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Effect of aggregate on elasticity and strength properties of mortars under simulated exposure conditions.

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EFFECT OF AGGREGATE ON ELASTICITY AND STRENGTH PROPERTIES OF MORTARS UNDER SIMULATED EXPOSURE CONDITIONS

By

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ABSTRACT

The purpose of the study was to investigate the relationships between properties of rock and the corresponding mortars under different environmental conditions as determined by compressive stress testing.

The mortars were prepared with different type of aggregates but the same proportions of water, cement and aggregate. The rock aggregates were mostly carbonate rocks (limestone and dolomite), which are currently quarried in Southern and Southeastern Ontario. The mortar blocks were cured for 28 days. Three cores were drilled from each mortar block. The cores were first tested for water adsorption and absorption. Then, a series of compressive tests, up to 6.9 MPa (1000 psi), were performed on the mortar cores. The compressive tests were carried out under seven different environmental conditions: room (ambient) relative humidity (about 40% RH) and 98% RH, saturated in water, and saturated in 3% NaCl solution. All the tests were done at room temperatures (about 21°C) and freezing temperature (-20°C). The mortar data so obtained were then combined with the rock aggregate test results from previous studies, which included compressive tests (under same conditions), adsorption, absorption and magnesium sulphate loss. The resulting database was then subjected to statistical analyses such as descriptive, t test, correlation, cluster analysis, factor analysis and regression.

The results showed that freezing temperature and brine saturation influence the elastic moduli of the rock and mortar samples the most. Furthermore, the modulus of elasticity of saturated mortars was higher than that of dry samples under 6.9 Mpa (1000 psi) stress. On the other hand, rock porosity and durability were not significantly related to mortar porosity and strength of mortar. However results support the suggestion that the type and properties of aggregate determines the amount of entrapped air in mortars, which affects the strength of mortar.

The research also revealed that the type of aggregate is important in the strength and durability of mortar. Dolomite produced stronger and more durable mortars in comparison to limestones under different environmental conditions. The explanation may lie in the porosity and textural differences between the two; more air voids in dolomitic mortars seem to provide sufficient space to prevent expansive pressure during freezing and saturated conditions.

DEDICATION

To My Parents,

And to My Brother and My Sister

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to Dr.Peter P. Hudec for his outstanding supervision during my studies at University of Windsor. His patience and support is greatly appreciated.

I would also like to thank all of the members of the Department of Earth Sciences at University of Windsor for their friendship, concern and kindness.

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1 INTRODUCTION

Rock and concrete are two of the best known and most used construction materials in the world. Despite their differences, they share some common properties. Concrete is defined as a composite material that is formed from water, cement and embedded particles of rock (aggregate). Aggregate is a granular material consisting of sand, gravel, and crushed stone, and forms 60-75% of its mass. If concrete contains smaller aggregates (usually less than mesh # 8, 2.36mm), it is called mortar or "experimental concrete" and is often used for experimental purposes.

Rock particles make up to three quarter of concrete and mortar by volume, rock properties therefore have a significant influence on concrete and mortar properties. Porosity, strength, elasticity and durability are some of the properties, which may show relationships between rocks and mortars. The aim of this research was to investigate the influence of rock on mortar behaviour. In particular, the main purpose was to determine which properties of aggregate affect similar or related properties of mortar. The study was carried out on identically prepared mortars containing aggregates with properties determined by other researchers (Pour Molk Ara (In progress), Rigbey (1980), Ondrasik (1996), Dananaj (2001)). Properties of mortar such as porosity (adsorption, absorption), modulus of elasticity and ultimate strength were compared both among mortar samples, as well as between mortar and the corresponding rock type. Effects of the two major types of aggregate (dolomite and limestone) on properties of mortar have been especially considered in this study.

2 LITERATURE REVIEW

Construction materials such as rock, gravel, mortar, and concrete are all porous materials. They have some common properties, and some that are distinctly different. The literature review in the section is therefore divided into three sections: The effect of environmental factors on rock and mortar properties, the discussion of specific properties of rock and rock aggregate, and the discussion of similar properties found in concrete and mortar. There are quite a few similarities in properties of rock and mortar, but sufficient differences exist that the mortar, which has similar properties to concrete, needs to be discussed separately.

2.1 EFFECT OF ENVIRONMENT ON CONSTRUCTION MATERIAL

The resistance of materials to weathering and wear depends on their internal structure; mainly pore properties, which in turn determines their other properties such as elasticity, strength and durability of material. Elasticity, strength and durability are affected by the environmental conditions e.g. changing temperature and moisture.

The resistance to deterioration or durability of materials is controlled by their internal structure, mainly the differences in their porous structure. The voids may represent wide range of total rock space, from extremely low (near 0% in metamorphic rocks) up to extremely high (60% in volcanic rocks). Mortar, on the other hand, develops the major part of its porosity during the hydration process. Many studies (Hudec, 1983, 1987,1989,1991,1993, Rigbey, 1980, Ondrasik, 1996) have shown that the porosity and liquid (water or solution) in the pores control the performance of a rock or concrete (mortar).

The most important macroscopic pore structure parameters of materials are porosity, permeability and the specific surface area (Dullien, 1979). Porosity affects many properties of material such as strength and modulus of elasticity. Porosity (η) is the fraction of the bulk volume of the porous sample occupied by the pore or void space, or simply the ratio n (or sometimes percent) of voids in a material:

$$n = \frac{v_p}{v_t} \times 100 \qquad (2.1)$$

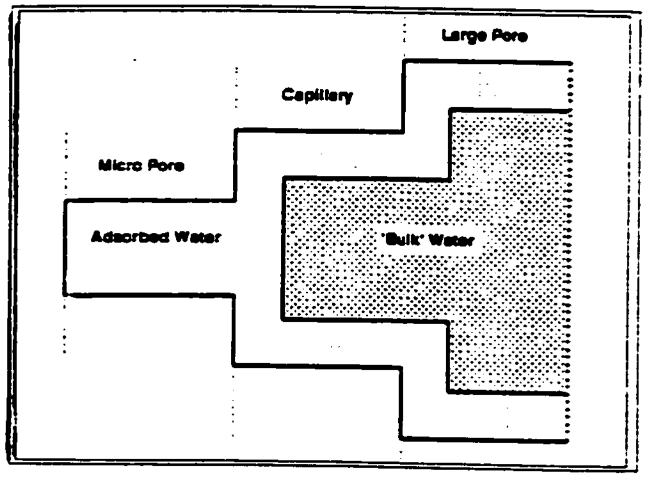
Where;

V_p is the volume of pores (including volume of air and water) in total volume, V_t. Pore size, pore shape and the nature of the pore surface are the three important properties of pores. The strength of a material is fundamentally a function of the volume of voids in it.

2.1.1. Effect of Humidity

The water behaviour in the pores is completely dependent on the pore characteristics; porous material can contain bulk (absorbed) and adsorbed water (Figure 2.1) in varying proportions. Absorbed water is the moisture required to bring a material from oven-dry to saturated -surface dry condition. Adsorbed pore water is surface-held by the attraction of the surface for the polar water molecules. Bulk or macro-pores contain absorbed water, which can be easily drained, and also adsorbed water. The total internal pore surface area controls the amount of adsorbed water in the pores. The different types of water and the processes that control it are discussed in the following sections.

Figure 2.1 Classification of pore (capillary) size based on the proportion of water adsorbed to normal water present in the pore (after Hudec, 1993).

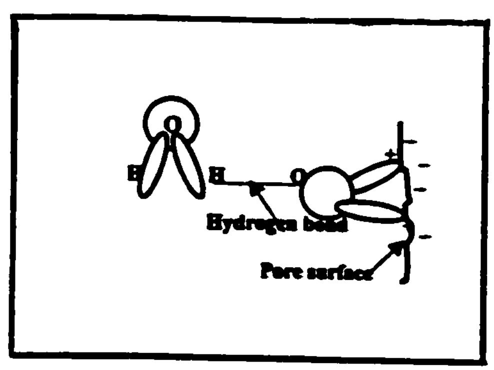


2.1.1.1 Adsorbed Water

Water adsorption is initiated when the pores are exposed to available moisture in the air and is due to the polarity of the surface and the water. The polarity of water molecules is the result of their hydrogen bonding (http://wow.nrri.umn.edu/wow/under/glossary.html, February 2001).

The water molecule is a relatively simple structure in which two hydrogen atoms are joined to a single oxygen atom by covalent bonds. The di-polar water attaches itself to the negatively charged surface of the pores (Figure 2.2).

Figure 2.2. Schematic diagram of the polar water molecule and its attachment to a negatively charged surface



The thickness of the adsorbed layer is a function of surface charge and the total amount of adsorption is a function of the surface area. Cations and anions on the surfaces and in the water increase the amount of adsorbed water (Powers, 1955 and Hudec, 1987).

The lack of thermodynamic equilibrium between gas (vapour) and adjacent solid surface causes adsorption (Dullien, 1979). Accumulation of the molecules of the gas (adsorbate) at the solid surface (adsorbent) establishes equilibrium and forms a thin layer of adsorbate on the adsorbent. Adsorption continues until there is a thermodynamic equilibrium between gas and adsorbed layer (Ondrasik, 1996). At equilibrium, the chemical potential of the adsorbed layer μ_a is equal to the chemical potential of the vapour μ_v (Dullien, 1979). μ_a is less than μ_v'' before equilibrium state and when *dn* moles of the adsorbate are transferred from the vapour to the adsorbed layer, at constant temperature (T) and pressure (P) of the vapour phase, the change in the Gibbs free energy ($dG_{T,P}$) is

$$dG_{T,P} = (\mu_a - \mu_v'')\, dn. \qquad (2.2)$$

$dG_{T,P}$ is equal to zero once the equilibrium is established (Ondrasik, 1996).

The chemical potential of the adsorbed layer (μ_a) depends upon the cohesive force between adsorbate (water) and adsorbent (rock or concrete surfaces). The cohesive forces are in turn controlled by the charge of the adsorbent surface, which attracts dipolar water molecules.

The total surface area available to the adsorbate also controls the amount of adsorption. To compare the ability of solids to adsorb, a concept of specific surface of the solid has been developed. The specific surface of a porous media is defined as the interstitial surface area of the voids and pores either per unit mass or per unit bulk volume of the porous material (Dullien, 1979).

Pores in rock can provide a large surface area, up to several ten thousands cm^2 per 1 cm^3 of solid, and surface area is controlled by the pore size (Hudec, 1993). The smaller the pores in the rock, the higher surface area. Pores may be completely filled with adsorbed water at certain relative humidity, if the pore size is small enough (< 5 μm). The pore size can be calculated by Kelvin's equation (Ondrasik, 1996):

$$Ln(p/p_0) = -2\sigma M / \rho RTr \qquad (2.3)$$

Where;

p, p_o - vapour pressure of adsorbed water and bulk water respectively (Pa)

σ - surface tension of water, [N/m], at absolute temperature T (°K)

r - capillary radius (m)

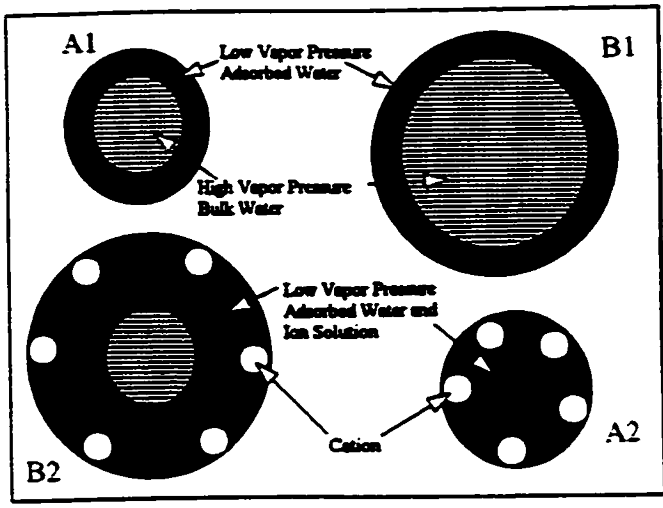
M - molecular weight of liquid, (kg)

R - the Gas constant

ρ - density of liquid, (kg/m^3)

According to Kelvin's equation, vapour pressure in the pores is a function of the solution, the temperature and the pore size.

Calculations based on the equation show that pores with radius 5 μm can be completely filled with adsorbed water at 95% RH. However, if cations are present, the pore size fully saturated with adsorbed water can be even greater (Figures. 2.3 and 2.4) (Hudec, 1993). Figure 2.3 illustrates how cations in a small pore can cause that pore to fill completely with adsorbed water, and also shows an increase the proportion of adsorbed water in a larger pore.



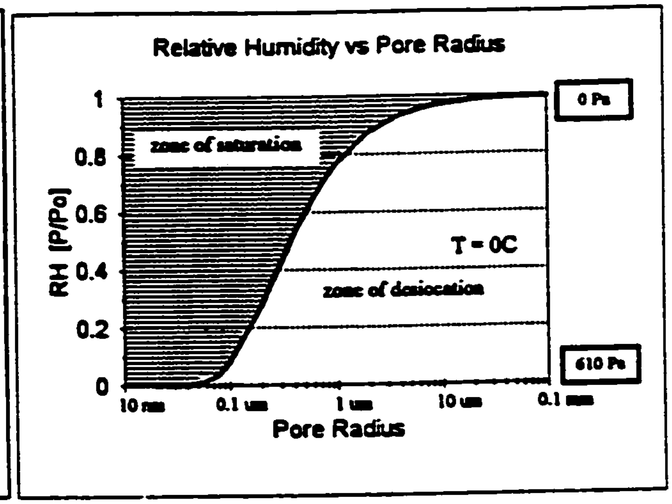


Figure 2.3 Effect of cations on the increase of the thickness of adsorbed water (black) in pores from A1 to A2 and from B1 to B2 (after Hudec, 1993)

Figure 2.4 Relationship between relative humidity, pore radius and water vapour pressure at zero degrees Celsius (after Ondrasik, 1996)

The difference in the magnitude of vapour pressure of bulk water and adsorbed water in pores with radius 0.1 μm and RH ≥ 0% is up to 610 Pa, as calculated by Kelvin's equation (Ondrasik, 1996).

The properties of adsorbed water are significantly different from those of normal water (Hudec, 1993), (Ondrasik, 1996). Adsorbed water does not freeze, because its vapour pressure remains below that of ice over the normal freezing range (down to –30C). The significance of adsorbed water to this research was discovered by Dananaj (2001). He found that adsorbed water is compressible, similar to ice, whereas normal absorbed water is incompressible.

2.1.1.2 Absorbed Water

When immersed in or exposed to water, porous, permeable materials such as soils, rock and mortar saturate by capillary action. Water is a polar, wetting fluid, and is attracted to solid surfaces. If the surface is in the form of a pore (capillary), water is pulled into it.

In a partially saturated solid, the capillary is occupied by both water and air, with a curved meniscus interface between them (Figure 2.5). The angle the meniscus makes with capillary walls is indicated by angled arrows. Water is under tension, as illustrated by horizontal arrows.

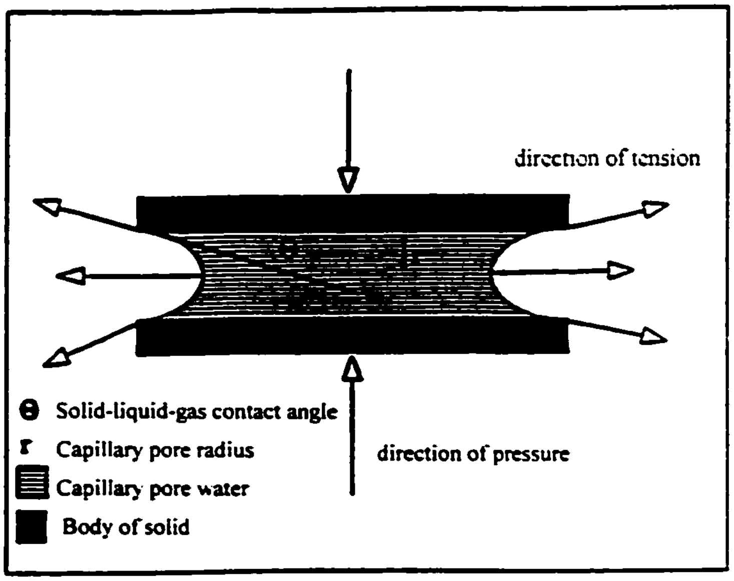


Figure 2.5 Tensile pressures on the water meniscus in a capillary pore (after Ondrasik, 1996)

The process of capillary pore filling is called absorption. Absorption capacity of a material can be defined as the total amount of absorbed water or solution required to bring the material from an oven dry to a saturated, surface dry (SSD) condition. In saturated-surface dry condition, majority of the permeable pores of the material are full of water. After vacuum saturation (or boiling) (VS), all the permeable pores are full. The difference between VS and SSD is the degree of saturation. When the SSD approaches that of VS or is above 91% saturation, the material is considered to be 'critically' saturated. The term 'critical saturation' is based on the concept that critically saturated solids are unable to accommodate the 9% expansion of water to ice phase transition that may disrupt the solid by tensional cracking.

The surface tension of water strives to flatten the meniscus, and pulls the water deeper into the solid, working against gravity, resistance to flow, and pressure of entrapped air. The meniscus remains curved and the water in tension until the capillary is filled. The curvature of the meniscus and the tension developed is a function of the capillary diameter. It can be expressed by this equation (Prausnitz, Lichtenthalre, Gomez de Azvedo, 1999):

$$H_c = \frac{2\sigma\cos\theta}{\rho_w G r} \qquad (2.4)$$

Where:

H_c = Capillary rise (cm) σ =Surface tension (g/s^2)

θ =Interfacial angle between water and solid ρ_w =Density of water (gr/cm^3)

G= Gravitational constant (cm/sec^2) r=Capillary radius (cm)

Considering all, capillary tension can be defined as the ability of capillaries to suck in the liquids. The smaller the capillary radius the larger the capillary tension becomes. The capillary radius in the presence of water would be the pore radius minus the thickness of the adsorbed water molecules.

There are several stages in absorption as saturation develops. The first introduction of water to the porous media is associated with filling the smaller capillaries; during this stage, the capillary tension causes contraction of the whole material. As more water is available, larger capillaries are filled; the meniscus flattens, and capillary tension decreases and the material relaxes to its original shape. If majority of the pores are less than 5μm in diameter, the material may continue to expand.

2.1.2. Effect of Temperature

When the temperature drops below 0°C, water may begin to freeze in the capillaries, and may cause a volume increase of the solid (Pigeon, 1995). According to Hudec (1987) the size distribution of the capillaries will determine if and how much, if any, of the water will freeze in an aggregate at a given temperature. Once the freezing is initiated, it proceeds almost instantly throughout the porous material, acting like a hammer impact. Freezing will stop when either the temperature of the system rises to above freezing due to liberation of heat of freezing, or when all the freezeable water is frozen.

The presence of cations will lower the freezing point of a solution by producing lower vapour pressure water (Hudec, 1993). Dissolved material such as de-icing salt, can lower the vapour pressure of the solvent and keep it lower than ice vapour pressure, so no freezing can take place. The bulk water in the larger pores that does freeze expels the cations from the ice crystal lattice into unfrozen solution in the smaller pores, increasing their cation concentration. Thawing of ice in the larger pores provides fresh water with higher vapour which then flows into smaller pores. Freezing thus causes an osmotic pressure flow from small pores to the larger pores, and thawing reverses it. This is explains why de-icing salts increases the severity of rock and mortar deterioration.

The adsorption, absorption, and freezing of the water in rocks and mortars, along with their strength, control their long-term durability. Although durability is not the main concern of this research, some of the properties of rocks and mortars that affect durability also affect their strength and elasticity. Thus, a cursory discussion of durability of rocks and mortars is in order. The effect of water saturation, freezing temperature and brine on mortar elastic properties is investigated in this study.

2.2 ROCK AND AGGREGATE PROPERTIES

The following discussion applies both to rock, crushed rock, aggregate, and to some degree to mortar and concrete. Rock is one of the most common construction materials. It is used in its original form as decorative stone or it is crushed and used as aggregates in mortar and concrete. For whatever purpose, i.e., whether as dimension stone, or as aggregate in concrete, bituminous mix, road base, or fill, the use of the rock is dictated by its physical properties, (Ondrasik, 1996). Rocks have a wide range of properties, which reflect their variety of structures, fabrics, and components; however, this study considers only the properties of strength, porosity and durability of rocks when used as aggregate. Strength determines the competency of the rock fabric to bind the components together. Porosity identifies the relative proportion of solids and voids. Durability indicates the tendency for eventual breakdown of components or structures, with degradation of rock quality.

Rock is a natural material composed of minerals and pore spaces that may contain water. The durability performance of a rock, as construction material, is controled by total porosity, pore size distribution, and the degree of saturation of pores (Powers, 1949, Verbeck and Landgren, 1960, Bager and Sellevold, 1987a, Hudec, 1991). Most of the rocks are weathering resistant under dry conditions and disintegrate only as a result of mechanical forces, such as wind erosion, thermal dilation or unloading. However, under humid conditions the rock behaves differently. Severe damage in rocks can be expected due to water which act either as a medium which transports chemical weathering agents (chemical weathering), or as an agent of weathering of the rock itself by its chemical, physical or thermodynamic properties (Ondrasik, 1996).

2.2.1 Structure of Rocks

From a genetic point of view, rocks are usually divided into three groups: igneous, metamorphic, and sedimentary. Geologists subdivide these primary groups further, but an engineer is interested more in the behavioural rather than genetic attributes of rocks. Therefore, for these purposes, the rocks can be classified as having: 1-crystalline texture, 2- clastic texture, 3- very fine –grained or coarse-grained rocks, and 4- organic rocks (Goodman, 1980). Crystalline rocks are composed of tightly interlocked crystals of silicate minerals or carbonate, sulphate, or other salts. Unweathered silicates that make fresh granite and other crystalline rocks are usually elastic and strong, and show brittle failure if loaded beyond their strength. However, if the crystals are separated by grain boundary cracks (fissures), such rocks may deform nonlinearly and plastically. Volcanic rocks such as basalts may contain numerous vesicles or vugs; otherwise, they behave similarly to granitic rocks (Goodman, 1980).

The clastic rocks, composed of pieces of various rock types and assorted mineral grains, owe their properties chiefly to the cement or binder that holds the fragments together. Some are stably and tightly cemented and behave in a brittle, elastic manner. Others are disaggregated upon soaking in water.

Shales are a group of rocks primarily composed of silt and clay that vary widely in durability, strength, deformability, and toughness. Cemented shale can be hard and strong. Organic rocks may deform in a viscose, plastic, and elastic fashion. Hard coal and oil shale are strong, elastic rocks, however, the former may be fissured (Goodman 1980).

2.2.1.1 Pores in Rocks and Aggregates

Numerous investigators have shown that many rock properties such as adsorption, absorption rate, resistance to freezing, thawing, and drying, wetting, chemical stability and resistance to abrasion are controlled by pore size (Haynes, 1973b, Darr and Ludwig, 1973, Litvan, 1972a 1972b and 1975, Banthia et al., 1989, Bager and Sellevold, 1986a and 1987, Morioka et al., 1973, Hudec, 1989, 1991, 1993).

The porosity of sedimentary rocks, formed by the accumulation of grains, rock fragments, or shells, the porosity varies form close to 0 to as much as 90%(n= 0.90) with 15% as a typical value for an average sandstone. In these rocks, porosity generally decreases with age (Goodman, 1980).

The porosity, especially in sedimentary rocks, can be inferred or determined from their grain size and the degree of cementation or compaction. Rigbey (1980) and Dananaj (2001) estimated the grain size of the rocks used in this study (Appendix B, Table B-3). In bulk crystalline limestone and evaporates, and most igneous and metamorphic rocks, a large portion of the pore space is comprised of planar cracks termed fissures. However, the number of fissures decreases as the sample size decreases, so in the rocks studied by Ondrasik (1996), Dananaj (2001), and Pour Molk Ara (In Progress) these have minimal influence. In the igneous rocks, porosity is usually less than 1 or 2 % unless weathering has taken hold.

Hudec (1987) divided pores according their shortest radius into four general groups (Table 2.1). The smallest pores or *Force pores* are less than one micrometer (μm) in radius and contain adsorbed water only. Force pores can fill under high humidity conditions alone. The *Micro-capillary* pores have a radius of between 1 μm - 5 μm and contain absorbed water and capillary water, and can saturate fully by capillary suction alone. The micro-capillary pores contain both adsorbed and capillary water, remain saturated under high humidity conditions, and are not free draining. The *Macro-Capillary* pores have radius range of 5μm - 1mm and, under normal conditions of immersion saturate only partly, because of entrapped capillary air. All interconnected pores can saturate fully with time, in boiling water, or under vacuum saturation. These pores drain freely when not immersed. Large bulk pores (> 1mm) contain mostly normal, bulk water and are readily saturated and drained.

Table2.1 Pore size classification and their occurrence in rocks according to Hudec (1987)

PORE CLASS	FORCE PORES	MICRO-CAPILLARY	MACRO-CAPILLARY	BULK PORES
PORE SIZE	< 1 μm	1-5 μm	5 μm -1 mm	> 1mm
Dominant in	Shale, chert	Fine-grained rocks	Medium grained rocks	Coarse grained rocks

The critical pore size can be considered as that which is filled with adsorbed water at or near 100% relative humidity.

Pore size, size distribution, and shape depend on the rock origin, type of minerals, type, and degree of cementation of grains. The surface is a zone of discontinuity between the solid and either air or solution. The nature of the pore surface has a significant effect on pore characteristics. All surfaces possess a residual charge due to partially satisfied atomic bonding, as their surface activity is a function of surface charge, which is usually negative. Fine-grained materials have a much greater internal surface area than coarse-grained materials.

2.2.1.2 Surface Charge

The pore surfaces, as all surfaces, posses a surface charge. Hudec (1987, 1993) proposed that the negative surface charge in rock aggregate pores depends on the surface type. He recognized four different surface types:(1) crystal surface, (2) cleavage surface, (3) surface of amorphous solid, (4) fracture surface. Chemical bonds between atoms on crystalline are largely satisfied and therefore these surfaces often have the least surface charge. The break along a fracture surface takes place in a random direction across the lattice of the solid. Thus, the fracture surface has the largest surface charges because of unsatisfied chemical bonds of the elements (atoms or ions) at the surface (Ondrasik, 1996)(Figure 2.6).

