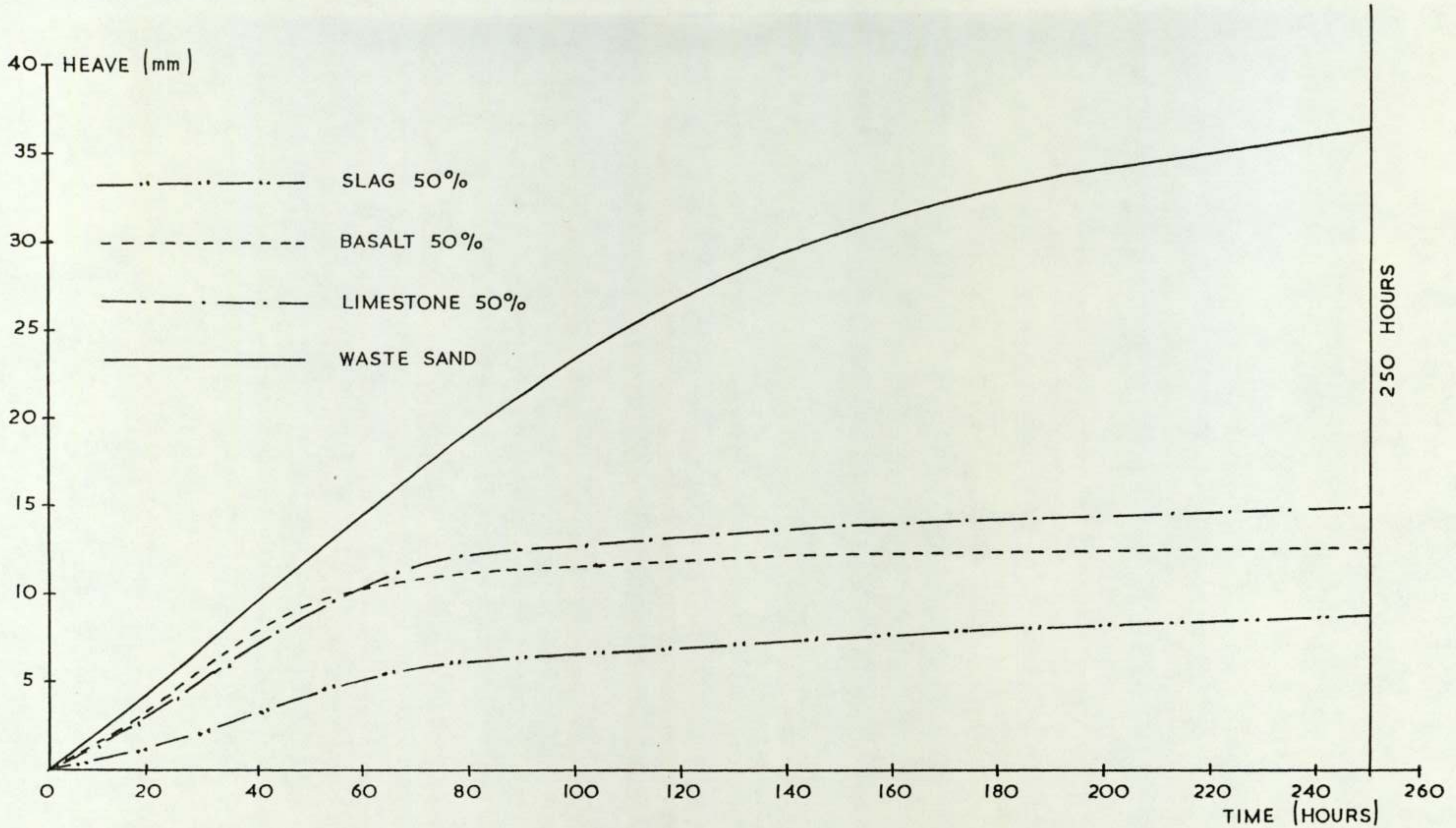


FIG. 10. 2. HEAVE AGAINST TIME FOR WASTE SAND AND 20–3.35mm AGGREGATES.