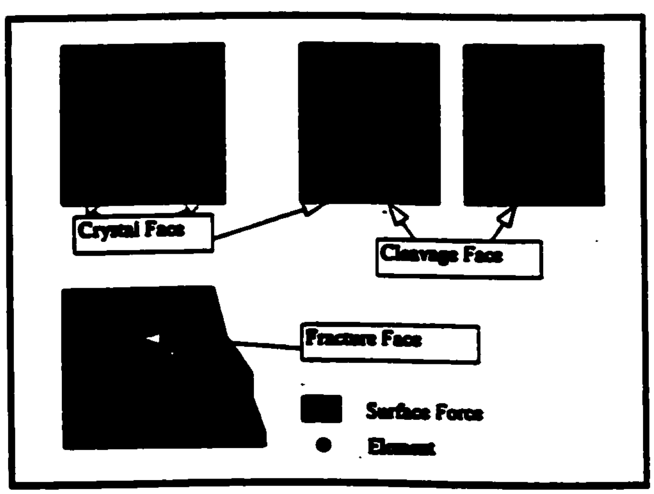


Figure 2.6 Surface forces on crystal faces, cleavage and fracture faces of minerals (after Hudec, 1993)

The cleavage surface, with moderate surface charges, contains planes along which the bonds between elements are relatively weak. The more difficult is the mineral to cleave, the higher surface charges. Hudec (1993) suggested that the thickness of the adsorbed water layer is proportional to the surface activity of the solid and by amount and type of cations adsorbed on the surface. The ions have a higher charge than the surfaces, and attract more water.

2.2.2 Elasticity and Strength Properties of Rocks

The environments of weathering that affect the durability of rock, such as drying and wetting and freezing and thawing, will also tend to affect their strength and elasticity. Unconfined and confined compression tests, and direct and indirect tension tests are used widely to characterize the strength of rock specimen.

Strength is the measure of the engineering capacity of metal, wood, rock, concrete, and other materials to withstand stress- strain (www.infoplease.com (1), Dec 2000). Therefore, strength is a property that expresses the quality of material. The stronger internal structure and bonds between atoms and molecules, and fewer internal fractures lead to higher strength in general, and generally higher the durability. Compressive, shear, tensile and torsional are the four different types of strength usually considered under various conditions.

2.2.2.1 Stress and Strain

Stress is the external force exerted by one part of an elastic body upon the adjoining part, and strain is the deformation or change in dimension occasioned by stress. When a body is subjected to pull, it is said to be under tension, or tensional stress, and when it is being compressed, i.e., is supporting a pressure, it is said to be under compressive stress.

Shear, or shearing stress, results when a force tends to make part of the body or one side of a plane slide past the other. Torsion, or torsional stress, occurs when external forces tend to twist a body around an axis. The compressive strength is the more often determined property, since compressive stress represents the more likely condition of the material in service. Materials are considered elastic in relation to an applied stress if the strain disappears after the force is removed. What is known as Axial (or Normal) Stress, often symbolized by the Greek letter sigma, σ, is defined as the force (F) perpendicular to the cross sectional area of the member divided by the cross sectional area (A) or:

$$\sigma = \frac{F}{A} \quad ({}^{ib}\!/_{in^2} \, or \, {}^{N}\!/_{m^2}) \qquad (2.5)$$

Unit of stress, N (Newton)/m^2, is expressed as Pascals (1 N/m^2=1 Pascal) (Popovics, 1998). Strain, ε, is a measure of the deformation of a material when a load is applied (Rahn, 1986):

$$\text{Strain}=\varepsilon=\frac{L-L_0}{L_0} \qquad (2.6)$$

L_0 = original length (mm)

L=length under axial load (mm)

Since the strain is a ratio of lengths, such as meter per meter, it is dimensionless.

2.2.2.2 Elasticity of Rocks

Elasticity is the ability of a body to resist a distorting influence or stress and to return to its original size and shape when the stress is removed. All solids are elastic for small deformations or strains, but if the stress exceeds a certain amount known as the elastic limit, a permanent deformation is produced. Both the resistance to stress and the elastic limit depend on the composition of the solid. The elastic limit is the maximum stress a material can sustain and still return to its original form. According to Hooke's law, the ratio of the stress to strain produced is constant within the elastic limit. In calculating the dimensions of materials required for specific application, the engineer uses working stresses that are ultimate strengths, or elastic limits, divided by a quantity called factor of safety. In laboratories materials are frequently "tested to destruction". They are deliberately overloaded with the particular force that acts against the property or strength to be measured. In the experiments, changes in form are measured to 10^{-6}m. For each kind of stress and the corresponding strain, there is a modulus, i.e., the ratio of the stress to the strain; the ratio of stress to strain for a given material is called its Young's modulus (E) (www.infoplease.com, (1) January 2001). It is a numerical constant, named for the 18th-century English physician and physicist Thomas Young, that describes the elastic properties of a solid undergoing tension or compression in only one direction, as in the case of a metal rod that after being stretched or compressed lengthwise returns to its original length (www.britannica.com, February 2001).

Young's modulus E is expressed as:

$$E = \frac{stress}{strain} = \frac{\Delta F / A}{\Delta L / L} \quad (\text{N/m}^2) \qquad (2.7)$$

Where $\Delta F / A$ = stress (force per unit area), L= original length and ΔL = change in length (Sheriff, 1991). Young's modulus of elasticity can be thought of as a measure of how well a substance stands up to pressure. Figure 2.7 illustrates the elasticity in different materials. Aggregate in the figure is shown to have the highest modulus, whereas cement paste the lowest. Concrete and mortar are somewhere in between.

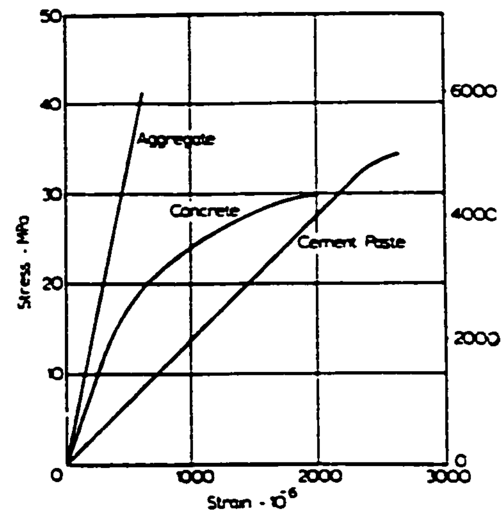


Figure 2.7 Stress-strain relationships for cement paste, aggregate and concrete (Neville, 1996)

2.2.2.3 Strength of Rocks

A good average value of the crushing strength of aggregate is about 200 Mpa (30000psi) but many excellent aggregates range in strength down to 80 Mpa (12000psi). Qualitatively, experiments have shown that the effective Young's modulus of concrete increases as the maximum aggregate size increases and densely graded concrete has higher effective Young's modulus (Li et al, 1999).

The strength of a given rock varies as the conditions under which the test is performed change. Some sedimentary rocks are weakened by the addition of water, as a result of a chemical deterioration of the cement or clay binder. Friable sandstone may, typically, lose 15% of its strength by mere saturation.

In most cases, however, it is the effect of pores and fissure water pressure that exerts the greatest influence on the rock strength. If drainage is impeded during loading, the pores will compress the contained water, raising its pressure. The rate of application of stress, specimen size, and permeability all determine whether the pore water will be put under pressure or will be allowed to drain. The compression tests done on the rock specimens used by Pour Molk Ara, (in progress) can be considered essentially undrained tests, as were the tests done by the author on the mortar specimens from these rocks.

2.2.3 Durability of Rocks

Durability of construction materials is considered as the ability of a building, assembly, component, product, element or construction system to maintain serviceability over time under specific conditions of use.

Durability of rocks is related to their other properties, such as strength and elasticity. As rocks deteriorate, their strength and elasticity also deteriorates. Research by Franklin-Chandra (1972) and Gamble (1971) established an index for durability of rocks. The results show that there is not a discernible connection between durability and geological age but showed that durability increased linearly and directly with density and inversely with water absorption.

Some rocks such as carbonates are shown to be expansive in saturated condition (Hudec and Sitar, 1975). Hudec (1993) showed the adsorption – expansion graph for carbonate aggregates (Figure 2.8).

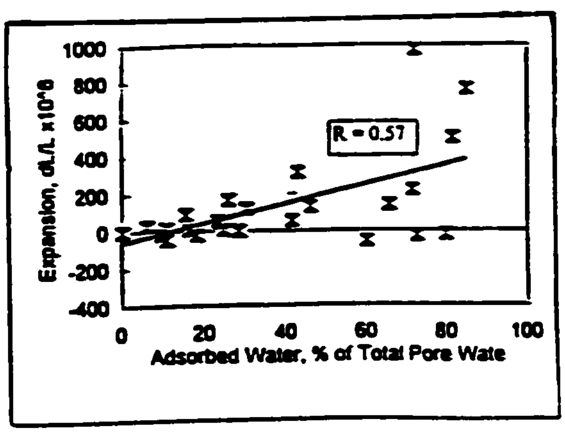
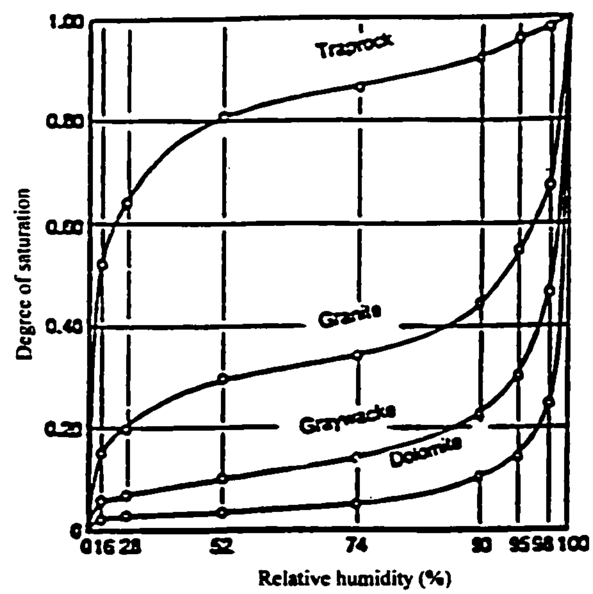


Figure 2.8 Observed expansion of carbonate rock aggregate as function of adsorbed water content (dL/L = length change/original length of samples) (after Hudec, 1993)

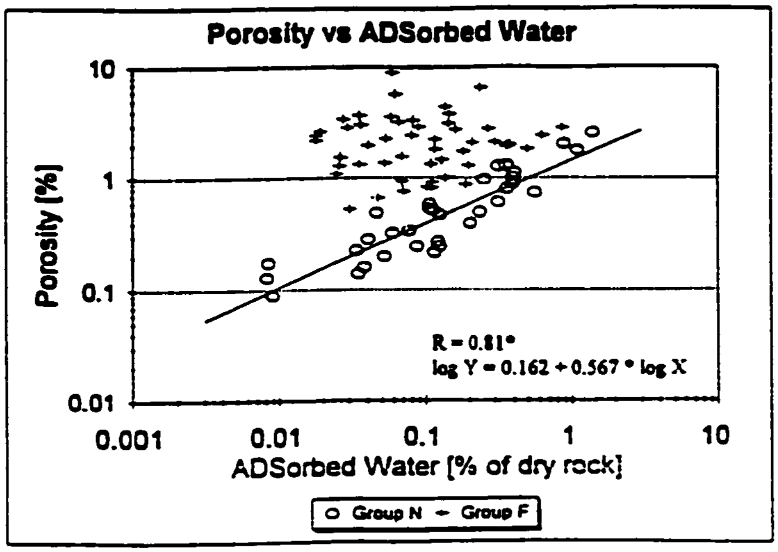
The figure shows that the more adso:bed water rock contains, the more it expands. The increased expansion associated with increased moisture contents may explain some types of natural weathering, as well as the instability of exposed rock faces under variable moisture and temperature conditions. These expansive rocks can be termed sorption sensitive, and deteriorate upon wetting and drying alone. As will be shown later, adsorbed water plays a significant role in elastic properties of rocks. The water adsorption of aggregate is defined as the increase in mass of an oven-dried sample after exposure to given vapour pressure. Figure 2.9 shows relationship between adsorption and saturation, at a given relative humidity, in different rock types.

Figure 2.9 Relationship between the relative humidity and the degree of saturation for four different types of aggregates (after Verbeck and Landgren, 1960)



Since most water in micro pores and force pores is adsorbed water which is not free-drying, the pores fully saturate at high relative humidity, and are subjected to rapid deterioration due to freezing and thawing or drying and wetting (Ondrasik, 1996). Figure 2.10 shows the relationship between adsorbed water and porosity in rocks (Ondrasik, 1996).

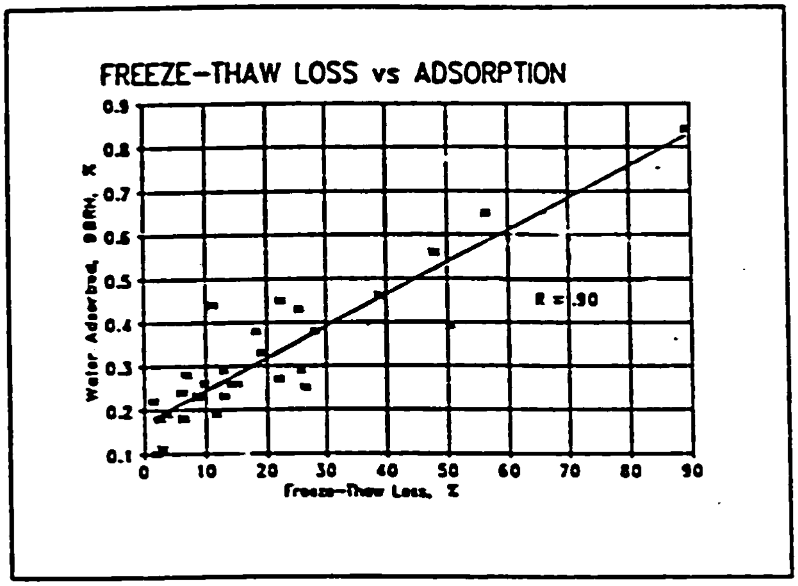
Figure 2.10 Graph of rock porosity versus adsorbed water (after Ondrasik, 1996)



It also shows that there is a log-log linear relationship between porosity and adsorbed water for those rocks where no freezing was observed (Group N), whereas no such relationship is evident for the rocks in whose pores water froze (Group F). The rocks where no freezing took place contained mostly adsorbed water in small pores, whereas those where freezing was observed contained normal, bulk water in larger pores. This linear relationship has a substantial effect on rock durability.

Frost sensitivity is another cause of destruction in rocks. Freezing and thawing is found to be more detrimental than wetting and drying at low stresses (Zaman, Zhu, and Larguros, 1999). Figure 2.11 represents a strong and positive relationship between adsorption and freeze-thaw loss. Freeze-thaw loss is the material loss on a given sieve size after five freezing-thawing cycles.

Figure 2.11 Effect of adsorbed water on the freeze-thaw loss of aggregates (after Hudec, 1991)



2. 3 CONCRETE AND MORTAR PROPERTIES

Mortar and concrete, although rock like, can be considered as a material quite distinct from rock, and therefore their properties need to be discussed separately. In the following sections, much of what is said about concrete applies to mortar as well, and vice versa.

Concrete is, basically, a mixture of two components: aggregate and paste. The paste, usually comprised of Portland cement and water, binds the aggregates into a rocklike mass as the paste hardens because of chemical reaction of the cement and water (Kosmatka, Panarese, Gissing and MacLeod, 1995).

The ideal mixture is that which solidifies with the minimum of voids, the mortar and small particles of aggregate filling all interstices. A typical proportioning of solid components for concrete is 1:2:5, i.e., one part of cement, two parts of sand, and five parts of broken stone or gravel, with the minimum amount of water consistent with a desired pouring consistency. A wide variety of additives allow the concrete to harden faster or slower, resist scaling, or adopt the final shape more easily.

Concrete is also a porous material. As the cement and water react to form a paste binding together the coarse and fine aggregates, voids are left in the originally water-filled spaces between the cement grains, which are not filled with the hydration products of the chemical reaction (Pigeon, 1995). The aggregate, which represents the major part of the volume and the weight of concrete, is also porous. The two porous media together determine and control properties of the product such as durability. Unless the temperature is high or the relative humidity is very low, pores are always filled with absorbed or adsorbed water. The expansion of water during freezing is the basic cause of damage to concrete. Very often, when concrete is damaged by freezing and thawing cycles, the use of de-icer salts is associated with at least part of the damage.

Strength of concrete is considered to be its most valuable property since strength of concrete is directly related to the structure of the hydrated cement paste and aggregate properties.

2.3.1 Concrete Components

As mentioned, cement, water and aggregate are the basic elements for producing the concrete. The paste, consisting of mix water and cement, ordinarily constitutes about 25% to 40% of the total volume of concrete (Kosmatka, Panarese, Gissing and MacLeod, 1995). A brief description and properties of each of these components is presented below.

2.3.1.1 Cement

In general sense of the word, cement can be described as a material with adhesive and cohesive properties, which make it capable of bonding mineral fragments into a compact whole (www.infoplease.com (3), Dec 2000).

For construction purposes, the term cement is restricted to the bonding materials used with rock, sand, bricks, building blocks, etc. Four compounds are usually regarded, as the major constituents of cement and are listed in Table 2.2, together with their abbreviation symbols. This shortened notation, used by cement chemist describe each oxide by one letter, viz.: CaO=C;SiO_2=S;Al_2O_3=A; and Fe_2O_3=F. Likewise, H_2O in hydrated cement is denoted by H, and SO_3 by $\bar{S}$.

In the presence of water, the silicates and aluminates of above table form products of hydration, which in time produce a firm and hard mass, the hydrated cement paste (Neville, 1996).

Table 2.2 Main compounds of Portland cement (Neville, 1996)

Name of compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

The two calcium silicates are the main cementitious compounds in the system. Making the approximate assumption that $C_3S_2H_3$ is the final product of hydration of both

C_3S and C_2S, the reactions of hydration can be written (as a guide, although not as exact stoichimetric equations) as follows (after Neville, 1996):

For C_3S

$$C_3S + 6H \longrightarrow C_3S_2H_3 + 3Ca(OH)_2 \qquad (2.1)$$

For C_2S

$$2\,C_2S + 4H \longrightarrow 4\,C_3S_2H_3 + Ca\,(OH)_2 \qquad (2.2)$$

Thus, on a mass basis, both silicates require approximately the same amount of water for their hydration, but C_3S produces more than twice as much $Ca\,(OH)_2$ as is formed by the hydration of C_2S. The two calcium silicate hydrates are broadly described as C-S-H.

The cement used in this research was Canadian No. 10, the most common type used in construction.

2.3.1.2 Water

One of the three main ingredients of concrete is water. Water plays a significant role for two different processes, hydration and curing. Water-cement ratio, as a major factor, which determines many properties of concrete including strength, is discussed in section (2.3.4). Tap water was used in the mixing of the mortar.

2.3.1.2.1 Hydration: In brief, the process, by which the strength of concrete is developed, is called *hydration*. Impurities in water in hydration may interfere with the setting of the cement and adversely affect the strength of concrete or cause staining of its surface (Neville, 1996).

Mixing water should not contain undesirable organic substances or inorganic constituents in excessive proportions. Even drinking water in some areas may contain an excessive amount of chloride, which causes alkali-silica reaction.

2.3.1.2.2 Curing: Curing is the name given to the procedure used for promoting the hydration of cement, and consists of controlling the temperature and the moisture movement from and into the concrete. Most specifically, the object of curing is to keep concrete saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement (equations 2.1and 2.2, pg 26).

There are two broad categories of curing which are using widely, depending on the conditions. The two methods may be broadly described as *wet curing* and *membrane curing* (Neville, 1996). The first method is that of providing water, which can be imbibed by the concrete. This requires that the surface of the concrete be continuously in contact with water for a specific length of time, starting as soon as the surface of the concrete is no longer liable to damage.

As far as quality of the water used for curing is concerned, ideally it should be the same as mixing water. It is essential that curing water be free from substances that attack hardened concrete. The temperature of the water should not be much lower than that of concrete in order to avoid thermal shock or steep temperature gradients, ACI 308-92 recommends a maximum difference of 11°C. Wet curing was employed in this study.

2.3.1.3 Properties of Aggregate for Use in Concrete

Since aggregates make up about 60% to 75% of the total volume of concrete, their selection is important (Kosmatka, Panarese, Gissing and MacLeod, 1995). The basic properties of rock and aggregate were discussed in section 2.2 dealing with Rock Properties. The additional properties pertinent to concrete are discussed below.

Aggregate size, for use in concrete, has been divided to two groups: fine aggregate and coarse aggregate. The former is not larger than 5mm or 3/16 in. and the latter is larger than sieve No 4 (4.75mm) in size, according to ASTM.

Natural aggregates come from parent rocks, by either crushing of bedrock or by the weathering/erosional processes, which produce gravel and sand. Thus, many properties of aggregate depend entirely on the properties of the parent rock, e.g. chemical and mineral composition, petrological character, specific gravity, hardness, strength and pore structure. On the other hand, there are some properties possessed by aggregate but absent in the parent rock: particle size and shape, surface texture, and surface absorption.

In addition to the petrological character of aggregate, its external characteristics are of importance, in particular the particle shape and surface texture. *Roundness* measures the relative sharpness or angularity of the edges and corners of particle; it is controlled largely by the strength and abrasion resistance of the parent rock. Voids in concrete mixture are related to the shape of aggregate.

The *surface structure* of the aggregate affects its bond to the cement paste and influences the water demand of the mix, especially in the case of fine aggregate. The shape and texture of fine aggregate have a significant effect on the water requirement of the mix.

The bond between aggregate and cement paste is an important factor in the strength of concrete, especially the flextural strength, but the nature of bond is not fully understood. The bond is due, in part, to the interlocking of the aggregate and the hydrated cement paste, due to the roughness of the surface of the surface of the former. A rougher surface, such as that of crushed particles, results in a better bond due to mechanical interlock.

Softer, porous and mineralogically heterogeneous particles do not have the same effect. The influence of aggregate on the strength of concrete is not only due to the mechanical strength of the aggregate, but also to its absorption and bond characteristics (Neville 1996). Clearly, the compressive strength of concrete cannot significantly exceed that of the major part of the aggregate contained therein, although it is difficult to test and obtain the strength of individual aggregate particles

The porosity, permeability and absorption of aggregates influence such properties as the bond between them and hydrated cement paste, the resistance of concrete to freezing and thawing and its chemical stability. The pores in the aggregate vary in size over a wide range, but are much larger than the gel pores in cement paste. Pores smaller than 5 μm are of special interest as they affect durability of aggregate in freezing-thawing condition.

Although there is no clear-cut relation between the strength of concrete and the water absorption of aggregate used, the pores at the surface of the particles affect the bond between the aggregate and paste and may thus exert some influence on the strength of concrete (Neville, 1996). Some of the pores are wholly within the solid; others open onto the surface of the particle.

The quality of concrete depends largely upon how well the aggregate is coated with paste. In properly made concrete, each particle of aggregate is completely coated with paste and all of the spaces between the aggregate particles are completely filled with paste (Kosmatka, Panarese, Gissing and MacLeod, 1995).

2.3.2 Structure of Mortar and Concrete

The internal structure of concrete, like many other composites, is quite complex. The initial structure of a fresh cement paste depends on the volume fraction, particle size distribution, and the chemical composition of the cement particles (Popovics, 1998).

2.3.2.1 Pores in Cement Paste

Many of the mechanical properties of hydrated cement and concrete appear to depend not so much on the chemical composition of hydrated cement as on the physical structure of the products of hydration (Neville, 1996). At any stage of hydration, the hardened paste consists of very poorly developed crystals of $Ca(OH)_2$, some minor components, unhydrated cement, and the residue of the water-filled spaces in the fresh paste.

Cement gel is a nanometer length scale structure, which, with pores and some unhydrated cement particles constitutes the cement paste. The surface area of the cement gel can be determined by the adsorption test. Depending on whether water vapour (Powers, 1960; Brunauer et al, 1970) or nitrogen (Feldman and Sereda1, 1968) is used as adsorbate, two models have been established to explain the concrete internal structure.

Within the gel itself, there exist interstitial voids, called gel pores. The nominal diameter of gel pores is about 3nm while capillary pores are one or two orders of magnitude larger (Figure 2.12 and Figure 2.53). The gel pores occupy about 28% of the total volume of gel, the solids material left after drying in a standard manner. Gel pores are much smaller than the capillary pores and the amount of water indicates directly the porosity of the gel (Neville, 1996).

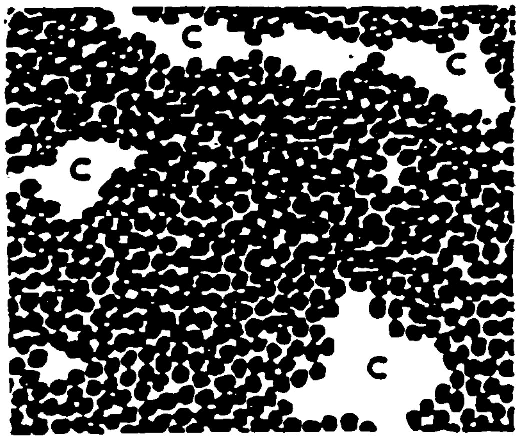


Figure 2.12 Simplified model (Powers-Brunauer model for structure of cement gel) of paste structure, solid dots represent gel particles and those marked C are capillary pores (from Powers, 1958)

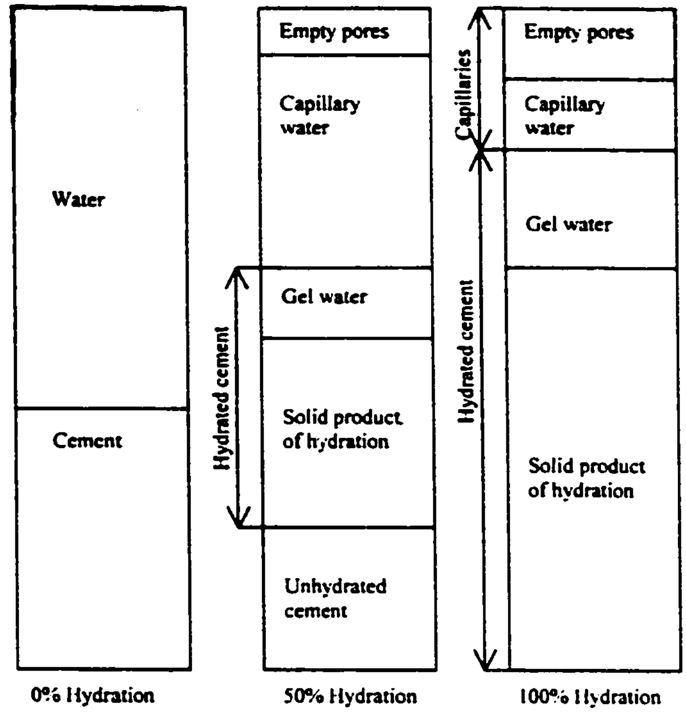
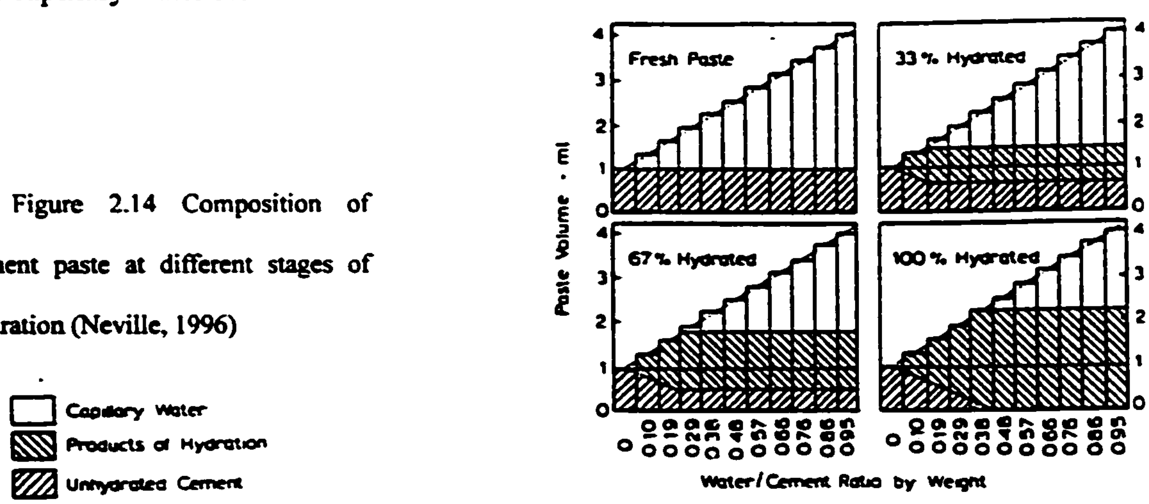


Figure 2.13 Diagrammatic representation of the volumetric proportions of cement paste at different stages of hydration (Neville, 1996)

Figure 2.14 shows the relative volumes of unhydrated cement products of hydration, and capillary water for mixes with different water/cement ratios.

Figure 2.14 Composition of cement paste at different stages of hydration (Neville, 1996)



According to Powers-Brunauer model, water can be present in three forms in hardened paste (Figure 2.12, after Neville, 1996).

1- Water combined chemically in hydration products, which is called *chemically combined* or *non-evaporable water*. The amount of this water is given by the mass loss of dried cement paste on heating at 1000° C.

2- Adsorbed water, which is held by short-range forces on the pore surfaces and is called *gel water* or *adsorbed water*.

3- Water in the free state, which fills the capillaries and is called *free* or *capillary water*.

The last two are evaporable water at 105°C.

Feldman and Sereda (1968) model suggests that the cement gel has a layered structure with pores as spaces between these layers (Figure 2.15). They broke down the evaporable water into two portions (Popovics, 1998)):

1- The actually (Physically) adsorbed water

2- The interlayer (Zeolitic) water, which behaves as a solid but whose outer part is evaporable at drying at 105°C

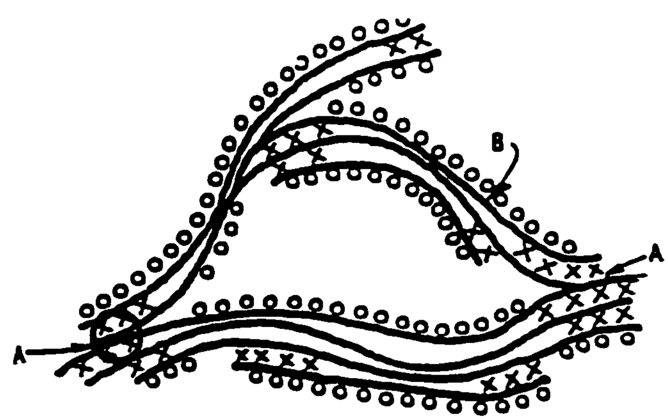


Figure 2.15 Simplified form of the Feldman-Sereda model for the structure of cement gel; interparticle bonds, inter-layer water, tobemorite sheets and adsorbed water are shown by A, X, B and O respectively (after Popovics, 1998)

2.3.2.2 Pores in Concrete

The pores, or voids in concrete consist of gel pores in the hardened cement paste discussed above, entrained or entrapped air voids and voids in aggregate (Hearn, Hooton and Mills, 1994). Porosity in the hardened cement paste is defined as the fraction of the volume of the saturated specimen occupied by evaporable water (Powers, 1958). Pores and voids are distributed randomly but statistically uniformly in a properly made concrete. The permeability of good concrete is less than 0.1 mdarcy and the porosities range from 6 to 10% (Dulien, 1979).

A very high-quality cement paste has a porosity of about 25% by volume, and when it is incorporated in concrete, the overall porosity reduces to about 7% by volume. Few normal aggregates have porosities greater than 5% by volume. The pore radii in a typical hydrated cement range up to about 10 μ m, but the bulk of the pore volume consists of pores of radii less than 1 μm and reaches into region under 100 A° (Hearn, Hooton and Mills, 1994).

The capillary pores are filled originally with liquid and the air voids with air in the fresh paste. Later, air may replace part of the liquid in the capillary pores and liquid can penetrate the air voids; that is, any pore can filled up with air or liquid or any combination of these (Czernin, 1962: Powers, 1958).

Capillary pores and air voids differ from each other in some aspects (Mielenz, 1969):

1- Capillary pores have tortuous or tube like shapes but air voids are shorter with much larger diameter (almost spherical).

2- Air voids are the result of incomplete consolidation, or entrained air, or both. The capillaries in a hardened cement paste are that portion of the originally water-filled spaces in the fresh cement paste that, as the result of hydration, has not become filled with the cement gel.

3- The volume of original air voids V_a (Figure 2.16) remains essentially constant during the life of the cement paste or concrete.

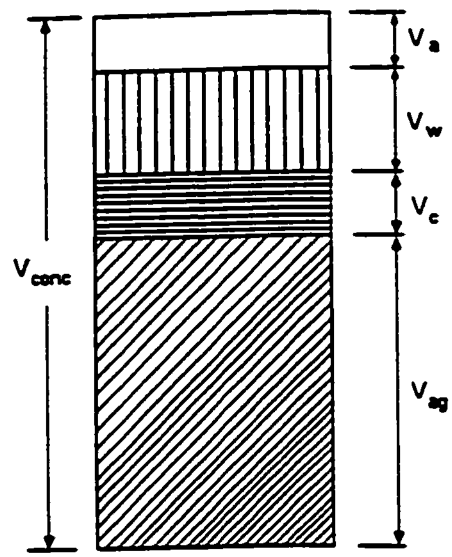


Figure 2.16 Schematic representation of the composition of fresh concrete, containing air, water, cement and aggregate. V_{ag} , V_c and V_w are volume of aggregate, cement and water respectively. (Popovics, 1998)

The number of large voids in a hardened concrete is practically the same at any age as the air content of the concrete in the fresh state. At any stage of hydration, the capillary pores represent that part of the gross volume that has been filled by the products of hydration (Neville, 1996). The volume of capillary porosity decreases with the age of the concrete under normal conditions because the solid hydration products fill up these pores gradually. Because these products occupy more than twice the volume of the original solid phase (i.e. cement) above, the volume of the capillary system is reduced with the progress of hydration. Thus, the capillary porosity of the paste depends on the water/cement ratio of the mix and on the degree of the hydration.

In this research all mortar specimens were prepared in identical fashion, so porosity, pore size distribution, and permeability of the paste are likely very similar if not identical. The only variable in the mortars is the aggregate.

2.3.3 Strength of Concrete

The compressive strength of concrete is one of its most important technical properties. It is frequently used as a measure of the overall quality of the concrete. The strength is determined partly by the quality and number of bonds between particles of the solid hydration products and partly by the porosity.

The strength of a hardened concrete may depend not only on these factors but also on certain properties of aggregate. Such properties are aggregate strength, deformability, chemical and mineralogical composition, absorption, and perhaps most importantly, the properties that control the bond between the concrete paste and the aggregate surface (Neville, 1996).

The compressive strength of concrete or mortar is usually determined by submitting a specimen of concrete section to uniformly distributed increasing axial compression load. This strength is expressed as load per cross sectional area, usually in psi, Pa or kg/cm^2 ($1\ kg/cm^2 = 14.2$ psi = 0.098MPa) (Popovics, 1998).

2.3.3.1 Effect of Concrete Porosity on strength

The influence of the volume of pores on strength can be expressed by a power function of the type (after Grudemo, 1975):

$$f_c = f_{c.0}(1-p)^n \qquad (2.8)$$

Where:

p = porosity

f_c = strength of concrete with porosity p

$f_{c,0}$ = strength at zero porosity ,and

n = a coefficient ; which is constant for particular mix characteristics.

Porosity is the primary factor influencing the strength of cement paste. A log-linear relation between strength and porosity, within the range of latter between 5 and 28 per cent, was established by Rossler and Older (1985). The effect of pores smaller than 20 nm in diameter was found to be negligible. Generally, at a given porosity, smaller pores lead to a higher strength of the cement paste. Figure 2.17 illustrates the relationship between porosity and strength (Neville, 1996).

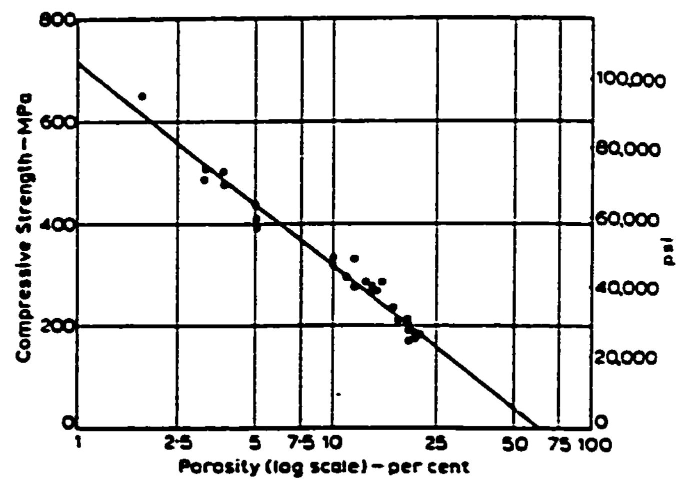


Figure 2.17 Relationship between the compressive strength and the logarithm of porosity of cement paste (Neville, 1996)

2.3.3.2 Effect of Aggregate on Strength of Concrete

The strength of aggregate has a positive relationship with strength of mortar and its elasticity characteristics. The influence of aggregate on the strength of concrete is due not only to the mechanical strength of the aggregate but also, to a considerable degree, to its absorption and bonding characteristics (Neville, 1996).

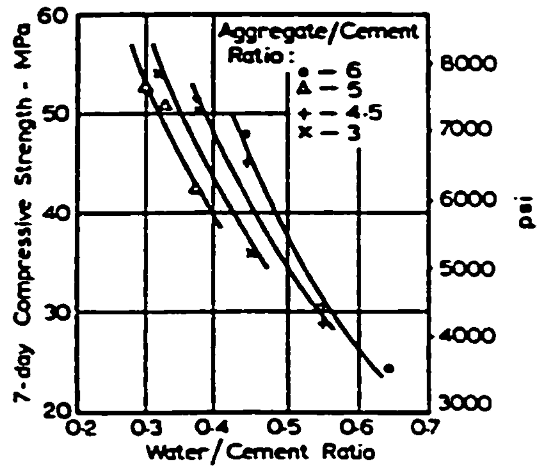
The strength or weakness the bond between aggregate and cement paste is determined by parameters of a zone between aggregate and cement paste, called the interfacial transition zone (ITZ). The cement paste in the ITZ around aggregate particles has a significantly higher porosity than bulk cement paste (Serivener and Nemati, 1996). The voids originate from air contained within the aggregate. The air gradually migrates out through the water filled pores in the aggregate, producing air voids. As water is drawn into aggregate particles by capillary absorption (during hydration), air is trapped inside the cement paste and pressurized (Buenfeld. and Okundi, 1999).

Test results showed that both porosity in mortar and in the ITZ develop at a similar rate (Zhang, 1998). The amount of voids in the ITZ, and consequently the strength of bond depend on the size and shape of the aggregate. The rougher surface and the smaller particles produce the stronger bond and mortar (Popovics, 1998).

The aggregate - cement ratio is a secondary factor in the strength of concrete. It has been found that, for a constant water- cement ratio, a leaner mix (i.e., less cement) leads to a higher strength (Fig. 2.18 after Neville, 1996). The aggregate-cement ratio was constant (by weight) in this study, so it was not a factor in mortar strength. On the other hand, aggregate of moderate or low strength and modulus of elasticity can be valuable in preserving the integrity of concrete (Neville, 1996).

Volume changes of concrete, arising from hygral or thermal causes, lead to a lower stress in the hydrated cement paste when the aggregate is compressible. Thus, compressibility of aggregate would reduce distress in concrete while strong and rigid aggregate might lead to cracking of the surrounding cement paste.

Figure 2.18 Influence of the aggregate/cement ratio, from 3 to 6, on strength of concrete (Neville, 1996)



2.3.3.3 Effect of Age on Strength of Concrete

In concrete practice, the strength of concrete is traditionally characterized by the 28-day value, and some other properties of concrete are often referred to the 28-day strength. There is no significance in the choice of the 28 days, it is simply that early cements gained strength slowly and it was necessary to base the strength description on concrete in which a significant hydration of cement had already taken place (Neville, 1996). Figure 2.19 shows the age influence on mortar and concrete strength. All mortars in this study were of the same age (28 days), so age is not a factor.

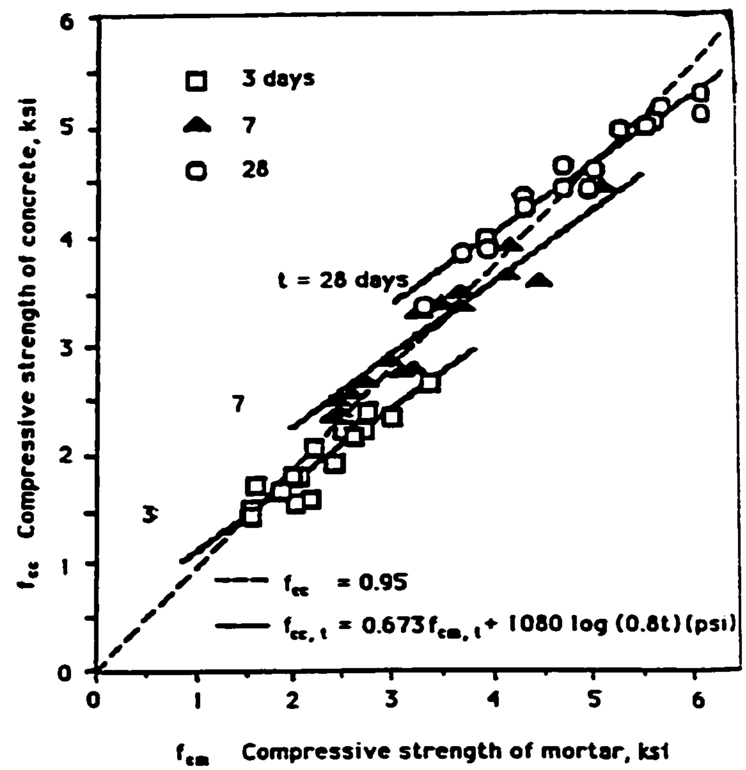


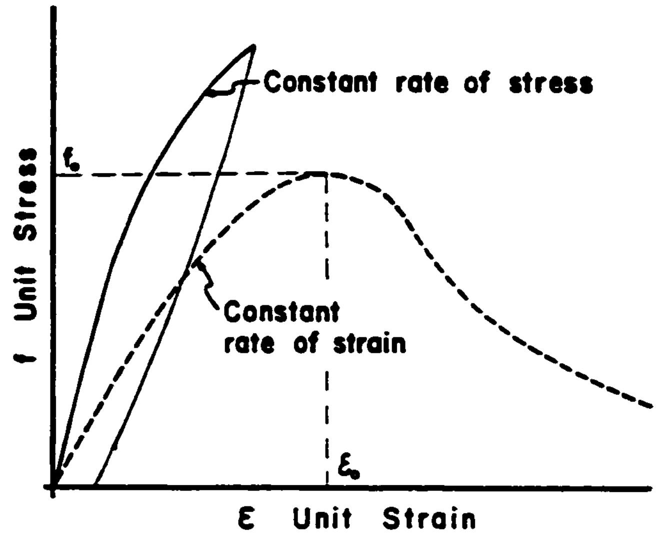
Figure 2.19 Relationship between the compressive strength of concrete samples and corresponding mortar samples at various ages (after Popovics, 1998)

2.3.3.4 Modulus of Elasticity and Concrete Strength

Concrete may undergo both elastic and plastic deformation; that is why it is called a viscoelastic material (Popovics, 1998).

The deformation of a rock or concrete under increasing load can be described conveniently by stress-strain diagram. The shape of such a diagram depends on the properties of the concrete and largely on the method of testing. Figure 2.20 shows two deformation curves, one for constant rate of stress and one for constant rate of strain of the same concrete under uniaxial compression or tension. Since at zero stress the deformation is also zero, the characteristic of such a stress-strain relationship is the slope of the straight line between two stress-strain points on the curve, called the modulus of elasticity, and also called the elastic constant (Popovics, 1998).

Figure 2.20 Two typical stress-strain curves for concrete under uniaxial load (after Popovics, 1998)



The term is defined, in general, by ASTM E6-89 (1994) as the ratio of stress to corresponding strain below the elastic limit. It is reasonable to expect that a stronger concrete has a higher resistance to deformation, that is, a higher modulus of elasticity. Many years ago, Walker (1919) suggested a power function for this relationship whose general form

$$E = k\ f_c^n \quad (2.9)$$

Where E =modulus of elasticity

f_c =compressive strength of the concrete

k and n = experimental parameters that depend on testing conditions

When psi units and cylindrical specimens were used, Walker obtained the values of k and n for normal-weight structural concrete having a unit weight of close to 145 lb/cu yd (2300kg/m^3) and the Walker equation in psi, as recommended by ACI, for similar concrete is (ACI, a983b).

$$E = 57000 f_c^{0.5} \qquad (2.10)$$

When E is expressed in Gpa and f_c in Mpa, this equation becomes:

$$E = 4.73 f_c^{0.5} \qquad (2.11)$$

The above equations relate moduli to strength. The focus of this study was the comparison of moduli under different conditions of environmental exposure. It is inferred through the above equations that the change in moduli will be reflected in the change of strength. The study also attempts to find the relationships among the different factors that affect strength and moduli of mortar, but focuses mainly on the effect of rock aggregate strength and moduli. Since the cement, water, and water/cement ratio were kept constant, and the method and the length of hydration were also constant, the mortar strength and moduli affected by these variables should also be constant.

2.3.4 Durability of Concrete

Durability and strength of concrete are related. As concrete deteriorates, it looses strength. The durability of concrete its ability to withstand the conditions for which it has been designed, without deterioration, over a certain time. There are several external or internal factors, which may cause lack of durability. Inadequate durability manifests itself by deterioration, which can be due either to external factors or to internal causes within the concrete itself (Neville, 1996).

The external factors that affect durability are physical, chemical or mechanical including temperature variations, abrasion, electrolytic action and industrial liquids and gases (Table 2.3). Many of these are the same or similar to the factors causing the deterioration of rocks. An important cause of damage is alternating freezing and thawing of concrete and the associated action of de-icing salts.

Table2.3 causes of deterioration of concrete (according to ASTM), 1978)

Physical	Temperature & expansion, freeze & thaw, etc.
Chemical	Alkali -silica reaction, alkali-carbonate reaction, etc.
Mechanical	Abrasion, erosion, caviation, etc.

If, during the freezing of saturated paste, the larger capillary pores are full and, as ice forms, a certain amount of water is forced out because the pores cannot expand (Pigeon. 1995). The water in the gel pores (containing adsorbed water) cannot be freeze because it's vapour pressure is always lower than that of ice (Dunn and Hudec, 1965). Litvan (1970, 1972) noted that the adsorbed water remains in liquid-like state well below the normal freezing point and migrates to larger pores and spaces during freezing. This migration induces hydraulic pressure in the larger pores and tension within the smaller pores. Thus, the temperature and duration of freezing and the amount of frozen solution in pores determine the frost durability of concrete (Cai and Liu, 1998).

Powers, working with Helmuth (1968), discovered that during freezing water tends to move towards the capillary pores where ice is forming, and that this creates shrinkage in the paste. They also found that the temperature at which ice can form decreases with the size of the pores. If the temperature of a saturated cement paste is slightly above 0°C, water in the capillary pores can be considered to be in thermodynamic equilibrium with water in the gel pores. If the temperature of this paste decreases sufficiently below 0°C, so that ice begins to form in a number of capillary pores, this equilibrium is disturbed because, at a given temperature, the free energy of ice is lower than that of liquid water.

The liquid water in the gel pores thus acquires a potential energy that forces it towards the capillary pores where ice starts to form. When this water reaches, the capillary pores, it freezes and the ice crystals increase in size. The growth of ice crystals creates pressure on the unfrozen film of water between the ice crystals and the solid walls of the pores. If, for various reasons, the pressure becomes too great before the system has time to re-establish equilibrium, permanent damage may occur to the mortar structure. This is known as osmotic pressure theory (Powers, 1975). Figure 2.21 represents schematically the saturated cement paste between two air voids, in which ice formation and water flow are shown (Pigeon, 1995).

Since the formation of ice causes an increase in the chemical concentration of the pore water solution, the equilibrium is disturbed between the concentrated pore water solution and that in the smaller pores (including the gel pores) where ice has not formed and where the concentration has not increased. Water in the smaller pores is attracted to that in the larger pores where ice has formed, in order to re-establish osmotic equilibrium between the concentrations. Therefore, if the paste is saturated, internal pressures start developing as soon as the ice starts forming. The pressures developed and released during freezing and thawing can destroy mortar and concrete, unless it is protected by presence of large air voids (entrained air). Although the above theory was developed for cement paste, it also applies to aggregate.

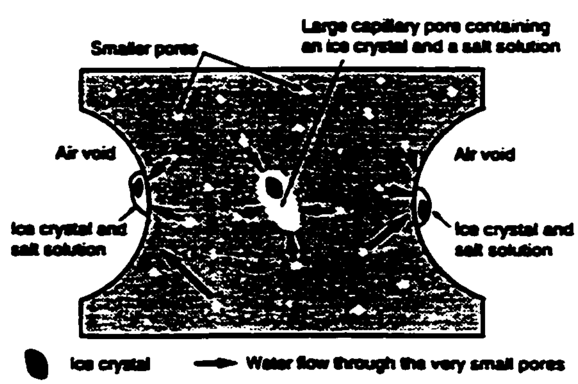


Figure 2.21 Schematic illustration of the osmotic pressure theory (Pigeon, 1995)

3 RESEARCH PROCEDURE

The purpose of the research was to compare the properties of mortar samples made with different aggregates to the properties of these aggregates. More specifically, properties of mortar such as indirect porosity indexes (adsorption, absorption), modulus of elasticity and ultimate strength were compared both among mortar samples, as well as between mortar and the corresponding rock type (rock data were based on Pour Molk Ara (in progress) and Dananaj (2001)).

Effects of the two major types of aggregate (dolomite and limestone) on properties of mortar have been especially considered in this study. Multivariate statistical procedures were used to compare the rock and mortar properties.

3.1 EXPERIMENTAL PROCEDURE

3.1.1. Sample Description

Thirty-nine mostly of carbonate rocks were chosen as aggregates for study in mortar. The rocks in the set were: 24 dolomite, 11 limestone, 2 samples of syenite and one sample each of sandstone and marble. These groups of samples were the same rock types as studied by Pour Molk Ara (in progress), and by Dananaj (2001). Thus, the properties of the rocks are well known, and can be compared to the properties of the mortar. The rocks samples are a sub-set of rocks originally collected by Rigbey (1980) from operating quarries in SW Ontario. The location of the quarries is shown on the geologic and sample location map found in Appendix A. Their lithologic description of the rocks is found in Appendix A.

3.1.2 Sample Preparation

Rock samples were crushed and sieved according to ASTM- C227. Table 3.1 illustrates the size distribution of the aggregates as eventually used in mortar preparation.

Table 3.1 Aggregate sizes and their percentage

Passing	Retained (Mesh No.)	Mass %
4.75 mm	2.36 mm (# 8)	10
2.36 mm	1.18 mm (# 16)	25
1.18 mm	600 μ m (#30)	25
600 μ m	300 μ m (#50)	25
300 μ m	150 μ m (#100)	15

The aggregates were then mixed with type 10(PCI) cement and tap water in proportions as prescribed in ASTM C 305 (Laboratory Testing Manual, 1996). The proportions for the water/cement ratio and aggregate/cement ratio were 0.5 and 2.25 respectively. A stationary mixer blended the mixture for three and half minutes, in accordance with the requirements of ASTM C 305. The mixed fresh mortar was then cast and set into a sealed and humid chamber and the mixture was allowed to set at room temperature (20°C) for 24 hours. Samples were then demolded, labelled, and placed in a limewater bath for a period of 28 days for curing. After the curing period, mortars were removed from the water, and cores were drilled.

Three cores were drilled from each of the 39 samples. Then, both ends of samples were cut and squared carefully to assure the accuracy of the compressive test results. Core samples were labeled and sized, i.e. cut to approximately the same length. The diameter of the cores was 19 mm and the length was about 55 mm.