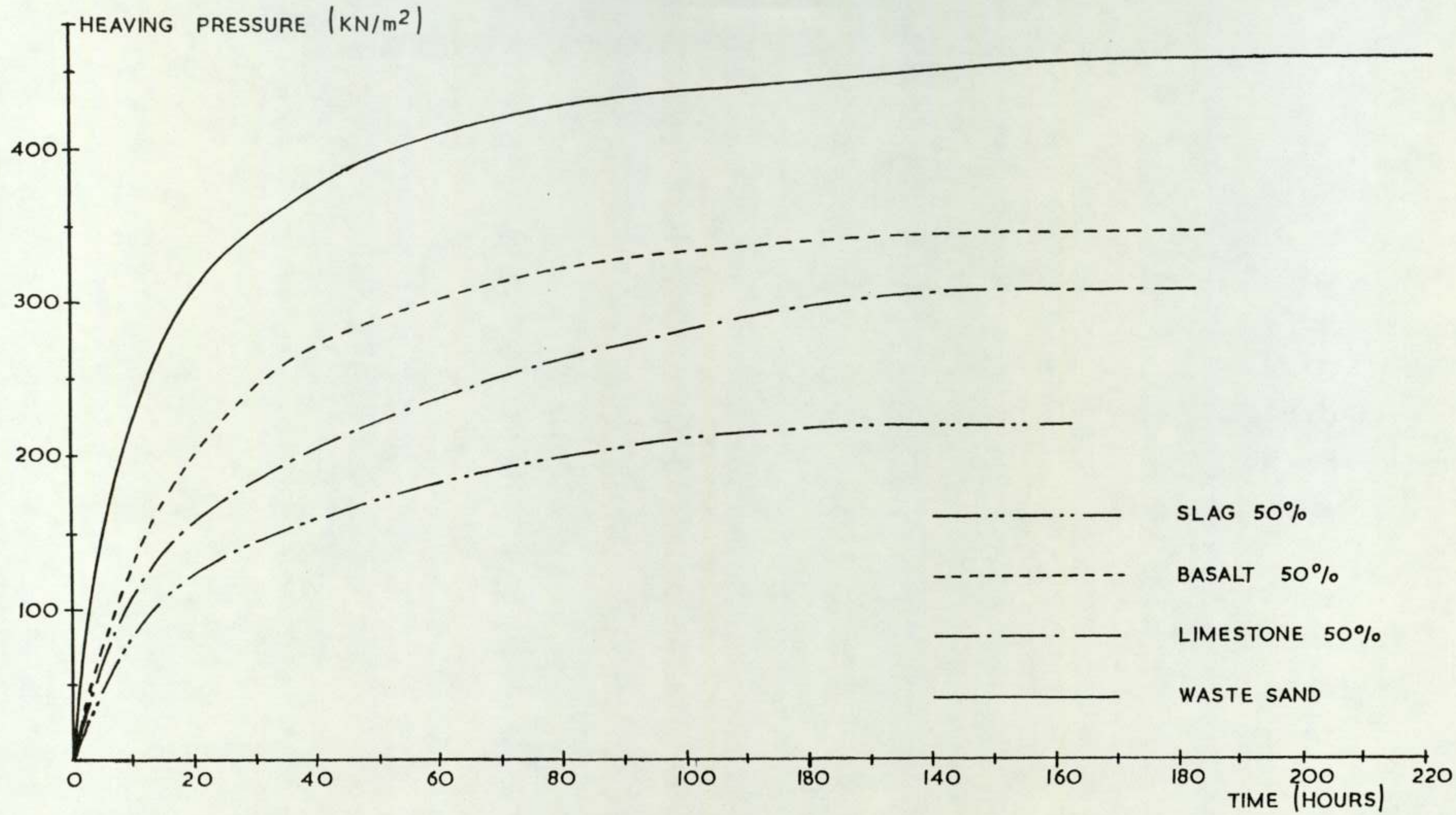


FIG. 10. 3. HEAVING PRESSURE AGAINST TIME FOR WASTE SAND AND 20–3.35mm AGGREGATES.