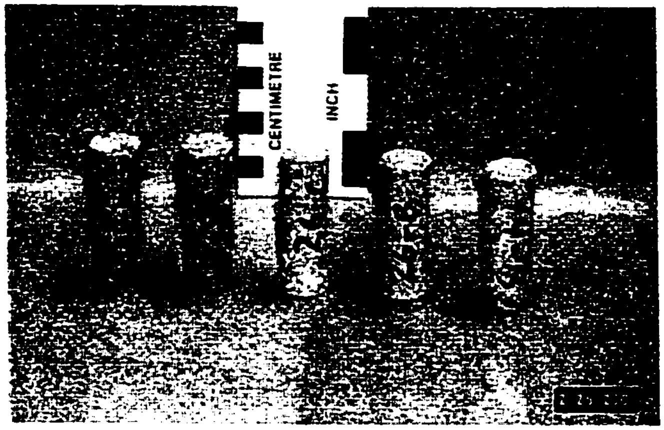


Figure 3.1 Mortar core samples

(Photographed by P.P.Hudec)

3.1.3 Outline of Experiments

All the tests were performed on the three cylindrical cores taken from each of the 39 cast blocks. In general, unless otherwise noted, the starting sample condition for each set of tests was dry, room temperature environment (at around 20°C). The samples were oven-dried at 100°C and allowed to cool to room temperature. The tests were performed in following order:

1. Adsorption
2. Absorption
3. Uniaxial compressive test
4. Modulus of elasticity
5. Ultimate strength test

3.1.4 Water Adsorption Test

The dry samples were weighed on a laboratory scale with an accuracy of ±0.01g. The core samples were put into an airtight chamber with a relative humidity (RH) of 98% at 18°C temperature. The 98% humidity was maintained using a super-saturated solution of hydrated copper ($CuSO_4$, $5H_2O$). Previous studies by Hudec (1983) showed that 72 hours was a sufficient amount of time to achieve equilibrium between the water vapour pressure in the chamber and adsorbed water in the pores. Samples were then removed and re-weighed and the weight gain of each sample, which represents the amount of water adsorption or ADS_w, was calculated. Adsorption percent were obtained by using the equation:

$$\text{Adsorption (\%)} = \frac{ADS_w}{m_s} \times 100\% \qquad (3.1)$$

Where:

ADS_w = weight of adsorbed water (gr) m_s = weight of dry sample (gr)

3.1.5 Water Absorption Test

Following the above test, the samples were stored in the lab environment for 48 hours and were weighed at room temperature. The humidity in the room was (19 %). Then the samples were submerged in tap water at room temperature for 24 hours. After this period, the samples were individually removed from the bath, toweled surface dry, and weighed to an accuracy of 0.01g. The difference between weight of dry and saturated surface dry samples is called ABS_w.

Equation that used for calculation of absorption is:

$$\text{Absorption (\%)} = \frac{ABS_w}{m_s} \times 100\% \qquad (3.2)$$

Where;

ABS_w = weight of absorbed water (gr) m_s = weight of dry sample (gr)

3.1.6 Uniaxial Compressive Modulus and Strength Test

The compressive test was performed by using a uniaxial compressive test frame, capable of loads up to 5000-psi pressure (34.5 MPa), which was interfaced to a personal computer. The test frame consists of vertical massive stainless steel arms connected to a solid base, which contains a sample holder with embedded load cell for stress measurements. Stress is applied via a mechanical hydraulic pump to a piston located within the top cross-brace of the frame. A strain gauge capable of measuring strain to 0.001mm is mounted to the piston and the stylus of the gauge impinges on the bottom of the frame. The analog data from the load cell and the strain gauge were fed to an analog to digital converter card, and stored on the hard drive of the attached PC. The Figure 3.2 shows the test frame. The software was set to collect both stress and strain readings every second. A sample output of the test run for sample 4 is given in Appendix B-Table B-1. The data was then transferred to a spreadsheet for analysis.

Although each sample consisted of three cores, the measurements on the cores were done in random order, i.e., not all three cores for a given sample were tested in sequence. The results of the tests for the three cores of each sample were averaged, and any one sample that deviated by more than one standard deviation from this average was rejected, and the remaining two samples re-averaged. Data of mortar elasticity and 'cleaned' averages for all of the tests described below are found in Tables B-2, 3,4 and 5 in Appendix B.

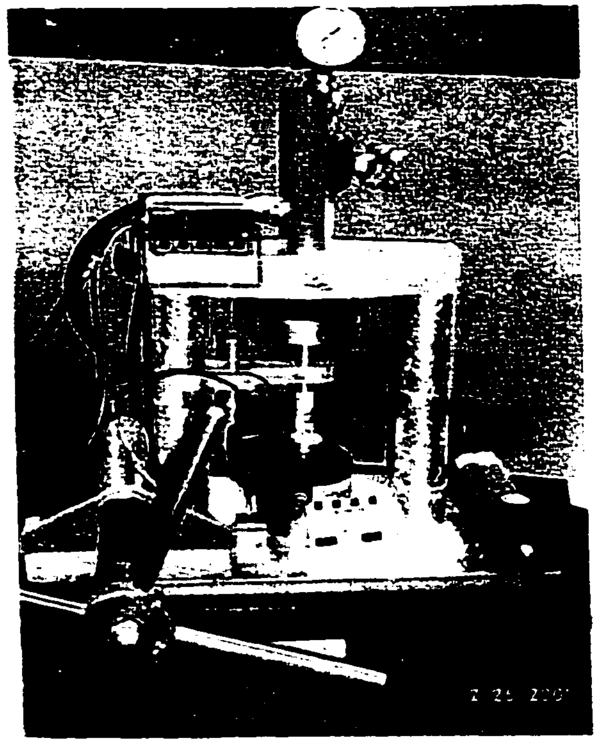


Figure 3.2 Test frame

(Photographed by Dr.P.P.Hudec)

3.1.6.1 Low Stress Range Modulus of Elasticity Tests

For the main set of low stress range experiments, the maximum pressure applied was approximately 6.9 Mpa (1000 psi). The relatively low stress was used to prevent damage to the specimens during the tests, and was well within the elastic limit of all the specimens. Modulus of elasticity was calculated from the stress and strain data by equation 2.7(Pg. 18). For simplicity, the area term of the equation was considered as unity (1). The 6.9 Mpa modulus test was repeated on mortars equilibrated under the following conditions. These conditions simulate those to which concrete and mortar are frequently exposed.

1. Room temperature, Room Humidity
2. Room temperature, 98% Humidity
3. Room temperature, fully saturated

4. Room temperature, Fully saturated with 3% NaCl
5. Frozen, Room Humidity
6. Frozen, fully saturated
7. Frozen, Fully saturated with 3% NaCl

The testing procedure is outlined below. Unless drying is specifically mentioned, the samples were kept at room temperature and humidity between tests. Room relative humidity varied from 19 to 25%, and temperature from 20 to 22 °C. These ranges are considered to have no significant effect on test results.

At the start of testing, the samples were oven dried at 100°C for 24 hours. Samples were allowed to cool and equilibrate under ambient lab conditions for 48 hours, and were then tested. In the next stage (2), the samples were exposed to 98% relative humidity in an air-tight chamber containing a super-saturated solution of hydrated copper ($CuSO_4$, $5H_2O$). The samples were placed in the chamber at 20° C, for 3 days. Then the samples were individually removed and tested.

In the third test, the samples were submerged in water for 24 hours at a room temperature. The samples were individually toweled surface dry and tested. In the fourth stage (4), the samples were oven dried, at 100°C for 24 hours, and again submerged, for 48 hours, in a 3% NaCl salt-water solution, then toweled surface dry and tested.

Stages 5, 6 and 7 are exactly the same as in steps 1,3, and 4 respectively, except the samples were frozen after exposure to the stated environment. Samples were oven dried at 100°C between stages 3 -4, 4-5 and 6-7. Samples were put into the freezer at –20°C for 48 hours then tested individually. The frozen state of the samples was maintained during the test by a thermal styrofoam jacket. The modulus results are found in Appendix B, Tables B-3, 4.

Repeatability of the test measurements using this equipment was performed on rock samples by Dananaj (2001) to evaluate both the equipment and the procedure. Four samples in both dry and saturated state were tested six times at three stress levels (3.45, 6.9, 10.3 MPa). Modulus was calculated and it was determined that, on average, 4 measurements out of 6 were within the range of mean ± one standard deviation of any one sample. These results apply to this study, since the conditions and stress levels were similar.

3.1.6.2 Full Range Modulus of Elasticity Test

At the end of the sequence of low stress modulus tests and prior to destructive uniaxial strength determination, a high load (up to 20,700 KPa (3000-psi) stress-strain measurements was performed on all the cores at room temperature (22°C) and room humidity (RH 25%). The results of modulus of elasticity as are presented in Appendix B, Table B-5.

3.1.6.3 Ultimate Strength Test

To obtain the approximate length for strength testing, the samples were cut and sized to 2:1 length: width ratio before the strength test. The samples were then loaded to beyond their elastic limit, i.e. to failure. The highest stress at failure as recorded by the computer represented their ultimate unconfined strength (Appendix B, Table B-5).

3.2 DESCRIPTION OF THE VARIABLES (DATA SET)

Rather than taking the straight average of results for the three cores per sample, the average was optimized by calculating the Z scores. Z score parameter identifies samples that are outside the normal distribution (Norusis, 1993) and is expressed as:

$$Z = \frac{X - \overline{X}}{S} \qquad (3.3)$$

Where Z = Z score

X= value of particular observation

$\overline{X}$ = mean of the distribution (three samples) S = standard deviation

Samples with Z score more than 1 or less than –1 (out of normal distribution) were removed. Since usually one sample is removable (Z>1 or Z<-1), the average of the two remaining samples were calculated and used the statistical procedures.

The mortar data set contained the various moduli of elasticity as a result of compressive test mortars, as well as adsorption and absorption data. Added to this were the moduli of elasticity for rocks re-calculated from raw data based on experiments performed by Pour-Molk Ara (in progress). Rock adsorption results, as well as rock grain size estimates and petrographic descriptions were obtained from Dananaj (2001). Magnesium sulphate test results for aggregates were taken from Rigbey (1980). Magnesium sulphate test is essentially a durability test, i.e., it simulates the response of the rock to freezing and thawing. The aggregate is saturated in super-saturated solution of magnesium sulphate, and oven dried. Saturation and drying are repeated for 5 cycles, and the deterioration or loss caused by salt crystallization in the pores is determined by back-sieving.

The combined data set contained 21 columns or variables (14 of these are moduli of elasticity) and 39 rows (rock and mortar results). The list of variables is given in Table 3.2.

Table 3.2 List of variables used in the statistical analysis

Rock		Mortar
RA	Room temperature –room humidity modulus	MA
RH98	Room temperature-98% humidity modulus	MH98
RS	Room temperature- saturated modulus	MS
RSALT	Room temperature-saturated with 3% salt water modulus	MSALT
RF	Frozen- room humidity modulus	MF
RFS	Frozen – saturated modulus	MFS
RFSALT	Frozen- saturated with 3% salt water modulus	MFSALT
RABS	Absorption	MABS
RADS	Adsorption	MADS
MAG.	Magnesium sulphate test on rocks	
	Modulus of mortars for 3000 psi	MODU.
	Ultimate strength of mortars	ULTIMATE

Rocks have higher moduli of elasticity than mortars by a factor of about 1000. The rock modulus data were reduced by this factor to facilitate comparison.

3.3 STATISTICAL ANALYSIS

Statistical analysis was employed to study the relationships between rock and mortar elastic properties, and the influence of limestone and dolomite aggregate on these properties. The data was analyzed by using three commercial statistical software packages. Statistical functions of Excel were used to determine certain bi-variate relationships and for plotting of the data. SPSS (V9.0 1998) and SYSTAT (V8.0 1998) are specialized programs for uni-, bi- and multi-variate statistics that were used for the multivariate analysis.

The analytical methods and the relevant software used in this research were:

- Descriptive and basic analysis (SPSS)
- T-test analysis, including: normality, two-paired and two groups (SPSS and SYSTAT)
- Correlation, including: splom or scatterplot matrix (SPSS, SYSTAT)
- Cluster analysis, including: discriminant and hierarchical (SYSTAT)
- Tree analysis (SYSTAT)
- Regression including: Linear and stepwise (Excel and SPSS)
- Factor analysis (SPSS)

3.3.1 Normal Distribution of Data Test

Normal distribution is required in many statistical analyses. In the Q-Q normal probability plot, the observed values are plotted against expected value from a normal distribution. Each observed value is paired with an expected value from the normal distribution. The expected values are based on the rank of the observed value and the number of cases in the sample. In a normal distribution points fall almost exactly on a straight line (SPSS software, 1998). The data for modulus of elasticity of mortars was put to the normality test, and the plots are given in Appendix C. As can be seen, the data plots on a straight line, and therefore is normally distributed. Similar results were obtained for rock samples. It is therefore valid to apply the various statistical techniques to the data set.

3.3.2 Summary of Results

Descriptive statistics give the summary information about the distribution, variability, and central tendency of a variable. The descriptive procedure displays univariate summary statistics for several variables in a single table.

The results of the descriptive analysis are shown in Tables 3.3 and 3.4, and represent the analysis of the data of Appendix B. As shown in the tables and the related graphs (Figure 3.3, 3.4), the modulus of elasticity of rock is much higher than those for the corresponding mortar.

Table 3.3 Descriptive analyses of rock data (moduli in KPa)

(based on Pour Molk Ara (in progress), Rigbey (1980) and Dananaj (2001))

	N	Minimum	Maximum	Sum	Mean	Std.	Variance
RA	36	1.2E+09	1.2E+10	2.7E+11	7.6E+09	2.2E+09	4.7E+13
RH98	36	1.2E+09	1.1E+10	2.6E+11	7.3E+09	2.1E+09	4.5E+13
RS	36	9.4E+08	1.2E+10	2.5E+11	6.9E+09	2.4E+09	5.5E+13
RSALT	35	1.1E+09	1.0E+10	2.4E+11	6.9E+09	1.9E+09	3.5E+13
RF	35	9.4E+08	1.3E+10	2.9E+11	8.4E+09	2.5E+09	6.2E+13
RFS	35	1.1E+09	1.1E+10	2.5E+11	7.1E+09	2.2E+09	4.8E+13
RFSALT	34	1.1E+09	9.7E+09	2.2E+11	6.5E+09	1.8E+09	3.2E+13
RABS	39	.07	3.78	46.57	1.1941	.9891	.973
RADS	39	.00	.70	6.63	.1700	.1867	3.484E-02
MAG.TEST	38	.55	95.00	456.10	12.0026	20.9976	440.897

Table 3.4 Descriptive analyses of mortar data (moduli in KPa)

	N	Minimum	Maximum	Sum	Mean	Std.Deviation	Variance
MA	39	3.1E+06	9.6E+06	2.5E+08	6.4E+06	1.3391E+06	1.8E+12
MH98	39	3.2E+06	9.1E+06	2.4E+08	6.2E+06	1.0836E+06	1.2E+12
MS	39	4.0E+06	9.6E+06	2.7E+08	6.9E+06	1.0393E+06	1.1E+12
MSALT	39	4.0E+06	9.0E+06	2.5E+08	6.4E+06	1.1698E+06	1.4E+12
MF	39	1.4E+06	9.1E+06	2.4E+08	6.1E+06	1.6691E+06	2.8E+12
MFS	39	3.7E+06	8.3E+06	2.4E+08	6.1E+06	1.0022E+06	1.0E+12
MFSALT	39	3.4E+06	9.3E+06	2.5E+08	6.3E+06	1.3777E+06	1.9E+12
MABS	39	4.18	7.00	214.73	5.5059	.6541	.428
MADS	39	1.30	3.58	80.78	2.0713	.5150	.265
MODULUS	39	4.0E+06	9.9E+06	2.4E+08	6.2E+06	1.2146E+06	1.5E+12
ULTIMATE	39	1.1E+04	2.2E+04	6.6E+05	1.7E+04	2.5917E+03	6.7E+06

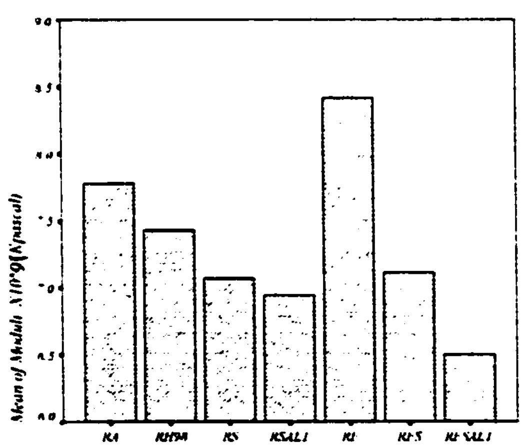


Figure 3.3 Rock moduli under different conditions

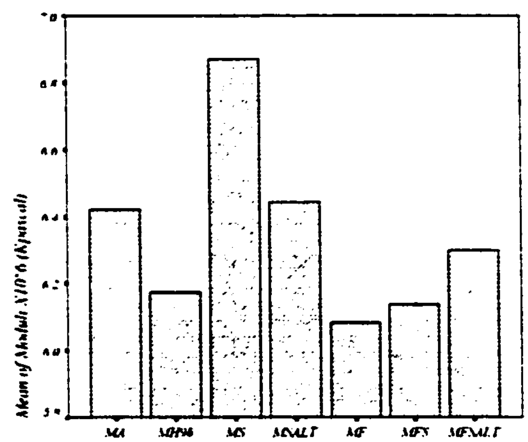


Figure 3.4 Mortar moduli under different conditions

3.3.3 Comparison and Explanation of The Results

3.3.3.1 *t*-test

The t test is a statistical model that can be used for testing the significance of difference between the means of two groups of populations, based on the means and distributions of two samples (Williams, 1985).

Two types of t-test were applied in this study:

- Two-sample t test, to compare the means within one variable (e.g. MA) for two contaired groups of cases (e.g. dolomite and limestone).

- Paired comparison t test, to compare the means of two variables (e.g. MA and M98) for a single group.

All t-tests were done within similar groups, i.e., the mortar modulus results were compared to only mortar modulus results, and not to mortar adsorption or rock modulus results.

Significance of the difference in means is expressed by significance level in paired t-test. The two-tailed significance level 0.01 means that the sample populations are different with 99% confidence level. Two-tailed significant level 0.05 means that the compared sample populations are different with 95% significance or confidence level. The results of the t-test are presented in Table 3.5 and full t-test results may be found in Appendix C. As can be seen, there are relatively few environmental conditions that produce moduli that are significantly different, although the data do show some trends that are discussed in the following paragraphs.

At room temperature, the modulus of elasticity is shown to decrease when moisture is introduced to the rock. Hudec (1991) explained the inverse effect of moisture on the strength and durability of rock due to osmotic pressure in different pores of rocks. The modulus of elasticity increases in frozen rocks (RF), but decreases again with increasing the moisture (RFS, RFSALT). The highest and lowest moduli of elasticity in rocks are found in frozen rocks (RF) and frozen saturated (in salt water) condition (RFSALT) respectively. Frozen samples are already thermally contracted (deformed) material, and deform the least during the additional loading process.

Table 3.5 Paired t test based on rock and mortar data

	RA	R98H	RS	RSALT	RF	RFS
RA						
R98H	+					
RS	+					
RSALT	+					
RF	-	-	-	-		
RFS	+				+	
RFSALT	+	+	+	+	+	+

	RADS
RADS	
RABS	-

	MA	MH98	MS	MSALT	MF	MFS
MA						
MH98						
MS	-	-				
MSALT			+			
MF			+			
MFS			+			
MFSALT			+			

	MADS
MADS	
MABS	-

\+ Column variable significantly greater than the row variable
\- Column variable significantly lower than the row variable

Mortars moduli of elasticity of mortars, which are 1000 times lower, show different trends in the various environments as a result of different structure and porosity. Unlike the rocks, frozen mortars (MF) have the largest deformation and the lowest moduli. The opposite is true for saturated mortars. Brandtzaeg (1927) found that the eventual failure of the material result from a gradual development of internal tension-microcracking throughout the specimen parallel to the direction of the applied compressive stress (quoted in Popovics, 1998). Low temperatures can increase the inside stress and microcracking and lower the moduli. Microcracking may occur because of different coefficient of thermal expansion (CTE) of aggregate and the paste. Freezing temperature can also freeze the water inside the aggregates, which causes expansion and may deteriorate the aggregate and also reduce the strength of aggregate-paste bond.

Saturated mortars (MS) resisted stress the most and posses the highest moduli. Under low stress, the increasing external load on the concrete specimen during strength testing develops an increasing internal pressure not only on the solid components but also on the liquid in the pores, trying to squeeze the liquid out of the specimen (Popovics, 1998). Since the migration of the liquid is not free due to the smallness of the capillary pore sizes, specimen resists easy deforming and shows high moduli.

The moduli of elasticity of rocks in various environments show greater variation than mortars according to the paired t test (Table 3.5). There are three conditions in rocks and one condition in mortars that show statistically significantiy different moduli from all other conditions. The results for ambient (RA), frozen (RF) and frozen saturated (in brine) (RFSALT) environments are significantly different from the rest of rock data. As the freezing of brine deteriorates the porous materials, resulting in the lowest moduli for RFSALT. During freezing, the solution in larger pores freezes and concentrates the ions in the small pores containing unfrozen water. The concentrated ions generate an osmotic force, which can break down the internal structure.

In case of mortars, only the higher moduli of saturated mortars, (MS) show a significant difference to other environmental mortar conditions, specifically, where mortar is salt-saturated (MSALT), frozen (MF), or both (MFSALT). This may be explained by the character of the adsorbed water existing in the microspores, bridging the pore space with tightly adsorbed, semi-rigid water molecules, giving the mortar added strength.

3.3.3.2 Cluster Analysis

Another way to explain the relationship between the different moduli is by cluster analysis based on variable clustering. Cluster analysis is a statistical method facilitating the search for relatively homogeneous groups or cluster of cases in an analyzed sample population (Ondrasik, 1996). This multivariate statistical technique groups samples rather than variables. (Hudec and Mitchell, 1999). All samples falling in a given group should behave in a similar manner (Hudec, 1997). By considering the means of test results falling within each group, the group behaviour can be identified. Discriminant and hierarchical are the clustering methods used in this study.

The two cluster trees (hierarchical trees) in figure 3.5 show the similarity between rock and mortar moduli. The distance along x- axis shows the degree of commonality therefore the smaller the distance, the closer are the variables correlated. Moduli in frozen saturated (in salt water) (MFSALT, RFSALT) and frozen samples (MF, RF) in both materials form the most distant clusters, which suggest a greater influence of temperature rather than moisture on the strength of materials.

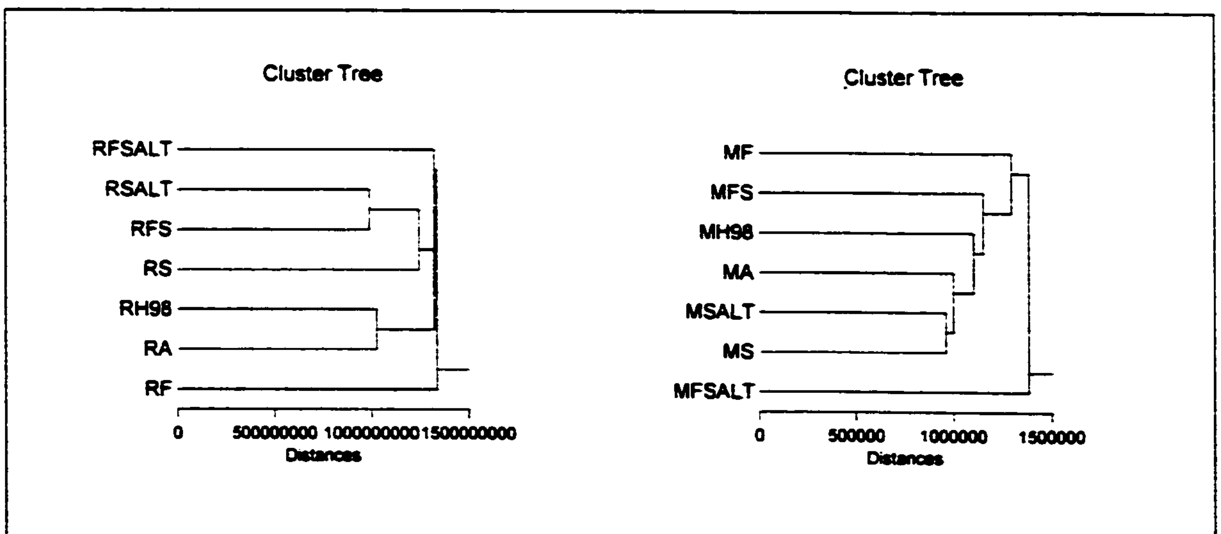


Figure 3.5 Relationship between rock / mortar moduli of elasticity

3.3.4 Effect of Rock Type on Mortar Properties

Dolomite and limestone were the two major aggregate types in the mortar. The effect of dolomites and limestones on mortar is shown by bar graphs, scatter graphs and by group t test.

3.3.4.1 Porosity and Water Adsorption and Absorption

Porosity in dolomite and limestone, as determined by water absorption is illustrated and compared in Table 3.6 and Figure 3.6.