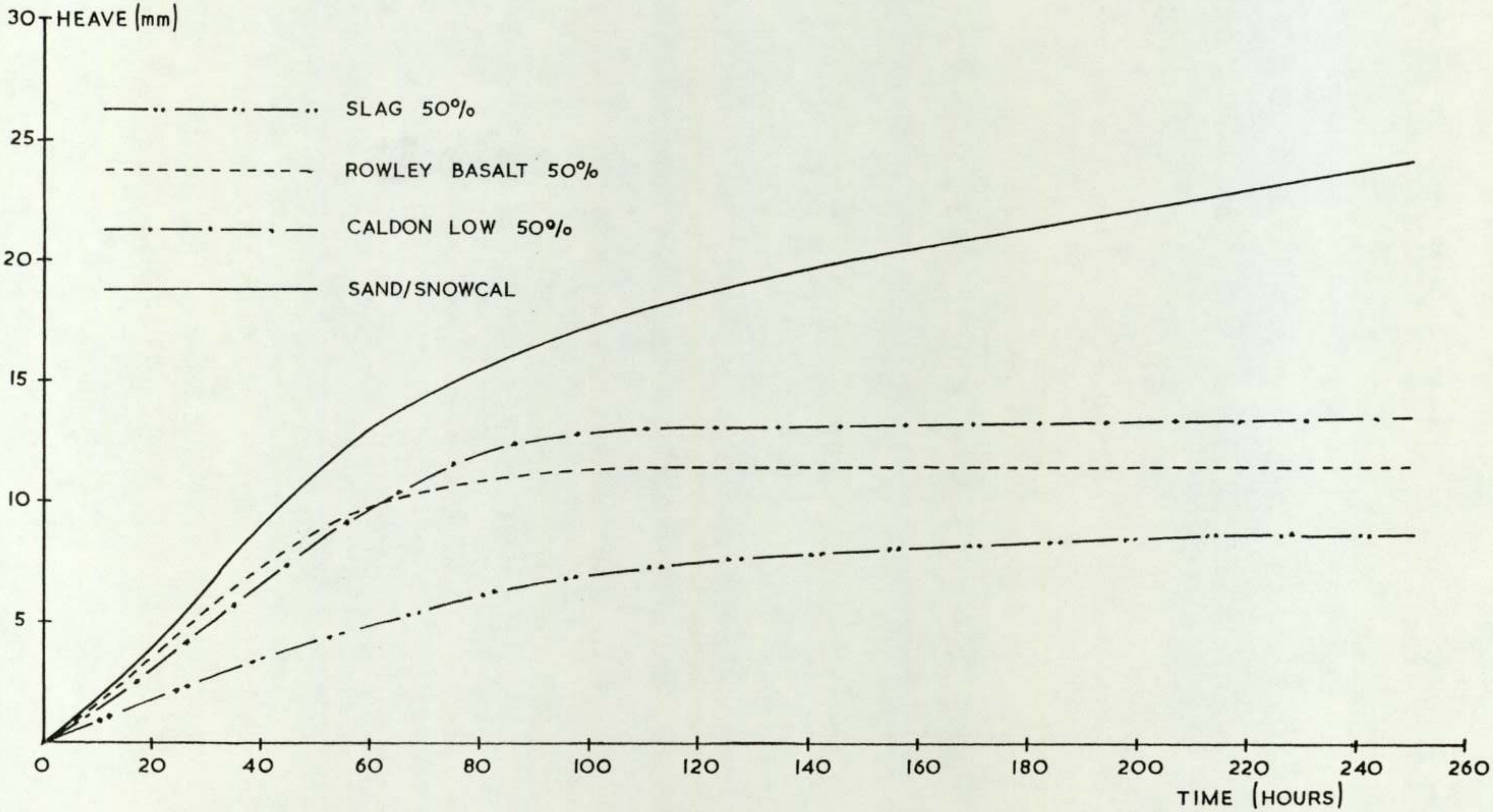


FIG. 10.4. HEAVE AGAINST TIME FOR SAND/SNOWCAL AND 20-3.35mm AGGREGATES.

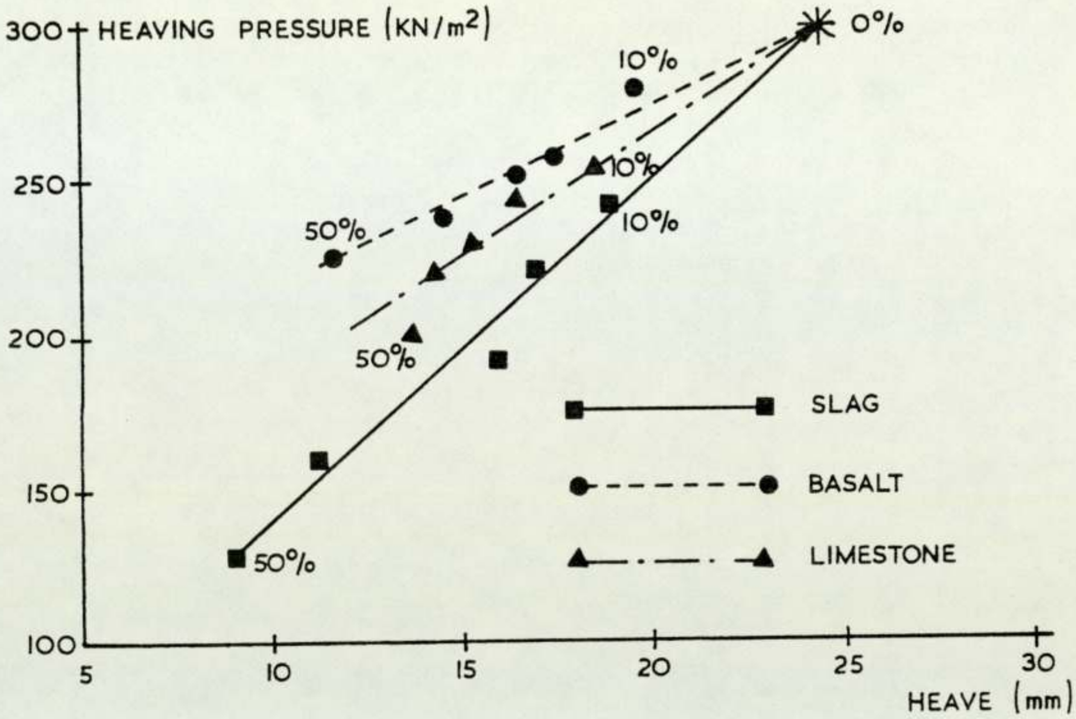


FIG. 10.5. FROST HEAVE - HEAVING PRESSURE RELATIONSHIP FOR 20-3.35mm AGGREGATE.