Table 3.6 Summary of adsorption/absorption results in dolomite (D) and limestone (L)

TYPE		MABS %	MADS %	RABS %	RADS %	MABS/MADS	RABS/RADS
D	Mean	5.60	2.20	1.48	.16	2.63	27.93
	N	24	24	24	24	24	24
	Std. Deviation	66	.55	1.01	.19	.39	40.55
L	Mean	5.56	1.90	.71	.25	3.03	3.32
	N	11	11	11	11	11	11
	Std. Deviation	.57	.46	.57	.18	.48	2.73
Total	Mean	5.59	2.10	1.24	.19	2.76	20.23
	N	35	35	35	35	35	35
	Std. Deviation	.63	.53	.95	.19	.45	35.34

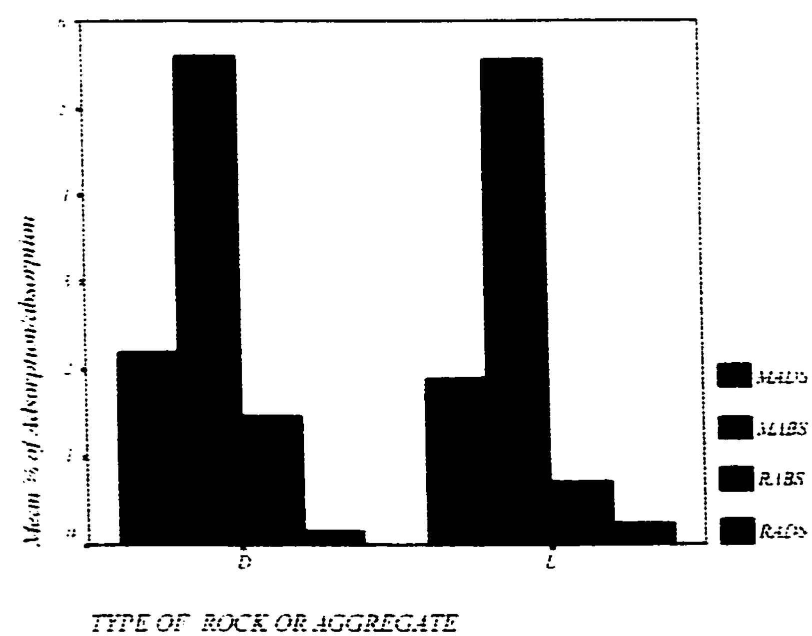


Figure 3.6 Comparison between absorption of dolomite (D) and limestone (L) in rock and mortars

Water absorption in dolomites is significantly higher than in limestones but the amount of adsorbed water is almost the same in both. This suggests that the pores in limestones are smaller, and contain mostly adsorbed water, since there is a significant relationship between absorbed and adsorbed water (Figures 3.6 and 3.7). The water absorbed by immersion in limestones is essentially equivalent to water adsorbed at high humidity. Dolomites, on the other hand, show no relationship between adsorbed and absorbed water, suggesting that the pores are large and contain mostly absorbed water.

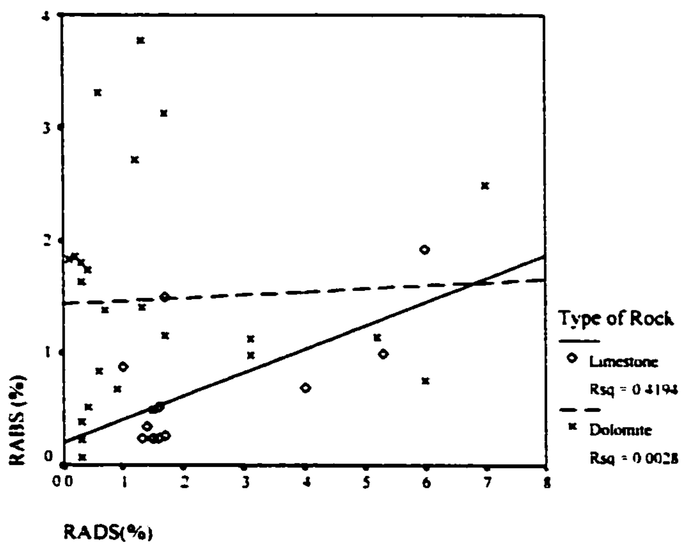
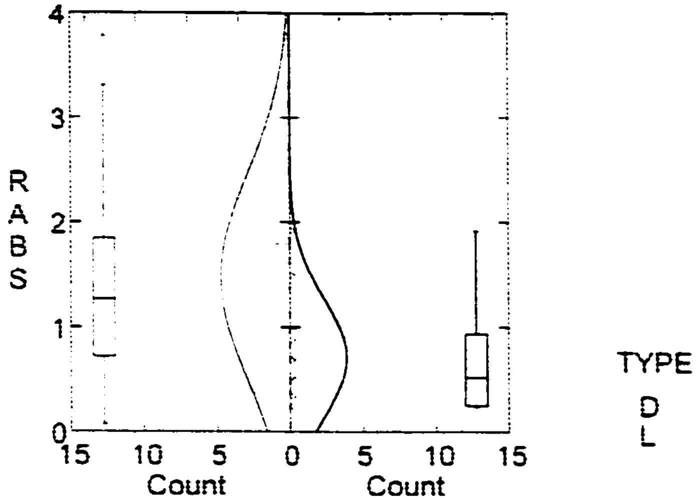


Figure 3.7 Water adsorption-absorption relationships of limestone and dolomite.

The difference in absorption between limestone and dolomite is statistically significant to 0.03 level according to group t test, and is shown in (Figure 3.8).

Figure 3.8 Significant differences between dolomite (D) and limestone (L) in-group t test based on rock absorption. The curves and boxes represent distribution of data and standard deviation respectively



Two-sample t test on RABS grouped by rock type

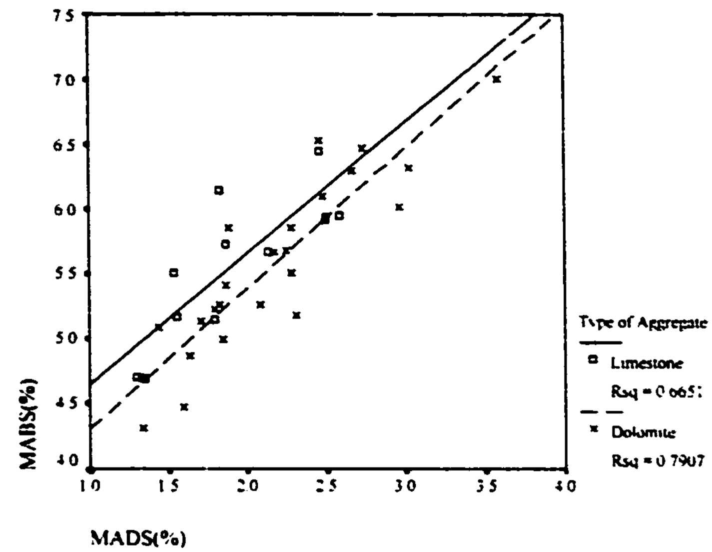
Group	N	Mean	SD
Dolomite	24	1.476	1.005
Limestone	11	0.711	0.569

Separate Variance t = 2.860 df = 31.3 Prob = 0.007
Difference in Means = 0.765 95.00% CI = 0.220 to 1.310

Pooled Variance t = 2.345 df = 33 Prob = 0.025
Difference in Means = 0.765 95.00% CI = 0.101 to 1.429

The mortars as a group show much more similarity in their water absorption (effective porosity), which may indicates the relatively negligible effect of aggregate porosity on mortar porosity and the dominance of paste porosity. However, as shown in Table 3.6 (Pg. 61), dolomite-containing mortars absorb slightly more water than the limestone mortars, though the difference is not statistically significant. Figure 3.9 shows that the adsorbed water in mortar pores is proportional to and a little less than half that of absorbed water.

Figure3.9 Water adsorption-absorption relationship in mortars containing limestone and dolomite aggregates.



The mortars mixes were identical in all respects, and therefore no absorption or adsorption differences due to the paste portion were to be expected. So, although there is a significant difference between limestone and dolomite rock absorption, when in mortar, the higher total porosity of the mortar overwhelms and masks this difference.

3.3.4.2 Modulus of elasticity

Tables 3.7 and 3.8, and Figures 3.10 and 3.11 represent the moduli of elasticity of limestone and dolomite, and the corresponding mortars under different conditions of exposure.

Table 3.7 Summary of rock moduli for dolomite (D) and limestone (L) (KPa x 10^9)

(based on Pour Molk Ara(in progress) data)

Report

TYPES		RA	RH98	RS	RSALT	RF	RFS	RFSALT
D	Mean	7.9324	7.5581	6.9888	6.9315	8.6940	7.1071	6.6950
	N	21	21	21	20	21	21	20
	Std. Deviation	2.1335	2.0675	2.2566	1.9218	2.6701	2.1354	2.0052
L	Mean	7.6009	7.2091	6.9100	6.8445	8.4530	7.3110	6.3510
	N	11	11	11	11	10	10	10
	Std. Deviation	2.3721	2.3994	2.8969	2.0272	2.3099	2.6529	1.6420
Total	Mean	7.8184	7.4381	6.9617	6.9006	8.6163	7.1729	6.5803
	N	32	32	32	31	31	31	30
	Std. Deviation	2.1857	2.1548	2.4482	1.9263	2.5232	2.2717	1.8704

Table 3.8 Summary of mortar moduli for dolomite mortar (D) and limestone mortar (L) (kPa x 10^6)

Report

TYPES		MA	MH98	MS	MSALT	MF	MFS	MFSALT
D	Mean	6.5308	6.2383	6.8175	6.3183	6.4446	6.2463	6.2208
	N	24	24	24	24	24	24	24
	Std. Deviation	1.4764	1.3004	1.1393	1.1821	1.5650	.9458	1.5241
L	Mean	6.2945	5.9427	7.1100	6.4509	5.4082	5.7900	6.2445
	N	11	11	11	11	11	11	11
	Std. Deviation	.9681	.6006	.9746	1.0255	1.7691	1.2435	1.1897
Total	Mean	6.4566	6.1454	6.9094	6.3600	6.1189	6.1029	6.2283
	N	35	35	35	35	35	35	35
	Std. Deviation	1.3276	1.1267	1.0847	1.1218	1.6780	1.0517	1.4099

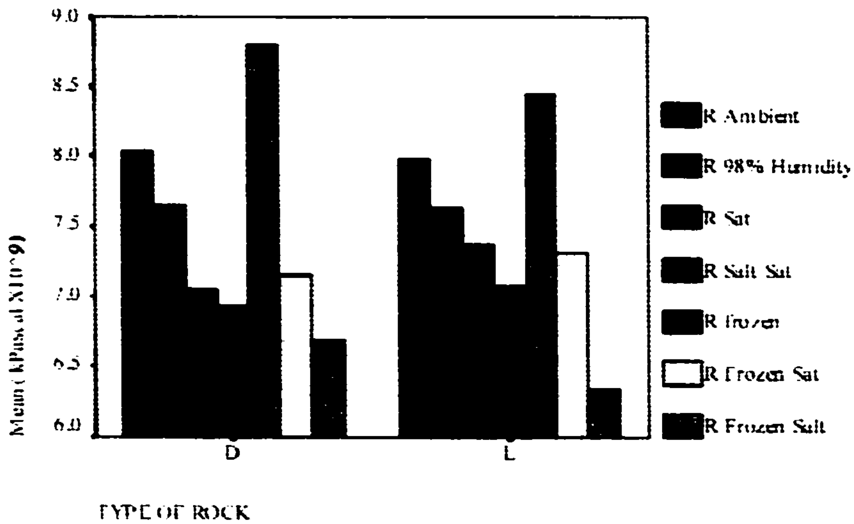


Figure 3.10 Moduli of different rock types under different exposure conditions (based on Pour Molk Ara (in progress) data)

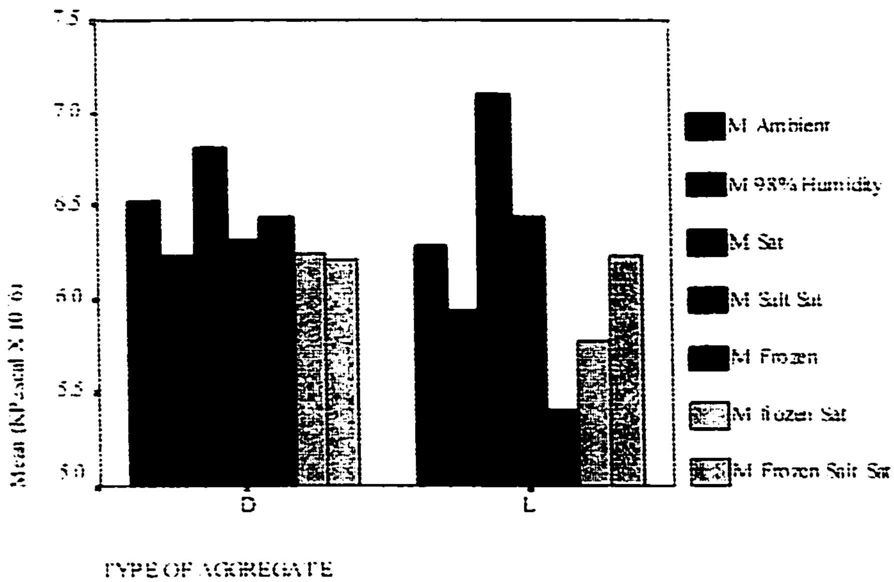


Figure 3.11 Moduli of different mortars under different exposure conditions

Effects of the environmental conditions of exposure on moduli of rocks followed the same general pattern (changes in moduli as exposure conditions change) in limestone and in dolomite (Fig 3.10). This is suggests that limestones and dolomites have similar pore size distribution, even though different effective porosity. The moduli were calculated in the 6.9mPa (1000psi) range (to maintain equivalence with mortar calculations), which is a very low stress environment for rocks.

However, the limestone and dolomite mortars show distinctly different pattern of behaviour as environmental conditions change. Moduli of dolomite mortars were quite uniform under different environments, but the limestone mortars showed a highly varied response, and especially to freezing temperature. The paired t test analysis in Table 3.9 shows that the conditions under which significantly different behaviour difference exists between limestone and dolomite are different for rocks than for mortars.

Table 3.9 Significant (with 95% confidence) differences between moduli of elasticity of rock and mortars based on rock/ aggregate type according to paired t test

MORTARS

Dolomite	ma	mh98	ms	Msalt	mf	mfs	mfsalt
ma							
mh98							
ms		-					
msalt			+				
mf							
mfs			+				
mfsalt							

Limestone	ma	mh98	ms	msalt	mf	mfs	mfsalt
ma							
mh98							
ms	-	-					
msalt			+				
mf			+				
mfs			+				
mfsalt			+				

ROCK

DOLOMITE	ra	rh98	rs	rsalt	rf	rfs	rfsalt
ra							
rh98	+						
rs	+	+					
rsalt	+	+					
rf	-	-	-	-			
rfs	+						
rfsalt	+	+			+		

Limestone	ra	rh98	rs	rsalt	rf	rfs	rfsalt
ra							
rh98							
rs							
rsalt							
rf		-	-	-			
rfs							
rfsalt	+	+		+	+		

\+ Column variable significantly greater than the row variable

\- Column variable significantly lower than the row variable

The moduli of limestones under room and high humidity conditions are significantly different from other conditions, whereas in dolomites, the dry frozen and salt solution frozen moduli differ from those under other conditions. This suggests that the smaller pore system in limestone, as indicated by the higher proportion of adsorbed water in their pores has a significant control over the elasticity of the rock. Conversely, the larger pore size and the brine water content of the pores exercises significant control on the elastic moduli of dolomite.

The significantly different moduli for both mortar types are:

- 98% humidity- saturated
- Brine saturated- saturated
- Frozen saturated – saturated

And specifically in limestone mortars are:

- Ambient – saturated
- Frozen saturated- saturated
- Frozen brine saturated-saturated

The examination of the above list indicates that the significant statistical differences occur between room temperature saturated mortars, and other saturated conditions. Since aggregate represent three-quarters of the volume of concrete, its porosity materially contributes to the overall porosity of mortar (Neville, 1995); and since the paste properties of mortars are identical, this suggests the main property causing the difference between dolomite and limestone mortars is the pore volume, pore size distribution, and pore structure of the aggregates. Table 3.6 (Pg.61) shows the ratio of water absorption to adsorption; greater the ratio, the larger is the proportion of large to small pores.

Higher modulus is indicative of higher strength, as will be shown later. The higher moduli under saturated condition and lower moduli under frozen state can be explained by considering the following: normal water is incompressible, ice is compressible, and adsorbed water is compressible (Dananaj, 2001). Thus, dry (ambient) mortar has higher modulus because the pore surface free energy is high and resists deformation. Under high humidity conditions, several molecular layers of water cover the surfaces, and the free energy of the pore system is reduced. Further, the adsorbed water is compressible (i.e., elastic).

Dolomite has larger capillary pores than limestone, as shown by the absorption/adsorption ratio in Table 3.6 (Pg.61). Thus, dolomitic mixes can generate large air voids during mixing by replacement of the air in their voids by mix water. This would tend to decrease the strength of mortar and affect its modulus. On the other hand, re-crystallized texture in dolomite and its higher density and strength would provide stronger bond and higher strength in dolomitic mortars in comparison with limestone mortars under low humidity (MA and M98).

Under saturated conditions, the pores are filled both with bulk and adsorbed water. However, bulk (absorbed) water is incompressible and resists deformation. This is also seen in that pure water saturated limestone mortars have higher moduli than those saturated with salt water (MS-MSALT). Salt water produces a greater amount of surface-held, adsorbed water, which is compressible (Dananaj, 2001). When frozen, the incompressible bulk water becomes compressible ice, thus lowering the elastic modulus of the system.

The dolomite mortars tend to follow the above scenario in a more muted manner, since the pores are uniformly large, and the effect of adsorbed water in the rock pores is minimal. During normal saturation, dolomite, because of its larger pores, does not saturate 'critically', i.e., the pores are not completely filled. Thus, freezing of the water in the pores does not fill the pores with ice, and the ice in the pores has less effect on the modulus of the rock. The opposite is true in limestones, which, because of the preponderance of smaller pores, have tendency to saturate more upon immersion. Salt water behaves as normal water in large pores. But, because less salt water freezes, less ice forms, thus the elasticity, and therefore modulus of the frozen system is not as decreased. That may explain less significant differences among the moduli of dolomitic mortars in compared to limestone mortars.

Furthermore, in compression tests on saturated samples (MS, MSALT), incompressible water in mortar capillaries is forced to move to any available space in order to release the pressure. The more porous and permeable dolomite mortar allows the water to escape to large air voids but water in limestone mortars cannot be easily drained. This also may explain the higher moduli of elasticity in saturated limestone mortars compared to those of dolomite mortars (water pore pressure resists deformation). The same phenomenon is possible under freezing conditions when water freezes and expands in the mortar and aggregate pores (MF, MFS and MFSALT). Because the damaging action of freezing and thawing involves expansion of water on freezing, it is logical to expect that, if excess water can readily escape into adjacent air-filled voids, damage of concrete will not occur (Neville, 1996).

3.3.4.3 Strength and Elastic Modulus Relationships

Figures 3.12 and 3.13 show the influence of rock type on the elastic moduli - strength relationship in mortars. The moduli were calculated for a relatively low stress range of around 6.9 MPa (1000 psi) to reflect the lower stress conditions that concrete or mortars are normally subjected to. The ultimate unconfined compressive strengths were determined on mortars after all the moduli data were obtained. First, note the positive and significant relationship between the modulus data and strength data. The higher the modulus, the higher the strength. Thus, it is proposed that the conditions that affect the moduli of mortars will similarly affect the strength of mortars. Lowest moduli were obtained in saturated, frozen limestones mortars. By extrapolation, these conditions would result in the weakest mortars. Second, note that although their behaviour is similar, i.e., the slopes of the lines of best fit (regression lines) are parallel; limestone mortars are marginally stronger under these conditions. This may be a tenuous conclusion, since the regression coefficient for limestone is not statistically significant, but nevertheless, it does show a trend. Limestone with lower density than dolomite provides more volume of aggregate in limestone mortars, which may have a positive influence on mortar strength, even though limestone is inherently weaker than dolomite.

When the same strength data is compared to moduli under higher stress conditions, a somewhat different picture emerges. The moduli were calculated for the full range of stress the samples were subjected to prior to breaking. Limestone mortars continue to show similar relationship as above, i.e., somewhat similar slope, but this time, the dolomite mortars show no significant relationship between modulus and the ultimate strength, whereas limestone mortars do. This may be due to a great dissimilarity of strength and elastic properties between the dolomite particle and the surrounding paste.

Figure 3.12 Relationship between modulus of elasticity at 6.9 MPa (1000 psi) and ultimate strength of mortars with limestone and dolomite aggregates

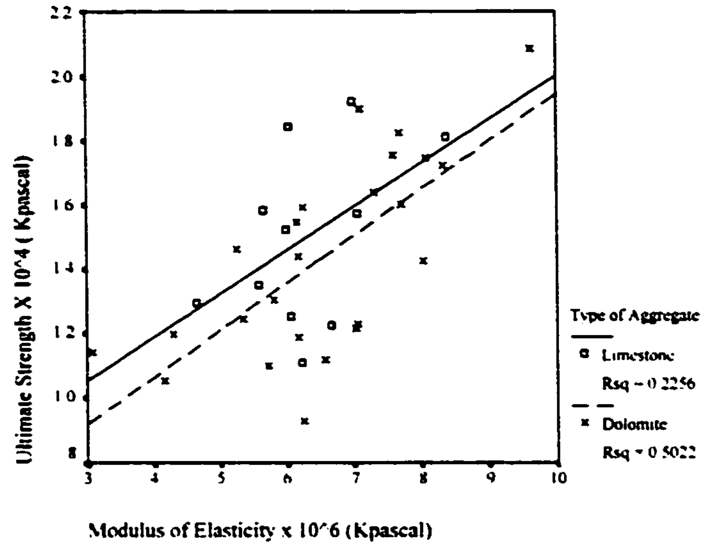
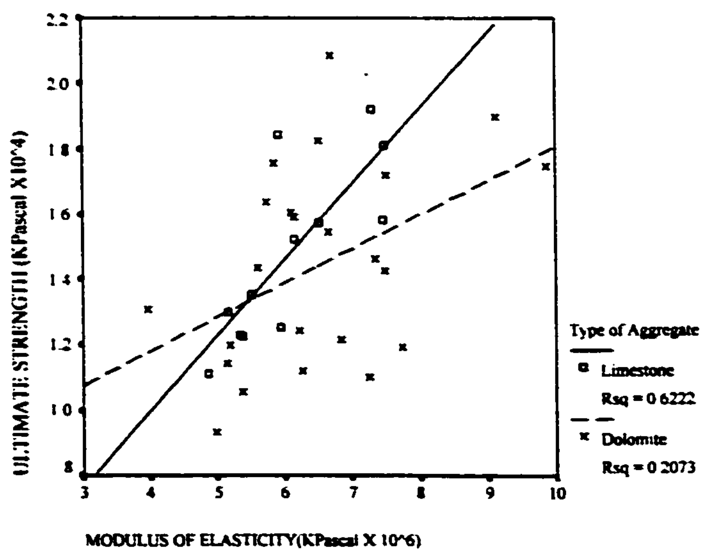


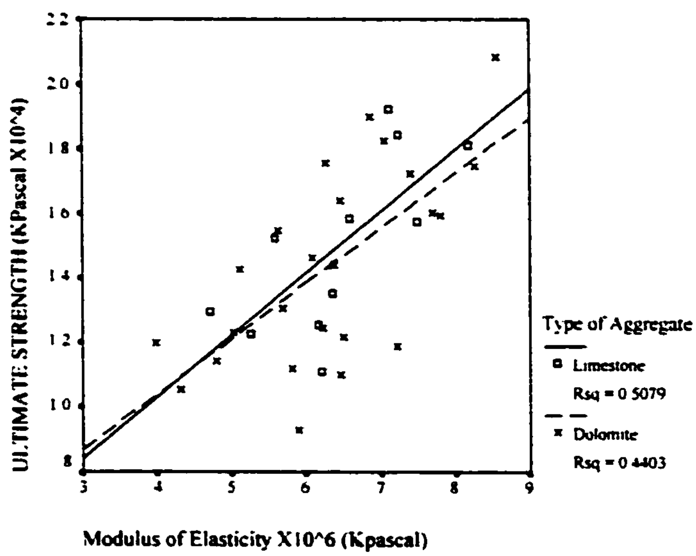
Table 3.7 (Pg.65) shows that dolomite rock samples have a greater modulus of elasticity than limestone, and much greater than that of the paste. In Table 3.8 (Pg. 66), note that limestone mortars have lower porosity and more aggregate volume, since dolomite is denser than limestone.

Figure 3.13 Relationship between moduli at 20.7 MPa (3000 psi) and the ultimate strength of dolomite and limestone mortars



Dolomite and limestone mortars under brine saturated conditions show only slight differences in relationship between their elasticity and ultimate dry strength as illustrated in Figure 3.14. This may be due to influence of salt on the amount and the effect of absorbed/adsorbed water in rock pores as explained above. Salt water increases the effect of the pore surface on the water, making more of it adsorbed, structured, and compressible. The inequality between limestone and dolomite in their elastic behaviour is thus reduced, and both rocks behave similarly under brine-saturated conditions.

Figure 3.14 Similarity in relationship between strength and moduli (under 6.9 Mpa stress) of different mortars under brine saturated (MSALT) condition



3.3.5 Relationships of Rock and Mortar Properties

3.3.5.1 Correlation

The relationships between any two sets of data are given by their correlation. Correlations measure the similarity and difference between the variables. The degree of this relationship is expressed by correlation coefficient (R). A correlation coefficient indexes a positive (+) or negative (-) relationship (Williams, 1985). The latter is also referred to as an inverse relationship

In general, that for a minimum statistical number of cases (N) of 40, the following can be said:

R from (-0.2, 0.2)	slight relationship
R from (-0.4, -0.2) or (0.4, 0.2)	low relationship
R from (-0.7, -0.4) or (0.4, 0.7)	moderate relationship
R from (-0.9, -0.7) or (0.7,0.9)	high relationship
R from (-1.0, -0.9) or (0.9,1.0)	very high relationship

However, the exact significance of R is determined mathematically, and is based on N, the number of samples being correlated. Significance of the correlation is expressed by significance level. The two-tailed significance level 0.01 means the correlation coefficient is significant to 99%. The two-tailed significant level 0.05 means that correlation coefficient is significant to 95%.