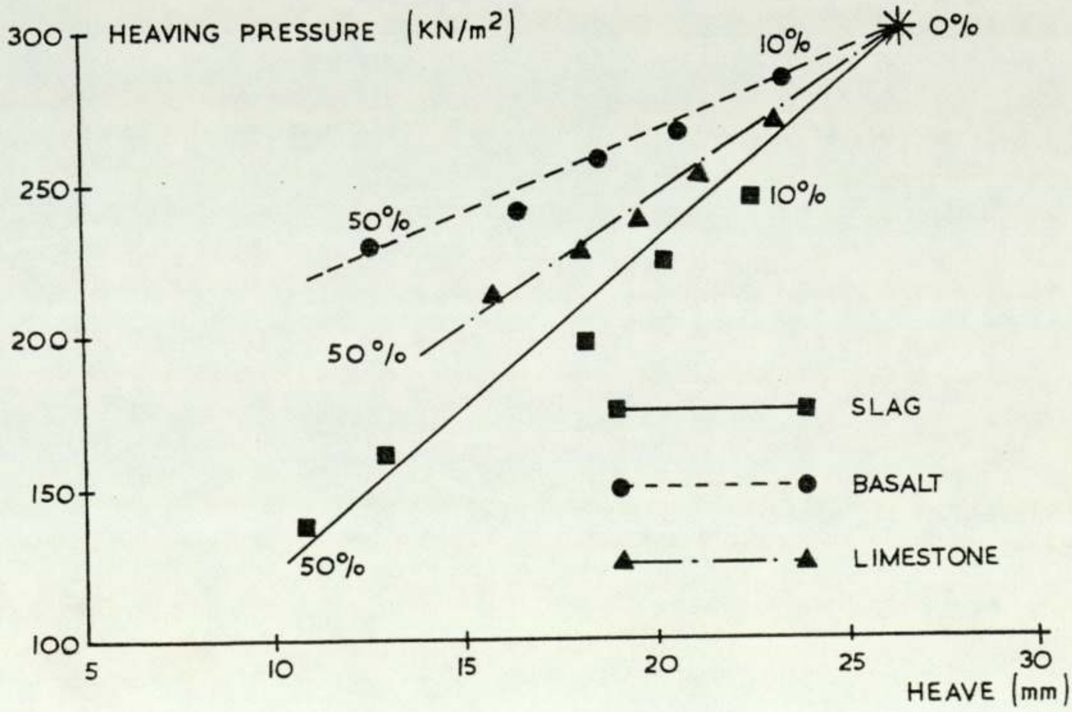


FIG. 10.6. FROST HEAVE-HEAVING PRESSURE RELATIONSHIP FOR 37.5-20mm AGGREGATE

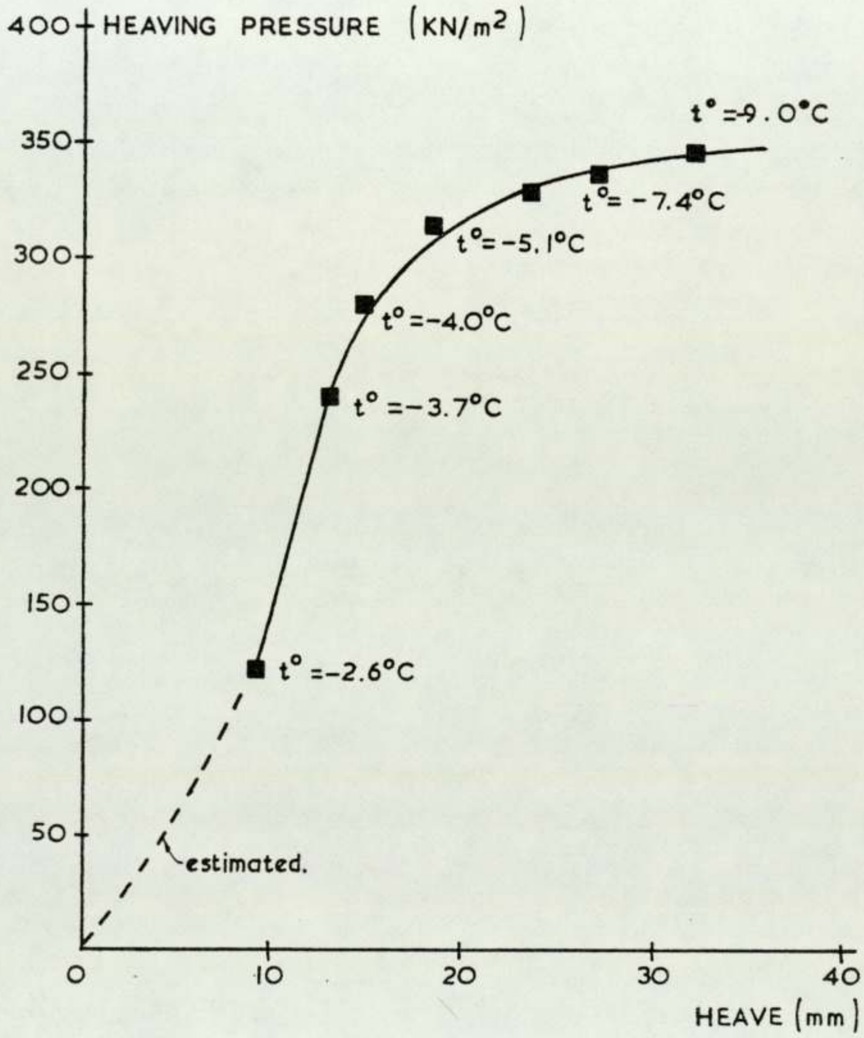


FIG 10.7. Heaving pressure against heave at different temperatures of the cooling plate for sand/snowcal matrix.