The correlations are shown in Table 3.10. Generally, rock moduli data have a better correlation among themselves than do the mortar results among themselves, and significant correlation between rock and mortar moduli exists only in few cases: frozen (MF), frozen saturated (MFS), brine saturated (MSALT) and frozen, brine saturated (MFSALT) mortars with equivalent rock variables, which indicates the aggregate influence on mortar. The significant level of 0.01 and 0.05 are in the tables designated by "**" and "*" respectively

Table 3.10 Significant correlation table

Correlations

	RA	RH98	RS	RSAL	RF	RFS	RFSA	MA	MH98	MS
RA	1.000	.894**	.792**	.762**	.879**	.695**	.754**	.115	.353*	.293
RH98	.894**	1.000	.843**	.800**	.920**	.775**	.757**	.063	.300	.268
RS	.792**	.843**	1.000	.838**	.799**	.841**	.783**	.135	.201	.201
RSALT	.762**	.800**	.838**	1.000	.776**	.900**	.773**	.259	.351*	.308
RF	.879**	.920**	.799**	.776**	1.000	.736**	.702**	.021	.214	.287
RFS	.695**	.775**	.841**	.900**	.736**	1.000	.787**	.326	.377*	.499**
RFSALT	.754**	.757**	.783**	.773**	.702**	.787**	1.000	.316	.553**	.540**
MA	.115	.063	.135	.259	.021	.326	.316	1.000	.568**	.664**
MH98	.353*	.300	.201	.351*	.214	.377*	.553**	.568**	1.000	.555**
MS	.293	.268	.201	.308	.287	.499**	.540**	.664**	.555**	1.000
MSALT	.166	.120	.275	.444**	.109	.467**	.536**	.689**	.563**	.695**
MF	.383*	.350*	.407*	.278	.382*	.435*	.418*	.361*	.307	.320
MFS	.340*	.319	.447**	.501**	.302	.520**	.373*	.228	.217	.248
MFSALT	.183	.249	.297	.391*	.295	.419*	.545**	.272	.348*	.376*
MABS	-.018	-.177	-.197	-.222	-.071	-.257	-.289	-.258	-.355*	-.288
MADS	-.017	-.183	-.211	-.193	-.037	-.227	-.314	-.226	-.328*	-.294
RABS	-.168	-.162	-.232	-.244	-.095	-.264	-.068	-.272	-.064	-.193
RADS	-.101	-.205	-.407*	-.377*	-.046	-.305	-.390*	-.387*	-.279	-.277
MAG.TEST	-.304	-.329	-.364*	-.352*	-.269	-.334	-.328	-.347*	-.168	-.357*
MODULUS	.201	.244	.282	.362*	.162	.410*	.452**	.434**	.597**	.363*
ULTIMATE	.192	.214	.235	.259	.130	.394*	.339	.654**	.612**	.623**

	MSAL	MF	MFS	MFSA	MABS	MADS	RABS	RADS	MAG.	MOD	ULTI
RA	.166	.383*	.340*	.183	-.018	-.017	-.168	-.101	-.304	.201	.192
RH98	.120	.350*	.319	.249	-.177	-.183	-.162	-.205	-.329	.244	.214
RS	.275	.407*	.447**	.297	-.197	-.211	-.232	-.407*	-.364*	.282	.235
RSALT	.444**	.278	.501**	.391*	-.222	-.193	-.244	-.377*	-.352*	.362*	.259
RF	.109	.382*	.302	.295	-.071	-.037	-.095	-.046	-.269	.162	.130
RFS	.467**	.435*	.520**	.419*	-.257	-.227	-.264	-.305	-.334	.410*	.394*
RFSALT	.536**	.418*	.373*	.545**	-.289	-.314	-.068	-.390*	-.328	.452**	.339
MA	.689**	.361*	.228	.272	-.258	-.226	-.272	-.387*	-.347*	.434**	.654**
MH98	.563**	.307	.217	.348*	-.355*	-.328*	-.064	-.279	-.168	.597**	.812**
MS	.695**	.320	.248	.376*	-.288	-.294	-.193	-.277	-.357*	.363*	.623**
MSALT	1.000	.324	.495**	.423**	-.304	-.238	-.309	-.489**	-.394*	.424**	.659**
MF	.324	1.000	.640**	.196	.090	.142	-.247	-.175	-.176	.293	.326*
MFS	.495**	.640**	1.000	.111	.128	.208	-.434**	-.392*	-.331*	.318	.370*
MFSALT	.423**	.196	.111	1.000	-.457**	-.381*	-.120	-.259	-.097	.344*	.269
MABS	-.304	.090	.128	-.457**	1.000	.848**	.176	.233	.378*	-.225	-.295
MADS	-.238	.142	.208	-.381*	.848**	1.000	.122	.147	.250	-.236	-.323
RABS	-.309	-.247	-.434**	-.120	.176	.122	1.000	.138	.534**	.072	-.274
RADS	-.489**	-.175	-.392*	-.259	.233	.147	.138	1.000	.802**	-.313	-.189
MAG.TEST	-.394*	-.176	-.331*	-.097	.378*	.250	.534**	.802**	1.000	-.198	-.223
MODULUS	.424**	.294	.318	.344*	-.225	-.236	.072	-.313	-.198	1.000	.484**
ULTIMATE	.659**	.326*	.370*	.269	-.295	-.323	-.274	-.189	-.223	.484**	1.000

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

3.3.5.2 Factor Analysis

Factor analysis attempts to identify the underlying variables, or factors, that explain the pattern of correlations within a set of observed variables. Factor analysis is often used in data reduction to identify a small number of factors that explain most of the variance observed in a much larger number of manifest variables (Williams, 1985). In this case, Factor analysis was used to identify the tests (variables) that correlate as a group, i.e., respond to similar property of the rocks and mortars.

The principal component analysis method was used to extract the eigen values. Significant factor is cut-off at the number of eigen values greater than or equal to one. A rotated factor-loading matrix is obtained by the varimax rotation method. Communality number describes the goodness of correlation between variables and factors. Communality number is a sum of squared correlation coefficients between variable and each factor (Williams, 1985). If this number is low, it means that the variable does not correlate with any of the extracted factors, and should be rejected from factor analysis. The importance of each variable is described by a loading. The higher the loading the higher influence of variable on the factor. A high positive loading means direct relationship and a negative loading means inverse direction of relationship.

The factor analysis was performed on the entire population and all the variables using Varimax rotation (Tables 3.11 and 3-12).

Table 3.11 Factor analysis table

Rotated Component Matrix[a]

	Component				
	Aggregate Modulus	Mortar Modulus	Mortar Absorption	Aggregate Absorption	Durability
RA	.909				
RH98	.935				
RS	.876				
RSALT	.852				
RF	.959				
RFS	.814				
RFSALT	.806				
MA		.739			
MH98		.832			
MS		.741			
MSALT		.660		.514	
MF		.429			
MFS				.680	
MFSALT			-.641		
MABS			.895		
MADS			.877		
RABS				-.685	
RADS				-.613	
MAG.TEST					.892
MODULUS		.650			-.478
ULTIMATE		.790			

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 8 iterations.

Table 3.12 Table of variances for each factor

Total Variance Explained

	Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %
Aggregate Modulus	6.007	28.604	28.604
Mortar Modulus	4.053	19.301	47.905
Mortar Absorption	2.546	12.122	60.027
Aggregate Absorption	2.221	10.577	70.604
Durability	1.427	6.796	77.400

Extraction Method: Principal Component Analysis.

The procedure found that all variables could be grouped into 5 factors (components). The 5 factors account for 77% of the total variance. Depending on the significant variables found in each factor, the factor was assigned a name that best described the group. Factor 1 is described as the *Aggregate Modulus* factor. It includes only the seven modulus of elasticity of rock variables and accounts for 28% of variance. Being exclusive to rock modulus, it suggests that no other variable tested has a direct influence on rock modulus. Second, or *mortar modulus and strength factor*, included 6 variables (most of the modulus of elasticity of mortar samples and ultimate strength). The inclusion of strength in this group underscores the relationship between elastic and strength properties of mortar. Factor 2 accounts 19 % of variance. Third and forth factors are called *Mortar Absorption* and *Aggregate Absorption* respectively, as they include absorption / absorption results in mortar and rock samples as their dominant variables. Note that the mortar porosity factor also includes MFSALT, i.e., brine containing, frozen mortar modulus. The MFSALT modulus is inversely related, suggesting that the higher the absorbtion, the lower the MFSALT modulus. Factor 4, the *Aggregate Absorption* factor contains frozen saturated (MFS) and brine saturated (MSALT) variables. This suggests that aggregate absorption is inversely tied to the moduli under these conditions. The significance of this is not clear. *Durability* factor, factor 5, is the last factor, and includes magnesium sulphate test results and has a low inverse relationship with dry, full range modulus of elasticity of the mortar. This suggests that rocks of low durability are inherently weaker, i.e., have a lower modulus.

3.3.5.3 Tree Analysis

The tree analysis can be applied to tests (variables), and to samples (cases). When applied to tests, the analysis effectively subdivides the chosen test (dependent variable) into segments, which are based on the properties of the samples as determined by other independent variables (Hudec and Mitchell, 1999). The independent variables are chosen by the procedure on the basis of having the greatest influence on the dependent variables.

Two tree analyses were run, with two selected dependent variables: ultimate strength and modulus of elasticity of mortar. As shown in Figure 3.15, the first limb of the tree divided the ultimate strength results into two groups: those in which the brine saturated moduli (MSALT) are less than 6600 MPa (left branch) and those with greater than 6600 MPa.

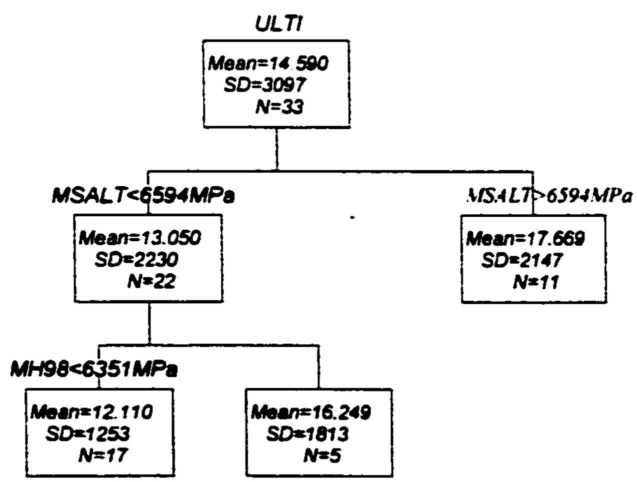


Figure 3.15 Tree analysis based on ultimate strength

The left branch is further divided into two sub branches based on 98% relative humidity (MH98) data. The mortar strength is thus influenced by the modulus of mortars when saturated in salt solution. For moduli lower than 6594 MPa under these conditions, the average strength is 13.1, whereas for higher moduli, it is 17.7 MPa. The strength of mortars whose moduli is less than 6600 is further controlled by the mortar moduli at 98% RH; for moduli less than 6350, the average strength is 12.1 MPa, whereas for those greater than this, the average strength is 16.2 MPa. The tree analysis suggests that the lowest mortar strength is obtained for mortars, which have lowest elastic moduli at high humidity and under salt-saturated conditions. The highest strengths are obtained for those mortars that have highest elastic moduli under salt-saturated conditions. Rock type influences these results only indirectly.

The second tree test was based on full load dry modulus (ultimate modulus) as the dependent variable (Fig. 3.16). This modulus was determined at the end of experiments as the samples were loaded close to their ultimate strength.

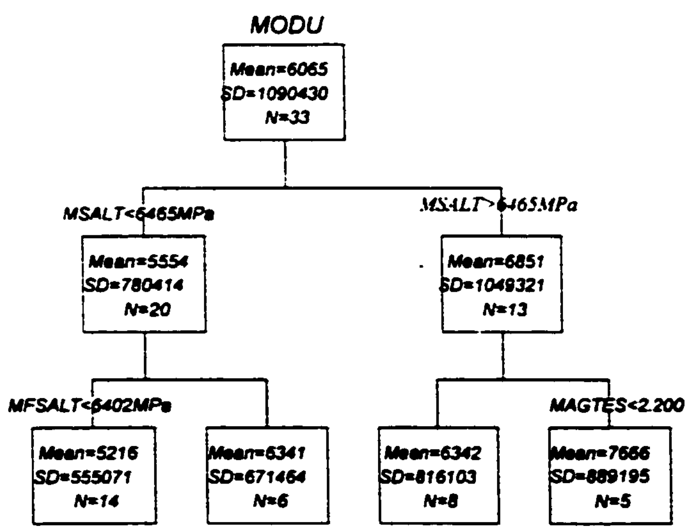


Figure 3.16 Tree analysis based on modulus of elasticity

As in the previous tree, the modulus of brine-saturated mortar has divided the dependent variable. Both the left and the right branches were subdivided further based on modulus of frozen brine saturated mortar (left branch), and magnesium sulphate test (right branch). In the initial division, the moduli lower than 6465 MPa under MSalt conditions, the average ultimate modulus of elasticity is 5554 MPa, and for MSalt higher than 6465 MPa, the mean ultimate modulus is 6851 MPa. The branch of the modulus of elasticity with less than 6465 MPa modulus of brine-saturated samples is further divided to two groups:

One group with less than 6402 MPa moduli (of frozen brine saturated) with average modulus of 5216 Mpa, and another group with average of 6341 MPa. On the other side, mortars with moduli higher than 6465 MPa are divided based on aggregate durability factor (magnesium sulphate test). This indicates the importance of aggregate properties in the modulus of elasticity of mortar. The group with lower magnesium loss (less than 2.2) contains the highest average of moduli (7666 MPa).

3.3.5.4 Discriminant Analysis

Discriminant Analysis is related to both multivariate analysis of variance and multiple regression. The cases are grouped in cells like a one-way multivariate analysis of variance and the predictor variables from an equation like that for multiple regression (SYSTAT software, 1998).

The canonical plot (Figure 3.17) is a part of discriminant analysis that separates the variables into mutually exclusive groups. All data, including rock and mortar moduli and water sorption results were used in the analysis. The plot illustrates that the three different rock groups (limestones, L, dolomites, D and group C including marble, sandstone and syenite) behave independently of each other, and form virtually non-interfering clusters.

This illustrates the different behaviour of mortars containing specific rock aggregates, and the effect of the aggregates on the mortar. When the rock data variables are removed from the canonical analysis there is was still a reasonable separation among the mortar data, based on their contained aggregate types (Figure 3.18).

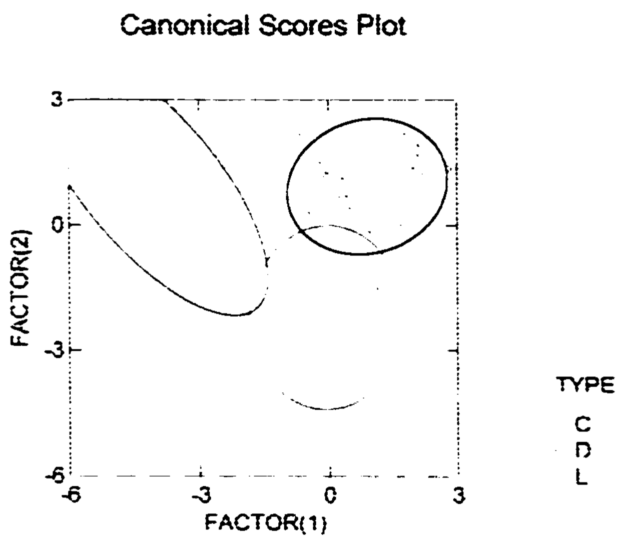


Figure3.17 Clusters of rock types according to cluster analysis: D (dolomite), L (limestone) and C (sandstone, marble and syenite)

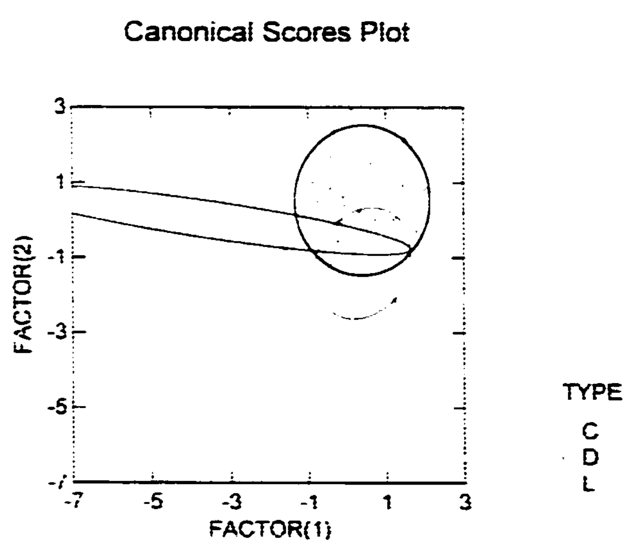


Figure 3.18 Clusters of mortars based on their aggregates according to cluster analysis: D (dolomite). L (limestone) and C (sandstone. marble and syenite)

3.3.6 Strength and Elastic Modulus of Mortar as Function of Rock and Mortar Properties (Step-wise regression Analysis)

3.3.6.1 Regression Analysis

Regression analysis is used to summarize and present the relationship between the data and fit this relationship into a mathematical model. Regression helps to draw inferences about population values based on sample results. The outcome model may be linear, parabolic, hyperbolic, etc.. Two types of regression were done on the data: bi-variate and multivariate.

3.3.6.1.1 Bi-variate Linear Regression: The model in linear regression is:

$$Y = XB + e$$

Where Y is a vector or matrix of dependent variables, X is a vector or matrix of independent variables, B is a vector or matrix of regression coefficients, and e is a vector or matrix of intercept on the y-axis.

A commonly used measure of the goodness of fit of a linear model is R^2, or the coefficient of the determination. Besides being the square of the correlation coefficient between variables X and Y, it is the square of the correlation coefficient between the observed value of the dependent variable (Y) and the predicted value of Y from fitted line (Norusis, 1993). If all the observations fall on the regression line, R^2 is 1. If there is no linear relationship between the dependent and independent variables, R^2 is 0.

The entire mortar data set was used in the analysis (i.e., the mortars were not separated by rock type). As expected, there was a significant relationship between the moduli of elasticity under different conditions and the ultimate strength.

Figures 3.19. 3.20 and 3.21 show the plot, regression equation, and the statistical significance (R^2) in some of these relationships. All R^2 coefficients are at 95% significance level. Figure 3.19 shows that a positive linear relationship exists between the ultimate strength and the modulus of elasticity of dry, room temperature mortars. More importantly, it shows that the moduli can be therefore used as an indication of the strength of the mortar. This implies that significant increase and/or decrease of the moduli under different environments is an indication of the increase and/or decrease of strength under the same environment.

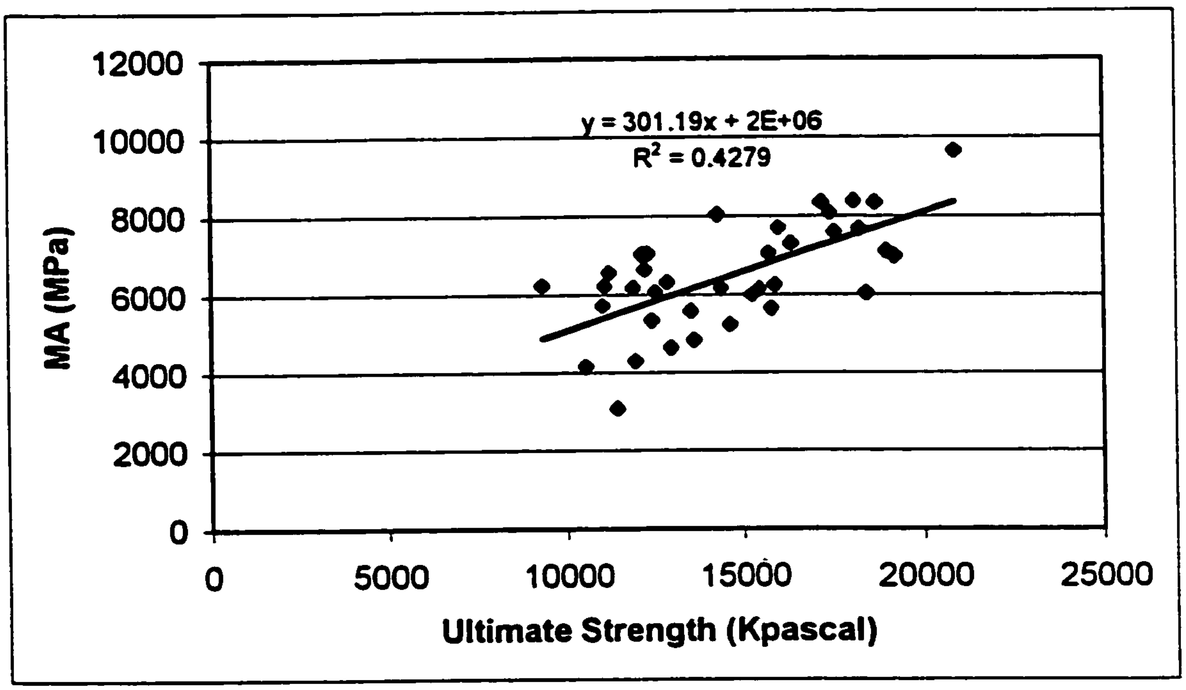


Figure 3.19 Graph of ultimate strength versus modulus of elasticity of mortar under ambient condition

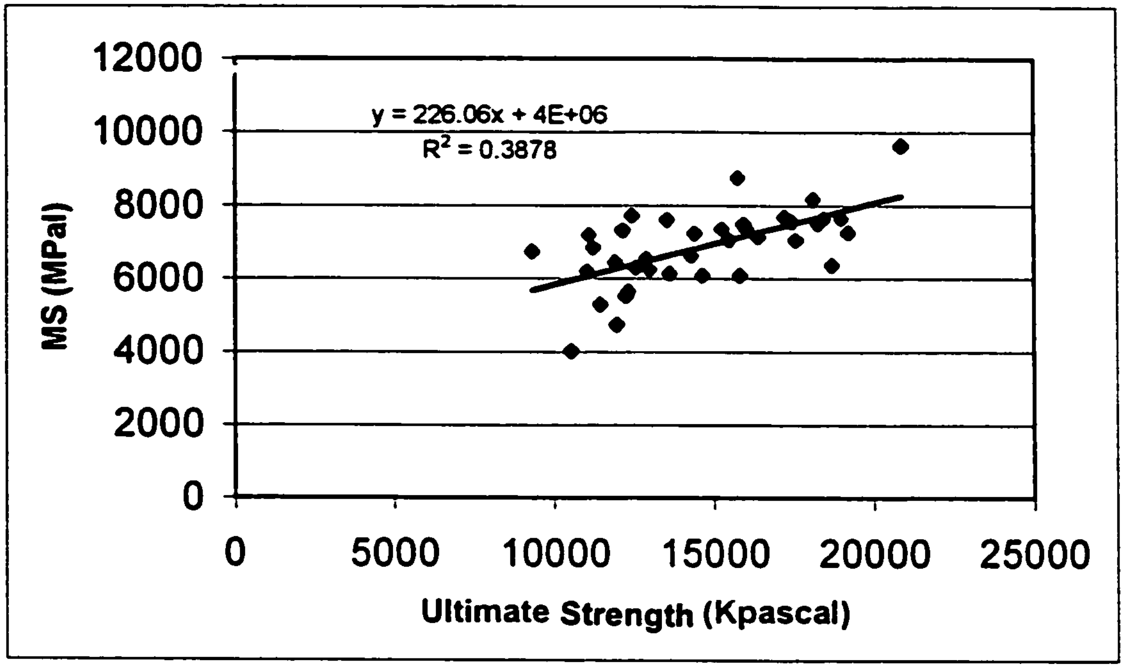


Figure 3.20 Graph of ultimate strength versus modulus of elasticity of saturated mortar

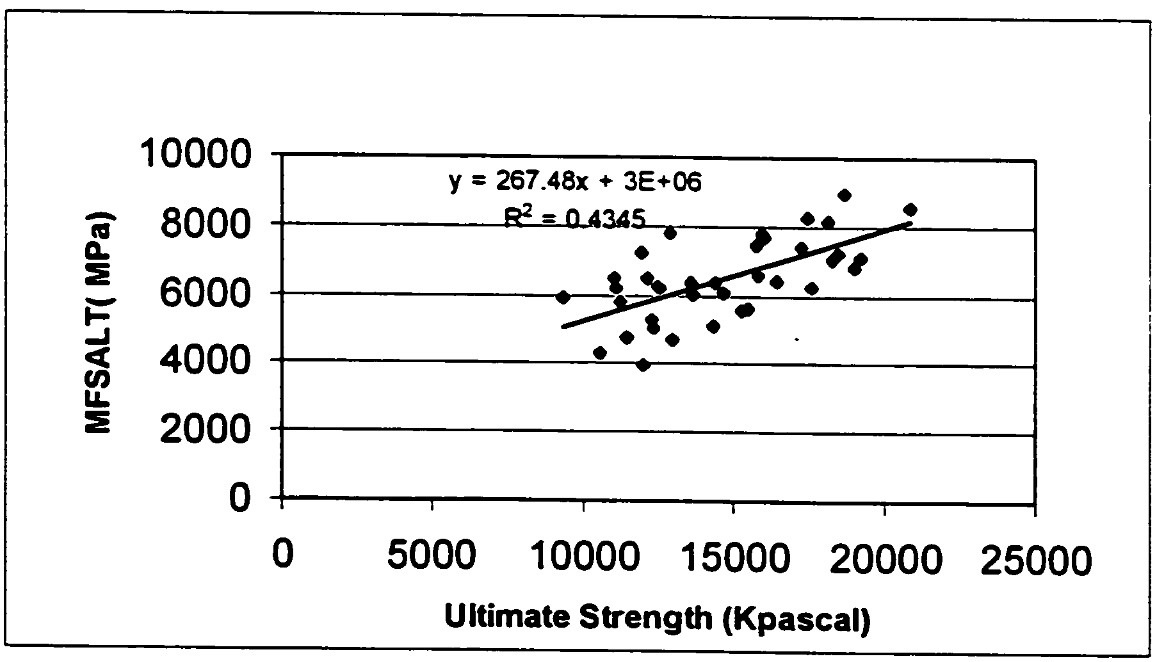


Figure 3.21 Graph of ultimate strength versus modulus of elasticity of frozen, saturated in salt water mortar

3.3.6.1.2 Multivariate Backward Regression: The linear regression procedure provides several equation-building methods including forward adding or backward elimination of variables. In this method selected variables are either entered one at a time or removed one at a time based on selected criteria (Norusis, 1993). In backward removal process, one variable, which has least influence on R^2, is removed and the remaining variables are seen to improve the model.

Step-wise regression with the ultimate strength as the dependent variable was done by the backward regression method. The ultimate strength of the mortar may be calculated by the equation obtained from Table 3.13 as follows:

$$\text{Ultimate strength}=[\text{MADS}*(-0.151)+\text{RABS}*(-8.63*10^{-2})+\text{Mag.Test}*(5.63*10^{-3})+\text{Modulus}*0.136]+0.978$$

The multiple correlation coefficient at 95% significance was 0.583. The equation illustrates that the mortar strength is largely a function of fine pore properties (adsorption in mortar and absorption in rock), the magnesium sulphate loss of rocks, and the mortar modulus of elasticity based on 20.7 MPa stress. Table 3.13 shows the relatively low influence of magnesium sulphate test on ultimate strength of mortar, since the coefficient of magnesium sulphate test is only 5.637E-03.

Table 3.13 Backward regression table for ultimate strength.