CHAPTER XI

CONCLUDING REMARKS

The experimental results obtained during this investigation have been discussed in detail in the earlier Chapters of the thesis. The following concluding remarks may, therefore, be presented.

11.1 Testing techniques

11.1.1 Frost heave test

1) Cement stabilised specimens, with permanently fixed thermocouples, were reliable and easy to use for checking temperature conditions and for assessing modification of test procedure.

2) Variations in both the temperature and level of the water in the base of the cold room trolley significantly influenced the value of frost heave.

3) Frost heave tests performed with 145mm diameter specimens produced consistently higher results than tests with 102mm specimens. These larger specimens could be adopted for assessing the frost susceptibility of coarse granular mixtures but the frost susceptibility criteria, established with 102mm specimens, would have to be adjusted accordingly.

11.1.2 Heaving pressure

1) The heaving pressure test produced reliable and repeatable values.

2) The effects of adfreeze and friction greatly influenced the measured heaving pressure, but they were eliminated by employing a multi-ring system with a lubricated rubber membrane.

3) Specimen size did not influence the generated heaving

pressure.

11.1.3 Controlled heave unit

1) The controlled heave unit (CHU), developed in this study, provided rigid control over the boundary conditions and produced repeatable data.

2) The results of the frost heave tests in CHU were compatible with those from the cold room facility and SRU.

3) The frost heave values obtained with the CHU can be used for frost susceptibility assessment using the TRRL criteria.

11.1.4 Test conditions

1) Boundary conditions had a significant influence on both heaving pressures and frost heave.

2) The position of the zero isotherm at the end of a freezing test was useful criterion for assessing the degree of control over the boundary conditions.

3) Very slow freezing in the CHU produced much higher values of frost heave than the standard frost heave test and so demonstrated the importance of the rate of freezing.

4) The duration of a heave test in the CHU is shorter than that in the frost heave test and rarely exceeded 100 - 120 hours.

5) The CHU, together with a Bellofram air diaphragm, provided a reliable system for assessing frost heave under different levels of surcharge.

11.2 Frost action

1) The introduction of coarse aggregate to the frost susceptible matrix leads to a decrease in frost heave and heaving pressure. The magnitude of the reduction was directly related to the coarse aggregate content.

2) The two particle groups studied, 20-3.35mm and 37.5-20mm, produced similar reductions with slightly larger reductions achieved with the 20-3.35mm particles.

3) The type of aggregate had a significant effect on frost heave and heaving pressure. The Slag aggregate produced the largest reductions and this was attributed to the large internal pores and the correspondingly lower thermal conductivity.

4) The total porosity was not uniquely related to frost heave. The magnitude of the reductions was directly related to the coarse aggregate content. However, it provided a useful parameter for estimating the changes in the thermal conductivity and permeability following the inclusion of coarse aggregates into the matrix.

5) Saturated hydraulic conductivity did not provide a criterion for heave prediction or the assessment of frost susceptibility.

6) Mechanical stabilisation was illustrated on a natural soil and it was shown that the freezing behaviour of this soil could be modified by the introduction of coarse particles.

7) Freezing behaviour was also modified by the application of surcharge loads.

8) Relatively low surcharges produced reductions in frost heave and, hence, frost susceptibility.

9) For all the materials, the surcharge required to render a material non-frost susceptible was dependent on the heaving pressure rather than the frost heave.

10) The ratio of surcharge pressure to heaving pressure can be used to predict the reductions in heave. A ratio of approximately 5 percent was sufficient to achieve a 50 percent reduction in heave and so considerably modified the frost susceptibility.

11) The frost heave was related to surcharge by a hyperbolic curve which depended on the type of material.

12) The complete elimination of the frost heave was not achieved, even at high levels of surcharge, although frost heave was considerably reduced.

13) The extent of frost action is significantly influenced by the thermal characteristics of the soil and the boundary conditions of the particular test.

CHAPTER XII

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the experimental work undertaken, a number of propositions are made for future work related to frost action and to testing of granular materials.