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
3	(Constant)	.978	.361		2.709	.011
	MADS	-.151	.084	-.265	-1.787	.083
	RABS	-8.63E-02	.044	-.293	-1.944	.060
	MAG.TEST	5.637E-03	.002	.402	2.347	.025
	MODULUS	.136	.045	.494	3.009	.005

3.4 SUMMARY DISCUSSION AND INTERPRETATION

The following discussion summarizes the differences and similarities observed between the mortars, and the rock aggregates they contain, from the point of view of their respective absorption (porosity), modulus of elasticity and strength. Note that absorption and porosity are often used interchangeably; although water absorption at 24 hours does not reflect the total porosity, but is proportional to it.

3.4.1 Absorption (Porosity)

Water absorption is one of the primary factors that determine other properties of material such as elasticity and strength (Hudec, 1983, 1987). In rocks, porosity is under influence of rock structure and texture and is the result of their origin and subsequent geologic processes. Figure 3.7 (Pg.62) shows that the rock porosity is largely the function of the rock type, as shown by the significant difference between absorption in dolomite and limestones (Fig. 3.8, Pg.63).

The sorption ratios in Table 3.6 (Pg.61) suggest that the dolomites contain fairly large pores whereas the more fine-grained limestones show less overall absorption and proportionally larger adsorption. On the other hand, the porosity of mortars is controlled mainly by their water-cement ratio and hydration process. Although rock comprises a major part of mortar as aggregate, analysis of the absorption / adsorption test results illustrates that the porosity between rocks and mortars are not significantly related (Fig 3.6, Pg.61).

The fact is that the porosity in mortar is overwhelmingly higher than that of rock, since majority of porosity is produced during the hydration process in mortar. The negligible effect of aggregate type on porosity indexes of mortars (Fig. 3.9, Pg.64) may be because the aggregate is coated with cement paste, which prevents further ingress of water necessary for saturation. On the other hand, according to Neville (1996), sufficient water is absorbed from the mix to bring the aggregate to a saturated condition. During the absorption process, the aggregate may release some of its pore air into the cement paste, which affects the interfacial zone and air voids. The water-cement ratio is higher in interfacial zone, around the aggregates, and therefore it contains high porosity (Scrivener, 1988). Air voids and saturated aggregates can be very influential on elasticity and strength especially under freezing condition.

Dolomites are expected, due to their higher porosity, to produce more air voids in mortars in comparison to limestones. Therefore, the porosity of aggregate may influence the properties of mortar by controlling the mortar texture (i.e. the amount of mortar air voids) as is supported by the elasticity test results of this research.

3.4.2 Modulus of Elasticity

Modulus of elasticity of rock and mortar are essentially different; since rocks are inherently stronger than mortar, their modulus is similarly higher. The basic analysis of rock and mortar results (Tables 3.3,3.4, Pgs. 55,56) shows the differences in elastic behaviour in rock and mortar cores. The influences of temperature and moisture are also different on the modulus of elasticity of mortar and rock either, mainly as a result of their different pore characteristics. However, the behaviour of mortar and rocks under some conditions are similar (Fig.3.5, Pg.60). Table 3.10 (Pg.75) presents a fairly good correlation between mortar and rock moduli under some conditions.

The lower modulus of mortar under 98% relative humidity conditions compared to dry mortars can be explained by the reduction of free energy of surfaces at adsorption sites (Fig. 3.4, Pg.56). A wetted surface of the microscopic mortar pores is under lower surface tension, which relaxes (expands) the mortar specimen. When stress is applied, the mortar is more easily deformed, since the applied stress is much larger than the surface tension change.

Moisture and salt presence decreases the moduli of rocks in both frozen and non-frozen cycles (Fig. 3.3, Pg.56). Mortar water saturated samples (MS) have the highest modulus of elasticity (Fig. 3.4, Pg.56). Under undrained compression conditions, the contained water is not compressible, and the internal hydrostatic pressure increases. Hydrostatic pressure, then, resists strain and increases the modulus of elasticity. Although rocks are not as porous as mortars, Goodman (1980) found similar response in rocks. Table 3.5 (Pg.58) also shows that the moduli of saturated mortars (MS) are significantly different from other conditions. Adding salt (MSALT) converts some of the absorbed water to adsorbed water and decrease the resistance of mortar to compression, since adsorbed water is compressible (Dananaj, 1991).

In frozen, mortar samples (frozen or MF, frozen saturated or MFS and frozen brine saturated or MFSALT), the modulus of elasticity also decreases. One reason could be the formation of micro-cracks under low temperature condition. According to Neville (1996), a consequence of the development of the cracks is a reduction in the effective area resisting the applied load, so that load stress is larger than nominal stress based on the later cross section of the specimen. It means that, strain increases at a faster rate than nominal applied stress and modulus of elasticity becomes lower. Micro-cracks are mostly generated due to water freezing inside the mortar. Mortars absorb significantly higher quantities of water than do rocks, and the water in the larger pores freezes readily. After freezing, the ice contracts at a rate an order of magnitude higher than that the paste material, putting the mortar in tension. Applying load to a pre-tensioned mortar increases its deformation. This is confirmed by the somewhat higher modulus of frozen salt-water saturated mortar compared to other moduli. Less ice is formed under these conditions, so tensioning is less, and modulus increases.

Even in dry condition, (MF), aggregate pores, which have adsorbed / absorbed some water during the hydration process generate enough pressure to produce micro cracks. When freezing occurs in concrete containing saturated aggregate, disruptive hydraulic pressures can be produced within the aggregate due to ice formation (Kosmatka, Panarese, Gissing and McLeod, 1995). Under freezing condition, water displaced from the aggregate particles during the formation of ice cannot escape fast enough to surrounding paste to relieve pressure and cause disruption in aggregate and a weak interfacial transition zone (ITZ). The osmotic pressure caused by the difference in vapour pressure in pores can intensify the damage.

Dolomite and limestone in mortars produce, in some cases, significantly different test results. Dolomites, under many conditions, were shown to produce higher elastic moduli in mortars than limestones (Fig. 3.11, Pg.66). One explanation may be that, because of their larger grain size and rougher surface, they make a better bond with cement paste than limestone with a predominantly micritic, cryptocrystalline texture. Dolomite (S.G.

2.72-2.84) also is denser than limestones (S.G. 1.55-2.75) and produces dense, less strong aggregates (Carmichael, 1989). Dolomite mortars have good resistance to stress under frozen dry condition (MF). The coefficients of thermal expansion (CTE) of the dolomite is 6.7 -8.6$\times$ 10^{-6} per °C and that of limestone is 0.9 - 12.2 $\times$ 10^{-6} per °C, which is a much larger range. The CTE of the hydrated cement is 11-16 $\times$ 10^{-6} °C (Neville, 1996). If the CTE of paste differs too much from that of aggregate, a major change in temperature may introduce differential movement and a break in the bond between the aggregate particles and surrounding paste. When the two coefficients differ by more than 5.5 $\times$ 10^{-6} per °C the durability of concrete subjected to freezing – thawing may be effected. Thus, dolomite could cause less cracking in the cement paste under frozen conditions. Because the CTE of limestone has such a wide range, limestone mortars show inconsistent results under different conditions (Fig.3.11, Pg.66).

Another reason could be the difference in the amount of air voids in various mortars. Under the frozen conditions (MF, MFS and MFSALT), water inside the paste and aggregate pores converts to ice and expands. Because the damaging action of freezing and thawing involves expansion of water on freezing, it is logical to expect that, if excess water can readily escape into adjacent air-filled voids, damage of concrete will not occur (Neville, 1996). Thus, dolomite particles can resist the expansion pressure since water can escape to the air voids while ice formation destroys the limestone aggregates and/or bond in containing mortars as there is less entrapped air. The statistical results of this research support this, showing that dolomite mortars have maintained their elasticity under frozen conditions but limestone mortars have failed to do so

A classification based on group means between limestone (L), dolomite (D) and coarse-grained rocks (C) show that these rock and aggregates have only a slight similarity in their performance (Figures 3.17,3.18, Pg83). On the other words, there is significant difference in the rock properties and performances in corresponding mortar.

3.4.3 Strength

The concrete strength may be influenced by three factors: (1) the strength of the hardened cement paste, (2) the strength of aggregate, and (3) the strength of the bond (interfacial zone) (Popovics, 1998).

The strength of cement paste and aggregate as brittle materials decreases rapidly with an increase in porosity (Mordy, 1973), due to lower density and fewer bonds. Air voids as a part of mortar porosity have the same influence. Statistical analysis supports this idea that dolomitic mortars may contain higher porosity and, thus, less strength. Furthermore, low density in limestones produces more volume of aggregates with the same weight in mortar, which increases the material and the strength of mortar. However, dolomite aggregates are stronger and assumed to produce a better bond with cement paste. Furthermore, there is no doubt about the positive relationship between the modulus of elasticity and strength. However, the increase in the modulus of elasticity of is progressively lower than the proportional increase in compressive strength (Neville, 1996).

The ultimate strength of mortar samples had a significant relationship with modulus of elasticity of mortars, under almost all conditions (Figures 3.19,3.20 and 3.21, Pgs. 85,86). However, dolomite mortars were shown to be stronger under 6.9 MPa (1000 psi) stress compared to limestone mortars (Fig. 3.12, Pg.72). The reverse is seen when 20.7 MPa (3000 psi) pressure is employed (Fig. 3.13, Pg.72). The reason could be the low modulus of elasticity of limestone. Because of the monolithic behaviour of concrete, aggregate with low moduli (that is, a modulus not very different from the modulus of elasticity of hydrated cement paste) leads to lower bond stress with the matrix so bond failure does not occur (Neville, 1996). In the last analysis, the strength of mortar is dependent on the strength of bonds between particles provided by cement paste.

The moduli of elasticity of rocks and mortars show a relatively good correlation (Table 3.10, Pg.75). Tests results on frozen and saturated samples of mortars had a better correlation with equivalent tests on rocks. Rheologic properties of ice would appear to play a significant part in the rheology of saturated frozen solid (both rock and mortar). This is supported by Table 3.11 (Pg.77), which illustrates that there is a strong relationship between rock porosity and modulus of elasticity of mortar shown by Factor Analysis Factor 4. This included rock absorption (RABS), rock adsorption (RADS), moduli of saturated in salt water mortars (MSALT) and moduli of frozen saturated samples (MFS). Durability of rock (magnesium sulphate test) has shown only slight correlation (Table 3.11, Pg.77) and relationship (Tables 3.10 and 3.13, Pgs.75,87) with mortar strength. This means that the potential durability of rock does not affect the initial strength of mortar as long as the rock remains unweathered. Different environmental conditions influence the strength as well as the moduli of elasticity of mortars. The effect of brine and freezing temperature on the rock and mortar moduli of elasticity is compared in Figure 3.5 (Pg.60). The patterns of the moduli variation of frozen (MF), rocks (RF) and frozen saturated (in brine) samples (RFSALT and MFSALT) were quite similar. In fact, these conditions have the same effect on the properties of rock and mortars.

The ultimate strength of the mortar samples is divided according to moduli of elasticity of mortars in saturated in brine (MSALT) and in 98% humidity (MH98) conditions as shown in Figure 3.15 (Pg.79). Thus, brine saturation has a significant influence on the ultimate strength. The moduli of elasticity under brine saturated and 98 % humidity conditions (MSALT and MH98) also have a significant correlation with ultimate strength (Table 3.10, Pg.75). Brine and moisture affect the surface properties of pores, pore pressure, and surface tension and may thus affect the strength. This is also supported by the analysis of modulus of elasticity (Fig. 3.16, Pg.80), where MSALT modulus results classified the full range modulus dependent variable.

Considering all of the above, it can be stated that the type of aggregate influences the properties of mortar as well as of concrete. Ozturan and Cecen (1997) found that there is also a major difference in the strength of concrete with different type of coarse aggregates. The impact of the type of coarse aggregate on the strength of concrete was more significant in high strength concretes. Dolomite aggregate seems to increase the performance of mortar under different conditions. The previous studies confirm the above statement and show higher strength in dolomitic mortars (Popovics, 1998). Dolomites have more strength than limestone and therefore produce higher moduli and strength in mortars and also create stronger bonds. Limestone aggregate, on the other hand, being less dense, provides greater volume of an essentially stronger component in a mortar or concrete mix, thus in part balancing the advantages of dolomite.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Based on the tests results and statistical analysis, the research results presented in this study lead to the following conclusions:

1. Aggregate porosity is not directly related to porosity of mortar, but it is an important factor in elasticity and strength of mortar. As water is introduced to the mix, aggregate particles start to absorb/adsorb part of water. Water displaces the air out of the pores and, results in a mortar with saturated aggregates and air voids around them. The amount and distribution of adsorbed/absorbed water and air voids determine the thickness of interfacial zone and strength of the bond between cement paste and aggregate. Consequently aggregate porosity influences the strength of mortar indirectly.

2. The main source of porosity in mortar is due to incomplete compaction during hydration of cement. Adsorption and absorption are respectively 10 and 5 times lower in aggregates than corresponding mortars.

3. The durability of aggregate as seen in results of the magnesium sulphate test by Rigbey (1980) had negligible effect on mortar properties. This is not surprising since the porosity parameters of rock and mortar have showed almost no association. Therefore, the potentially poor aggregate in its undegraded form has no effect on mortar strength.

4. Adsorption decreases the modulus of elasticity and the strength of mortars. Previous studies showed that as soon as rock adsorbs water its pore

walls relax and cause lowering in elasticity. Similar explanation can be made in the case of mortar elasticity. On the other hand, absorption increases the strength of mortar under low stress. This is more noticeable in limestone mortars in which the smaller pore prevent fast water exit due to fineness and texture of voids. Frozen water in mortar pores has a negative influence on the elasticity but adding salt increases the amount of adsorbed and structured water and increases the elasticity.

5. The study shows that mortar strength is a function of aggregate rock type. Moduli of elasticity of rock and mortars showed a good correlation and the aggregate strength was a major factor. The strength of mortar is not only related to the cement paste properties (i.e. porosity) but also reflects the aggregate strength and the bond quality between aggregate and cement paste. Aggregate strength and the cement-aggregate bond are a function of properties such as density, texture and porosity.

6. Two types of carbonate rocks, limestone and dolomite, which are extensively used as aggregate in Ontario, produced mortars of different properties, based on their dissimilarities in density, texture, compressibility, strength and porosity.

7. Dolomite aggregates provide high performance concrete which maintain its properties under most of the conditions. The moduli of elasticity of dolomitic mortars remain almost unchanged under various environmental conditions.

4.2 RECOMMENDATIONS

1. The petrography of aggregate, as the major part of concrete structure, should be investigated more thoroughly, as their properties such as porosity, texture, mineralogy, strength, etc. have high influence on concrete performance.

2. In order provide details about porosity and microcracking of mortars, further studies should be accompanied by microscopic studies of mortar structure. A microscopic study may reveal the influence of aggregate type on interfacial zone (bond) and air voids as well.

3. This research should be continued using other aggregate types commonly used in concrete industry. More rock type and a larger number of tests will provide more reliable and complete analysis. Study of the use of different aggregate–cement ratio, and water-cement ratio may also yield useful results.

4. Higher stress range during compressive tests under different environmental conditions should be tried to see if the relationships hold under these conditions. The amount of stress can change the relative deformability of cement paste and aggregates and therefore, provide different results.

5. In order to minimize human errors, an automatic, constant rate stress loading should be used to increase the reliability of the results and minimize the effect of the rate of loading on the moduli.

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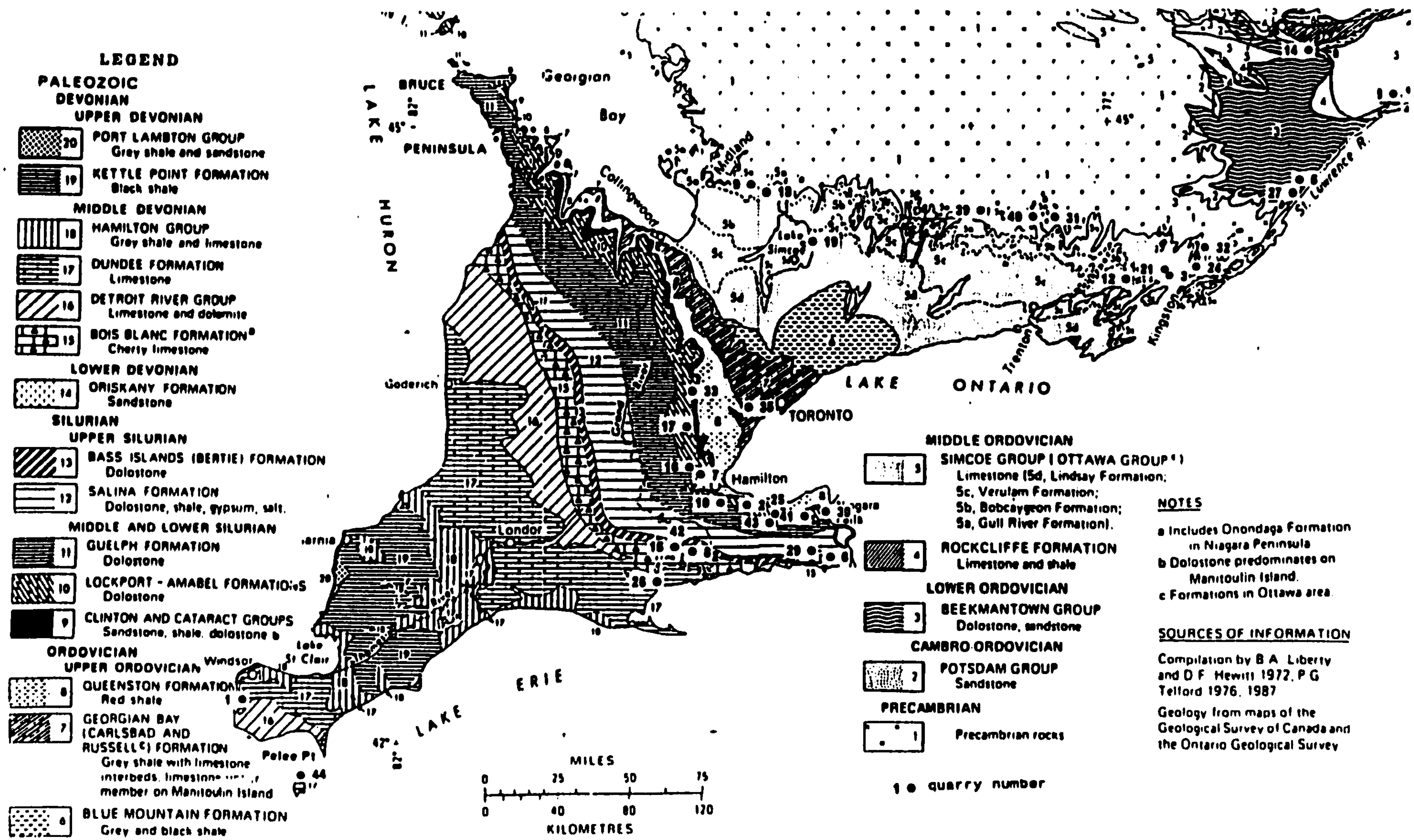
APPENDIX A

Sample Location and Description

- Geological Map of Southern Ontario
- Sample Localization and Lithological Description



FigureA_1 Map of Southern Ontario showing bedrock geology and sample location.

Table A-1 Sample Localization and Lithological Description

1. MacGregor Quarry: County Essex; Township Anderdon; lot 10; 10 km Northeast of Amhersberg

4-L	Limestone; Formation Lucas; Member Anderdon; buff and light gray color bonding; aphanitic to microcrystalline

2. Vinemount Quarry: County wentworth; Township Saltfleet; Lot 5; 4 km South of Winona

8-D	Dolomite; Formation Lockport; Member Eramosa; medium brown with dark gray streaks; argillaceous, silty, aphanitic

3. Wings (Maitland) Quarry: County Grenville; Township Augusta; Lot 24; 6 km North of Maitland

16-D	Dolomite, Formation Oxford; brown to dark gray; calcareous, medium crystalline

4. Ridgemount Quarry: County Welland; Township Bartie; Lot 8; 4 km South of Stevensvill

18-D	Dolomite; Formation Bertie; Member Arcon; medium brown to gray; fine crystalline to aphanitic; shaly partings
19-D	Dolomite; Formation Bertie; Member Arcon; mottles light and medium gray; Aphanitic

5. Dundas Quarry: County Wentworth; township West Flamborough; Lots 10, 11; Northwest of Hamilton

21-D	Dolomite; Formation Guelph; Light gray; vuggy, fine crystalline to aphanitic
22-D	Dolomite; Formation Guelph; Light gray; buff weathering, slightly vuggy, fine crystalline to aphanitic
23-D	Dolomite; Formation Lockport; Member Eramosa; Light brown; fine crystalline aphanitic; thick bedded, shaly parting
24-D	Dolomite; Formation Lockport; Member Eramosa; gray to dark brown; fine crystalline to aphanitic; thick bedding

6. Cayunga Quarry: County Haldimand; Township North Cayuga; Lots 45,46; 5.5 km west of village Cayuga

26-D	Dolomite; Formation Bartie; Member Arcon; light brown and light gray; aphanitic; thin laminates clastic in part

7. Stoney Creek Quarry: County Wentworth; Township Saltfleet; Lots27, 28; West of Highway 20, Southern edge of Stoney creek

34-D	Dolomite; Formation Lockport; Member Eramosa; medium brown; aphanitic; gray shale partings

8. MacLeod Quarry: County Stormont; Township Cornwall; Lot 4; 5km north of Cornwall

37-D	Dolomite; Formation Gull River; Member Lower; light gray; fine crystalline to aphanitic; thick bedded

9. J.Dennison (Napanee) Quarry: County Lennox and Addington; ownship North Fredericksburgh; Lot 21; North side of Highway2, eastern of Napanee

39-L	Limestone, Formation Gull River; Member D; brownish gray; aphanitic ; shale partings
40-L	Limestone; Formation Gull River; Member D; brownish gray; aphanitic; medium bedded, similar to sample #39

10. Boyce (south Golucester) Quarry: Township Gloucester; Lot 25; 3 km north of the Hamlet of South Gloucester

41-D	Dolomite; Formation Oxford; light gray; calcareous, aphanitic, shaly partings, thinly laminated in part

11. Northwest Quarry: County Haldimand; Township Walpole; Lots 12, 13

46-D	Dolomite; formation Bertie; buff to light brown; aphanitic; monor shaly partings
53-D	Dolomite; Formation Bertie; medium brown; aphanitic; shaly laminations

12. Flamboro Quarry: Township West Flamboro; Lots 6; West side of Brock Road

55-D	Dolomite; Formation Lockport; Member Eramosa; Light to medium brown; aphanitic; minor shale as thin laminations

56-D Dolomite; Formation Guelph; light gray; aphanitic; vuggy with crystal development

57-D Dolomite; Formation Guelph; light gray to buff; aphanitic

13. Halton Quarry: County Halton; Township Nassagaweya; Lot 8; 6 km West of Milton

58-D Dolomite; Formation Amable; medium gray; reefy, fossiliferous, fine crystalline

60-D Dolomite; Formation Amable; Member middle Silurian; light gray; fossiliferous, stylolitic megaporous, fine crystalline

14. Gamebridge Quarry: County Ontario; Township Mara; Lot 11; I km Northwest of Gamebridge

65-L Limestone; Formation Bobcaygeon; medium gray to buff; diliceousm clastic, medium grained

15. Kingston Quarry: County Frontenac; Township Kingston; Lot 9; West of Highway 38 – Highway 401 interchange

68-L Limestone; Formation Gull River; light gray, aphanitic, clastic crystals and stringers

16. Pittsburg Quarry : County Frontenac; Township Pittsburg; 3 .5 km North of Barriefield

74-L Limestone; Formation Gull River; Member Middle Ordovician; light brownish gray; fine crystalline; buff weathering, silty

75-L Limestone; Formation Gull River; Member Middle Ordovician; medium brownish gray; aphanitic; occasional clastic crystals

17. MacLanchlan (Beamsville) Quarry: County Lincoln; Township Clinton; Lot 20; 6.4 km South of town

76-D Dolomite; Formation Lockport; Member Erasoma; medium brown; sugary, fine crystalline; occasional shaly partings

79-D Dolomite; Formation Lockport; Member Erasoma; brownish gray; aphanitic; mottled, vuggy with some calcite crystals

18. <u>Brockville Quarry: County Leeds; Township Elizabethtown; Lot 4; Eastern outskirts of the city of Brockville</u>

83-Lst Limestone; Formation Middle Black River; medium gray: fine crystalline

19. <u>Port Colborne Quarry: County Welland; Township Humberstone; Lots 24, 25; 2km Northeast of Cornwall</u>

90-D Dolomite; Formation Berite; Member Arkon: dark gray: aphanitic: streaked, laminated layers with small dolomite rhombs, abundant shaly partings

20. <u>Queenston Quarry: County Lincoln; Township Niagara; Lots 47,48,49; 3 km West of Queenston</u>

93-D Dolomite; Formation Decew; medium gray; aphanitic; massive

94-Lst Limestone; medium gray; calcitic, calcite crystals in vugs, massive, medium crystalline

95-D Dolomite; Formation Lockport: Member Gasport; light gray vugs with calcite crystals, massive, medium crystalline

96-L Limestone; formation Irondequoit; Light gray; aligned elongate crystals throughout, slightly fossiliferous, medium to fine crystallie

97-Lst Limestone; Formation Irondequoit; light to medium gray; medium to fine crystalline

21. <u>Madam Area Quarry : 4.8 km Southeast of town</u>

99-M Marble; white; aphanitic, fine crystals

22. <u>Kingston Quarries: County Frontenac; Township Storrington; Lot 11</u>

102-Sst Sandstone; Formation Potsdam; gray pink, black; coarse to medium grained; color banding, medium bedded, some argillaceous material

23. <u>Nephton Quarry: County Peterborough; Township Methuel</u>

115-SY Nepheline Syenite; white with black dots; phaneritic; random orientation of mafics, approximately 5%

117-SY Syenite, white with black dots; phaneritic; random orientation of mafics, approximately 5%

APPENDIX B

Data Set

- Sample of Raw Data
- Individual Data of Mortar Elasticity
- Moduli of Elasticity of Rocks
- Moduli of Elasticity of Mortars
- Additional Data of Rocks and Mortars