12.1 Testing techniques

1) Investigation of the frictional and adfreeze resistance developed in the standard TRRL test, when a specimen is wrapped in a waterproof paper would be useful. Such modifications could require revision of the heave criteria but it may also produce a better correlation with field performance.

2) The heaving pressure test could be modified by employing an identical specimen to that used in the frost heave test. It would eliminate any variation between these two tests due to differences in specimen preparation and specimen size and should, therefore, provide a better correlation between these two major parameters.

3) The CHU could be improved by adding an active temperature control unit in the water bath. This would provide improved control over the temperature and would also allow the bath to be operated over a wide range of temperatures. This assembly could be transferred to the cold room, operating near $0^{o}C$, so as to reduce possible heat losses from the specimen.

4) The CHU facilities could be extended to accomodate three, or even six, specimens with the cryostat system as the cooling device. The viability could be assessed of such a system for standard frost heave testing.

5) In surcharge tests with the CHU, the present system of

specimen carrier and porous plate should be replaced with a more robust system to enable test to be undertaken with much higher surcharges.

6) Temperature monitoring in all the freezing tests, should be increased by installing thermocouples in all specimens. By using a datalogging system the temperatures could be monitored continuously so that the movement of the zero isotherm could be accurately established.

12.2 Theoretical aspects

The present investigation has provided a considerable amount of basic experimental data concerning frost action in granular materials, and so it would be useful to develop a suitable mathematical model for describing such behaviour. For that purpose additional data is necessary and it is suggested that following properties should be considered:-

1) The CHU provides close control over the boundary conditions, and so it should enable a thorough study to be made of the rate of heat extraction, the rate of frost penetration and temperature distribution.

2) Pores structures require a more thorough investigation. Whilst the mercury porosimeter proved to be reliable, only small portions were tested. Consideration should, therefore, be given to appropriate pre-treatments, such as rapid freeze-drying, which could permit the preparation of representative samples, possibly by thin slicing.

3) The data related to saturated permeability collected in this investigation should be extended to the unstaturated flow

conditions usually related to soil freezing.

4) Frost heave - heaving pressure - surcharge relationship was studied in this investigation for granular materials. It would be interesting to extend this study to fine grain soils, where the freezing process is more complex than in granular soils.

APPENDIX A

This represents various analyses of the frost heave data given in Tables 5.3, 5.4, 5.5 and 5.6. The basic data has already been given in these Tables and this Appendix is concerned with the statistical analysis appropriate to each Table. The analysis of each Table are presented separately using the appropriate techniques (140) (141).

A.1 Table 5.3

This Table contains the frost heave details for the standard specimens of 102mm diameter. The analysis is concerned with establishing whether the frost heave was influenced by trolley location (a or b) and/or specimen position (1 to 9). The results from Table 5.3 have been re-grouped into Table A.1 so that the influence of these factors can be assessed by subjecting them to a two-way Analysis of Variance (141).

Trolley Location	Specimen Position								
	1	2	3	4	5	6	7	8	9
a	28.13 21.28 22.36	23.45 23.07 21.19	23.61 25.05 25.12	24.69 22.02 21.25	21.46 24.89 28.50	24.80 26.35 25.59	25.73 23.56 22.96	28.66 24.68 23.78	25.32 29.13 23.80
b	24.03 23.29 22.15	22.46 27.10 25.64	25.55 30.54 23.12	22.80 22.58 24.59	25.02 20.26 23.15	24.52 22.62 25.84	25.22 26.84 25.16	26.00 25.13 27.03	23.50 21.20 23.10

TABLE A.1 Experimental data for the 102mm specimens

In this analysis, Row R refers to the trolley location and Column C refers to the specimen position. The results of this analysis are presented in Table A.2 with the appropriate F-values given for the various sources of variation. These are compared with the appropriate

Source of variation	Sum of squares SS	Degrees of freedom, V	Mean Square MS	F-ratio	
				Data	5% level
Row R	0.08	1	0.08	0.02	4.10
Column C	39.43	8	4.93	1.08	2.20
Interaction I	47.46	8	5.93	1.30	2.20
Error E	164.32	36	4.56		
Total	251.29	53			

TABLE A.2 ANOVA Table for 102mm specimens

values, extracted from standard Tables, for the individual degrees of freedom. In all cases the calculated values are less than the extracted values. This, therefore, indicates that neither trolley location or specimen position influenced the heave values in the standard frost heave test.

A.2 Table 5.4

In this Table, the individual heave results, given in Table 5.3, are presented in groups three. It is generally considered (61) that the mean heave of three specimens should give a reliable indication of the frost heave and, hence, frost susceptibility. It was, therefore, decided to perform "Students-t" tests to assess the reliability of these subgroups for such determinations. The results of the three specimens were compared with those of the nine specimens, by considering the difference of means of the two samples (140). This consisted of calculating the population variance, σ , and hence the 't' parameter for comparison with the appropriate value from "Students-t" tables. These calculations are summarised in Table A.3.

Samples		Mean		Variance		σ	t
1	2	m_1	m_2	σ_1	σ_2		
1-9	1,2,3	24.36	24.28	0.42	1.52	1.22	0.11
1-9	4,5,6	24.36	23.75	0.42	1.19	0.98	1.08
1-9	7,8,9	24.36	25.04	0.42	1.07	0.89	1.32
1-9	1,4,7	24.36	23.80	0.42	1.44	1.16	0.83
1-9	2,5,8	24.36	24.36	0.42	0.58	0.55	0.00
1-9	3,6,9	24.36	24.93	0.42	0.98	0.83	1.20

(Note: $n_1 = n_2 = 6$ for all tests)

TABLE A.3 Summary of Student's-t tests on subgroups of three specimens

For all these tests the degrees of freedom are, $N_1 + n_2 - 2$, 10 and so, at the 5 percent level of significance, the critical 't' value is 2.23. As all the calculated 't' values in Table A.3 are below this value, it is apparent that the subgroups provide a reliable estimate of frost heave.

A.3 Table 5.5

This Table contains the frost heave details for the specimens of 145mm diameter. The analysis is concerned with establishing whether the heave of those specimens was influenced by trolley location (a or b) and/or specimen position (1 to 4). The results from Table 5.5 have been regrouped into Table A.4 so that the influence of these factors can be achieved by subjecting them to a two-way Analysis of Variance.

Trolley Location	Specimen Position			
	1	2	3	4
a	29.96 30.72	23.56 27.60	24.78 26.24	27.35 22.14
b	30.10 25.90	28.98 23.89	27.27 27.42	26.60 24.30

TABLE A.4 Experimental data for the 145mm specimens

The results of these analysis are presented in Table A.5 and in this Table, Row R refers to the trolley location and Column C refers to the specimen position.

Source of variation	Sum of squares SS	Degrees of freedom, V	Mean Square MS	F-ratio	
				Data	5% level
Row R	0.28	1	0.28	0.05	5.32
Column C	36.88	3	12.29	2.07	4.07
Interaction I	9.79	3	3.26	0.55	4.07
Error E	47.46	8	5.93		
Total	94.41	15			

TABLE A.5 ANOVA Table for 145mm specimens

The appropriate F-values are given for the various sources of variation. These are compared with the appropriate values, extracted from standard Tables, for the individual degrees of freedom. In all cases the calculated values are less than the extracted values and so, again, indicates that neither trolley location or specimen position influenced the heave values of the 145mm specimens in the frost heave test.

A.5 Table 5.6

This Table is concerned with examining the influence of specimen size (102mm and 145mm) on frost heave and summarises the data given in Tables 5.3 and 5.5. The analyses of these data have already shown that the results were not influenced by trolley location or specimen size. Thus, it is only necessary to perform a "Students-t" test on the grand overall results, treating the 102mm specimens as a single group of 54 values and the 145mm as a single group of 16 values, i.e.

102mm	145mm
$n_1 = 54$	$n_2 = 16$
$m_1 = 24.42$	$m_2 = 26.68$
$s_1 = 2.17$	$s_2 = 2.42$

This gives a population variance, σ, of 2.26 and the t value is 3.61. For the 68 degress of freedom the t value, corresponding to the 5 percent level, is 2.00. The value for the experimental data exceeds this figure and so indicates that the frost heave is influenced by the size of the specimen.

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