Table B-1 A sample of raw data of mortar stress- strain

Sample 4-A			
Date	Time	Pressure (psi)	Length change (mm)
22/02/00	3:59:18 PM	68.359	-0.001
22/02/00	3:59:19 PM	92.773	-0.002
22/02/00	3:59:20 PM	107.422	-0.005
22/02/00	3:59:21 PM	136.719	-0.008
22/02/00	3:59:22 PM	146.484	-0.008
22/02/00	3:59:23 PM	166.016	-0.01
22/02/00	3:59:24 PM	180.664	-0.012
22/02/00	3:59:25 PM	200.195	-0.013
22/02/00	3:59:26 PM	219.727	-0.014
22/02/00	3:59:27 PM	239.258	-0.016
22/02/00	3:59:28 PM	268.555	-0.018
22/02/00	3:59:29 PM	292.969	-0.02
22/02/00	3:59:30 PM	307.617	-0.021
22/02/00	3:59:31 PM	322.266	-0.022
22/02/00	3:59:32 PM	332.031	-0.024
22/02/00	3:59:33 PM	361.328	-0.025
22/02/00	3:59:34 PM	385.742	-0.026
22/02/00	3:59:35 PM	395.508	-0.028
22/02/00	3:59:36 PM	415.039	-0.028
22/02/00	3:59:37 PM	429.687	-0.03
22/02/00	3:59:38 PM	454.102	-0.032
22/02/00	3:59:39 PM	488.281	-0.033
22/02/00	3:59:40 PM	507.812	-0.034
22/02/00	3:59:41 PM	517.578	-0.034
22/02/00	3:59:42 PM	546.875	-0.036
22/02/00	3:59:43 PM	556.641	-0.037
22/02/00	3:59:44 PM	571.289	-0.038
22/02/00	3:59:45 PM	595.703	-0.04
22/02/00	3:59:46 PM	629.883	-0.041
22/02/00	3:59:47 PM	639.648	-0.042
22/02/00	3:59:48 PM	693.359	-0.044
22/02/00	3:59:49 PM	712.891	-0.045
22/02/00	3:59:50 PM	708.008	-0.045
22/02/00	3:59:51 PM	712.891	-0.046
22/02/00	3:59:52 PM	747.07	-0.047
22/02/00	3:59:53 PM	766.602	-0.048
22/02/00	3:59:54 PM	791.016	-0.049
22/02/00	3:59:55 PM	820.312	-0.052
22/02/00	3:59:56 PM	839.844	-0.053
22/02/00	3:59:57 PM	859.375	-0.054
22/02/00	3:59:58 PM	893.555	-0.056
22/02/00	3:59:59 PM	908.203	-0.057
22/02/00	4:00:00 PM	927.734	-0.057
22/02/00	4:00:01 PM	952.148	-0.058
22/02/00	4:00:02 PM	966.797	-0.06
22/02/00	4:00:03 PM	1010.742	-0.061

Table B-2 Data of moduli of mortar elasticity(kPascal)

SAMPLE	EXT.	ROCK TYPE	STRAIN	MA	STRAIN	M98	STRAIN	MS	STRAIN	MSALT
4	A	Lst.	1.111E-03	5.59E+06	1.213E-03	5.12E+06	1.134E-03	5.48E+06	1.154E-03	5.38E+06
4	B		1.214E-03	5.12E+06	1.076E-03	5.77E+06	9.942E-04	6.25E+06	8.925E-04	6.96E+06
4	C		9.102E-04	6.82E+06	1.064E-03	5.84E+06	7.802E-04	7.96E+06	1.102E-03	5.63E+06
8	A	Dolomite	1.766E-03	3.52E+06	1.408E-03	4.41E+06	1.290E-03	4.82E+06	1.576E-03	3.94E+06
8	B		1.009E-03	6.16E+06	1.114E-03	5.57E+06	1.112E-03	5.58E+06	1.178E-03	5.27E+06
8	C		1.149E-03	5.41E+06	8.777E-04	7.07E+06	8.730E-04	7.11E+06	1.092E-03	5.69E+06
16	A	Dolomite	8.571E-04	7.25E+06	9.057E-04	6.86E+06	8.902E-04	6.98E+06	8.425E-04	7.37E+06
16	B		6.453E-04	9.62E+06	7.057E-04	8.80E+06	8.052E-04	7.71E+06	7.602E-04	8.17E+06
16	C		1.441E-03	4.31E+06	7.190E-04	8.64E+06	8.723E-04	7.12E+06	1.163E-03	5.34E+06
18	A	Dolomite	9.360E-04	6.63E+06	9.708E-04	6.40E+06	1.072E-03	5.79E+06	1.156E-03	5.37E+06
18	B		8.280E-04	7.50E+06	9.279E-04	6.69E+06	7.801E-03	7.96E+05	9.289E-04	6.69E+06
18	C		7.781E-04	7.98E+06	9.054E-04	6.86E+06	9.683E-04	6.41E+06	9.206E-04	6.75E+06
19	A	Dolomite	1.052E-03	5.90E+06	9.024E-04	6.88E+06	9.112E-04	6.82E+06	1.093E-03	5.68E+06
19	B		8.565E-04	7.25E+06	1.396E-03	4.45E+06	8.761E-04	7.09E+06	1.046E-03	5.94E+06
19	C		1.259E-03	4.93E+06	1.164E-03	5.34E+06	1.166E-03	5.33E+06	1.106E-03	5.61E+06
21	A	Dolomite	8.730E-04	7.11E+06	1.053E-03	5.90E+06	9.631E-04	6.45E+06	1.490E-03	4.17E+06
21	B		9.853E-04	6.30E+06	1.282E-03	4.84E+06	8.812E-03	7.05E+05	9.588E-04	6.48E+06
21	C		1.117E-03	5.56E+06	1.399E-03	4.44E+06	1.017E-03	6.11E+06	1.302E-03	4.77E+06
22	A	Dolomite	7.919E-04	7.84E+06	7.428E-04	8.36E+06	5.421E-04	1.15E+07	6.281E-04	9.89E+06
22	B		5.439E-04	1.14E+07	8.810E-04	7.05E+06	7.389E-04	8.40E+06	9.524E-04	6.52E+06
22	C		1.134E-03	5.48E+06	1.219E-03	5.09E+06	7.992E-04	7.77E+06	8.843E-04	7.02E+06
23	A	Dolomite	9.650E-04	6.43E+06	8.084E-04	7.68E+06	8.391E-04	7.40E+06	1.146E-03	5.42E+06
23	B		7.734E-04	8.03E+06	5.840E-04	1.06E+07	9.233E-04	6.73E+06	1.004E-03	6.18E+06
23	C		8.607E-04	7.21E+06	1.071E-03	5.80E+06	7.745E-04	8.02E+06	8.693E-04	7.14E+06
24	A	Dolomite	8.095E-04	7.67E+06	8.641E-04	7.19E+06	8.980E-04	6.92E+06	1.026E-03	6.05E+06
24	B		1.274E-03	4.87E+06	8.463E-03	7.34E+05	7.806E-04	7.95E+06	9.935E-04	6.25E+06
24	C		1.070E-03	5.81E+06	9.290E-04	6.68E+06	1.021E-03	6.08E+06	7.723E-04	8.04E+06
26	A	Dolomite	1.099E-03	5.65E+06	9.717E-04	6.39E+06	9.397E-04	6.61E+06	8.902E-04	6.98E+06
26	B		8.934E-04	6.95E+06	8.627E-04	7.20E+06	8.106E-04	7.66E+06	7.539E-04	8.24E+06
26	C		9.031E-04	6.88E+06	8.890E-04	6.99E+06	9.050E-04	6.86E+06	9.050E-04	6.86E+06
34	A	Dolomite	1.901E-02	3.27E+05	9.175E-04	6.77E+06	1.125E-03	5.52E+06	1.086E-03	5.72E+06
34	B		9.445E-03	6.57E+05	8.034E-04	7.73E+06	8.763E-04	7.09E+06	1.168E-03	5.32E+06
34	C		8.740E-04	7.10E+06	9.536E-04	6.51E+06	1.070E-03	5.80E+06	1.149E-03	5.40E+06
37	A	Dolomite	1.453E-03	4.27E+06	1.944E-03	3.19E+06	1.471E-03	4.22E+06	9.630E-04	6.45E+06
37	B		1.546E-03	4.02E+06	1.863E-03	3.33E+06	1.672E-03	3.71E+06	1.582E-03	3.92E+06
37	C		9.840E-04	6.31E+06	1.067E-03	5.82E+06	1.020E-03	6.09E+06	1.253E-03	4.96E+06
39	A	Lst.	1.032E-03	6.01E+06	1.134E-03	5.48E+06	1.120E-03	5.54E+06	9.498E-04	6.54E+06
39	B		1.071E-03	5.80E+06	1.073E-03	5.79E+06	1.129E-03	5.50E+06	1.148E-03	5.41E+06
39	C		9.098E-04	6.83E+06	1.042E-03	5.96E+06	9.848E-04	6.31E+06	9.848E-04	6.31E+06

Table B-2 (Cont.)

SAMPLE	EXT.	ROCK TYPE	STRAIN	MA	STRAIN	M96	STRAIN	MS	STRAIN	MSALT
40	A	Lst.	1.031E-03	6.02E+06	1.071E-03	5.80E+06	6.448E-04	9.63E+06	8.607E-04	7.22E+06
40	B		7.811E-04	7.95E+06	1.004E-03	6.19E+06	7.458E-04	8.33E+06	8.005E-04	7.76E+06
40	C		9.650E-04	6.44E+06	1.000E-03	6.21E+06	8.611E-04	7.21E+06	1.019E-03	6.09E+06
41	A	Dolomite	6.726E-04	9.23E+06	9.224E-04	6.73E+06	1.241E-03	5.00E+06	1.693E-03	3.67E+06
41	B		9.014E-04	6.89E+06	8.511E-04	7.30E+06	8.663E-04	7.17E+06	9.901E-04	6.27E+06
41	C		1.357E-03	4.57E+06	1.166E-03	5.33E+06	7.252E-04	8.56E+06	7.912E-04	7.85E+06
46	A	Dolomite	1.056E-03	5.88E+06	9.900E-04	6.27E+06	9.797E-04	6.34E+06	1.086E-03	5.72E+06
46	B		2.018E-03	3.08E+06	1.008E-03	6.16E+06	1.323E-03	4.69E+06	9.205E-03	6.75E+05
46	C		1.089E-03	5.70E+06	1.448E-03	4.29E+06	1.154E-03	5.38E+06	1.132E-03	5.48E+06
53	A	Dolomite	1.127E-03	5.51E+06	2.218E-03	2.80E+06	1.091E-03	5.69E+06	1.728E-03	3.59E+06
53	B		1.883E-03	3.30E+06	1.806E-03	3.44E+06	1.273E-03	4.88E+06	1.045E-03	5.94E+06
53	C		2.081E-03	2.98E+06	1.202E-03	5.16E+06	9.514E-04	6.53E+06	1.023E-03	6.07E+06
55	A	Dolomite	6.250E-04	9.94E+06	9.139E-04	6.79E+06	8.959E-04	6.93E+06	8.270E-04	7.51E+06
55	B		1.009E-03	6.15E+06	1.025E-03	6.06E+06	9.925E-04	6.26E+06	8.748E-04	7.10E+06
55	C		9.815E-04	6.33E+06	9.875E-04	6.29E+06	7.899E-04	7.86E+06	1.149E-03	5.41E+06
56	A	Dolomite	9.891E-04	6.28E+06	7.136E-04	8.70E+06	9.080E-04	6.84E+06	1.009E-03	6.16E+06
56	B		1.065E-03	5.83E+06	9.235E-04	6.72E+06	8.460E-04	7.34E+06	9.401E-04	6.61E+06
56	C		2.042E-03	3.04E+06	2.591E-03	2.40E+06	1.765E-03	3.52E+06	1.567E-03	3.96E+06
57	A	Dolomite	1.034E-03	6.01E+06	1.036E-03	6.00E+06	8.660E-04	7.17E+06	9.037E-04	6.87E+06
57	B		7.794E-04	7.97E+06	9.762E-04	6.36E+06	1.102E-03	5.63E+06	8.301E-04	7.48E+06
57	C		1.011E-03	6.14E+06	1.013E-03	6.13E+06	9.917E-04	6.26E+06	8.925E-04	6.96E+06
58	A	Dolomite	1.106E-03	5.61E+06	1.040E-03	5.97E+06	1.040E-03	5.97E+06	1.086E-03	5.72E+06
58	B		9.459E-04	6.57E+06	9.816E-04	6.33E+06	9.820E-04	6.32E+06	9.820E-04	6.32E+06
58	C		1.577E-03	3.94E+06	9.479E-04	6.55E+06	1.016E-03	6.11E+06	9.649E-04	6.44E+06
60	A	Dolomite	1.054E-03	5.89E+06	1.037E-03	5.99E+06	8.007E-04	7.76E+06	1.116E-03	5.56E+06
60	B		1.256E-03	4.94E+06	1.144E-03	5.43E+06	8.013E-03	7.75E+05	8.839E-04	7.03E+06
60	C		1.037E-03	5.99E+06	1.019E-03	6.09E+06	9.752E-04	6.37E+06	1.100E-03	5.65E+06
65	A	Lst.	9.330E-04	6.66E+06	1.259E-03	4.93E+06	1.204E-03	5.16E+06	1.204E-03	5.16E+06
65	B		8.206E-04	7.57E+06	9.318E-04	6.66E+06	8.184E-04	7.59E+06	1.120E-03	5.54E+06
65	C		1.346E-03	4.61E+06	1.180E-03	5.26E+06	1.163E-03	5.34E+06	1.011E-03	6.14E+06
68	A	Lst.	8.893E-04	6.98E+06	1.131E-03	5.49E+06	8.896E-04	6.98E+06	9.768E-04	6.36E+06
68	B		9.670E-04	6.42E+06	9.331E-04	6.66E+06	8.090E-04	7.68E+06	8.069E-03	7.70E+05
68	C		1.107E-03	5.61E+06	1.248E-03	4.98E+06	1.235E-03	5.03E+06	9.527E-04	6.52E+06
74	A	Lst.	8.426E-04	7.37E+06	8.929E-04	6.95E+06	7.309E-04	8.50E+06	9.586E-04	6.48E+06
74	B		7.319E-04	8.48E+06	1.008E-03	6.16E+06	7.736E-04	8.03E+06	8.577E-04	7.24E+06
74	C		1.786E-03	3.48E+06	9.886E-04	6.28E+06	1.128E-03	5.51E+06	7.168E-04	8.66E+06
75	A	Lst.	9.352E-04	6.64E+06	9.796E-04	6.34E+06	1.134E-03	5.48E+06	1.075E-03	5.77E+06
75	B		1.061E-03	5.85E+06	7.209E-04	8.61E+06	7.889E-04	7.87E+06	1.156E-03	5.37E+06
75	C		8.330E-04	7.46E+06	9.899E-04	6.27E+06	7.508E-04	8.27E+06	8.892E-04	6.98E+06
76	A	Dolomite	8.914E-04	6.97E+06	1.435E-03	4.33E+06	1.259E-03	4.93E+06	1.281E-03	4.85E+06

Table B-2 (Cont.)

SAMPLE	EXT.	ROCK TYPE	STRAIN	MA	STRAIN	M98	STRAIN	MS	STRAIN	MSALT
76	B		8.904E-04	6.97E+06	1.334E-03	4.66E+06	1.224E-03	5.07E+06	1.224E-03	5.07E+06
76	C		8.705E-04	7.13E+06	1.026E-03	6.05E+06	1.023E-03	6.07E+06	1.349E-03	4.60E+06
79	A	Dolomite	7.907E-04	7.85E+06	9.500E-04	6.54E+06	8.229E-04	7.55E+06	9.691E-04	6.41E+06
79	B		1.235E-03	5.03E+06	1.104E-03	5.63E+06	1.259E-03	4.93E+06	8.493E-04	7.31E+06
79	C		9.977E-04	6.22E+06	9.088E-04	6.83E+06	8.696E-04	7.14E+06	7.881E-04	7.88E+06
83	A	Lst.	1.089E-03	5.70E+06	7.647E-04	8.12E+06	9.605E-04	6.47E+06	9.405E-04	6.60E+06
83	B		8.294E-04	7.49E+06	1.108E-03	5.60E+06	9.064E-04	6.85E+06	1.007E-03	6.17E+06
83	C		1.060E-03	5.86E+06	1.083E-03	5.73E+06	1.059E-03	5.86E+06	1.102E-03	5.63E+06
90	A	Dolomite	8.607E-04	7.21E+06	9.855E-03	6.30E+05	9.809E-04	6.33E+06	9.621E-04	6.45E+06
90	B		7.390E-04	8.40E+06	1.348E-03	4.61E+06	7.851E-04	7.91E+06	9.328E-04	6.66E+06
90	C		1.050E-03	5.91E+06	9.914E-04	6.26E+06	1.339E-03	4.64E+06	9.680E-04	6.42E+06
93	A	Dolomite	1.543E-03	4.02E+06	9.820E-03	6.32E+05	1.588E-03	3.91E+06	1.814E-03	3.42E+06
93	B		9.707E-04	6.40E+06	1.342E-03	4.63E+06	1.149E-03	5.41E+06	1.347E-03	4.61E+06
93	C		1.331E-03	4.66E+06	1.158E-03	5.36E+06	1.718E-03	3.62E+06	1.478E-03	4.20E+06
94	A	Lst.	1.155E-03	5.38E+06	9.942E-04	6.25E+06	1.051E-03	5.91E+06	1.159E-03	5.36E+06
94	B		1.537E-03	4.04E+06	1.223E-03	5.08E+06	9.346E-04	6.64E+06	1.272E-03	4.88E+06
94	C		1.262E-03	4.92E+06	1.283E-03	4.84E+06	1.383E-03	4.49E+06	1.345E-03	4.62E+06
95	A	Dolomite	7.056E-04	8.80E+06	7.415E-04	8.38E+06	1.106E-03	5.62E+06	1.088E-03	5.71E+06
95	B		7.683E-04	8.08E+06	9.007E-04	6.89E+06	7.672E-04	8.09E+06	6.741E-04	9.21E+06
95	C		7.789E-04	7.97E+06	8.801E-04	7.06E+06	9.298E-04	6.68E+06	8.621E-04	7.20E+06
96	A	Lst.	9.630E-04	6.45E+06	9.448E-04	6.57E+06	1.030E-03	6.03E+06	9.209E-04	6.74E+06
96	B		9.878E-04	6.29E+06	9.705E-04	6.40E+06	8.177E-04	7.59E+06	1.683E-03	3.69E+06
96	C		1.069E-03	5.81E+06	1.224E-03	5.07E+06	1.090E-03	5.70E+06	1.148E-03	5.41E+06
97	A	Lst.	1.024E-03	6.06E+06	1.026E-03	6.05E+06	9.811E-04	6.33E+06	1.092E-03	5.69E+06
97	B		1.041E-03	5.96E+06	1.072E-03	5.79E+06	8.748E-04	7.10E+06	9.225E-04	6.73E+06
97	C		1.137E-03	5.46E+06	1.185E-03	5.24E+06	1.097E-03	5.66E+06	7.603E-04	8.17E+06
99	A	Marble	6.450E-04	9.63E+06	8.409E-04	7.39E+06	7.056E-04	8.80E+06	9.951E-04	6.24E+06
99	B		1.260E-03	4.93E+06	1.226E-03	5.06E+06	1.010E-03	6.15E+06	6.705E-04	9.26E+06
99	C		8.462E-04	7.34E+06	9.096E-04	6.83E+06	8.161E-04	7.61E+06	7.533E-04	8.24E+06
102	A	Sst.	1.212E-03	5.12E+06	1.302E-03	4.77E+06	8.826E-04	7.04E+06	1.218E-03	5.10E+06
102	B		1.200E-03	5.18E+06	1.030E-03	6.03E+06	8.870E-04	7.00E+06	1.034E-03	6.00E+06
102	C		1.273E-03	4.88E+06	8.360E-04	7.43E+06	1.298E-03	4.78E+06	1.623E-03	3.83E+06
115	A	Syenite	8.136E-04	7.63E+06	9.537E-04	6.51E+06	8.299E-04	7.48E+06	7.925E-04	7.84E+06
115	B		9.919E-04	6.26E+06	1.041E-03	5.96E+06	8.077E-04	7.69E+06	7.853E-04	7.91E+06
115	C		9.700E-03	6.40E+05	6.824E-04	9.10E+06	9.692E-04	6.41E+06	9.046E-04	6.86E+06
117	A	Syenite	1.292E-03	4.81E+06	1.047E-03	5.93E+06	1.001E-03	6.21E+06	1.027E-03	6.05E+06
117	B		1.255E-03	4.95E+06	1.062E-03	5.85E+06	1.051E-03	5.91E+06	9.522E-04	6.52E+06
117	C		1.277E-03	4.86E+06	7.702E-04	8.06E+06	2.116E-03	2.93E+06	1.847E-03	3.36E+06

Table B-2 (Cont.)

SAMPLE	EXT.	ROCK TYPE	STRAIN	MF	STRAIN	MFS	STRAIN	MFSALT
4	A	Lst.	1.676E-03	3.70E+06	1.771E-03	3.51E+06	1.113E-03	5.58E+06
4	B		1.582E-03	3.93E+06	1.664E-03	3.73E+06	1.167E-03	5.32E+06
4	C		1.064E-03	5.84E+06	8.317E-04	7.47E+06	1.141E-03	5.44E+06
8	A	Dolomite	1.206E-03	5.15E+06	1.678E-03	3.70E+06	1.351E-03	4.60E+06
8	B		9.640E-04	6.44E+06	1.047E-03	5.93E+06	1.287E-03	4.83E+06
8	C		7.997E-04	7.77E+06	1.191E-03	5.21E+06	1.072E-03	5.79E+06
16	A	Dolomite	7.676E-04	8.09E+06	9.855E-04	6.30E+06	7.153E-04	8.68E+06
16	B		6.909E-04	8.99E+06	7.127E-04	8.71E+06	1.362E-03	4.56E+06
16	C		8.569E-04	7.25E+06	1.018E-03	6.10E+06	1.334E-03	4.66E+06
18	A	Dolomite	8.391E-04	7.40E+06	1.139E-03	5.45E+06	1.300E-03	4.78E+06
18	B		7.815E-04	7.95E+06	7.714E-04	8.05E+06	1.417E-03	4.38E+06
18	C		6.989E-04	8.89E+06	7.143E-04	8.69E+06	8.571E-04	7.25E+06
19	A	Dolomite	1.094E-03	5.68E+06	1.478E-03	4.20E+06	7.290E-04	8.52E+06
19	B		7.909E-04	7.85E+06	8.649E-04	7.18E+06	6.838E-04	9.08E+06
19	C		8.838E-04	7.03E+06	1.304E-03	4.76E+06	6.285E-04	9.88E+06
21	A	Dolomite	9.105E-04	6.82E+06	2.326E-03	2.67E+06	9.699E-04	6.40E+06
21	B		8.723E-04	7.12E+06	8.460E-04	7.34E+06	9.928E-04	6.26E+06
21	C		8.120E-04	7.65E+06	9.357E-04	6.64E+06	1.058E-03	5.87E+06
22	A	Dolomite	7.260E-04	8.55E+06	9.281E-04	6.69E+06	7.706E-04	8.06E+06
22	B		9.045E-04	6.87E+06	9.031E-04	6.88E+06	7.582E-04	8.19E+06
22	C		8.854E-04	7.01E+06	9.693E-04	6.41E+06	8.843E-04	7.02E+06
23	A	Dolomite	1.072E-03	5.79E+06	1.759E-03	3.53E+06	1.436E-03	4.32E+06
23	B		1.091E-03	5.69E+06	1.069E-03	5.81E+06	8.747E-04	7.10E+06
23	C		8.695E-04	7.14E+06	7.429E-04	8.36E+06	7.429E-04	8.36E+06
24	A	Dolomite	6.281E-04	9.89E+06	6.964E-04	8.92E+06	8.063E-04	7.70E+06
24	B		6.843E-04	9.08E+06	9.758E-04	6.36E+06	7.984E-04	7.78E+06
24	C		7.647E-03	8.12E+05	1.056E-03	5.88E+06	7.611E-04	8.16E+06
26	A	Dolomite	8.935E-04	6.95E+06	8.406E-04	7.39E+06	7.902E-04	7.86E+06
26	B		9.579E-04	6.48E+06	9.288E-04	6.69E+06	8.444E-04	7.35E+06
26	C		7.779E-04	7.98E+06	1.374E-03	4.52E+06	8.565E-04	7.25E+06
34	A	Dolomite	8.800E-04	7.06E+06	8.768E-04	7.08E+06	7.796E-04	7.97E+06
34	B		7.652E-04	8.12E+06	1.986E-03	3.13E+06	8.457E-04	7.34E+06
34	C		8.563E-04	7.25E+06	1.506E-03	4.12E+06	9.706E-04	6.40E+06
37	A	Dolomite	1.548E-03	4.01E+06	1.558E-03	3.98E+06	1.839E-03	3.38E+06
37	B		1.513E-03	4.11E+06	8.631E-04	7.20E+06	1.727E-03	3.60E+06
37	C		8.405E-04	7.39E+06	1.152E-03	5.39E+06	1.556E-03	3.99E+06
39	A	Lst.	9.879E-04	6.29E+06	1.099E-03	5.65E+06	8.566E-04	7.25E+06
39	B		1.088E-03	5.71E+06	9.627E-04	6.45E+06	8.312E-04	7.47E+06
39	C		1.070E-03	5.80E+06	8.333E-04	7.45E+06	9.280E-04	6.69E+06

Table B-2 (Cont.)								
SAMPLE	EXT.	ROCK TYPE	STRAIN	MF	STRAIN	MFS	STRAIN	MFSALT
40	A	Lst.	1.178E-03	5.27E+06	9.682E-04	6.28E+06	7.201E-03	8.62E+05
40	B		9.710E-04	6.40E+06	1.110E-03	5.59E+06	7.401E-04	8.39E+06
40	C		8.459E-04	7.34E+06	8.611E-04	7.21E+06	8.260E-04	7.52E+06
41	A	Dolomite	9.389E-04	6.61E+06	2.934E-03	2.12E+06	9.893E-04	6.28E+06
41	B		2.902E-03	2.14E+06	1.043E-03	5.95E+06	8.840E-04	7.02E+06
41	C		2.712E-03	2.29E+06	8.738E-04	7.11E+06	1.450E-03	4.28E+06
46	A	Dolomite	1.004E-03	6.18E+06	1.065E-03	5.83E+06	8.945E-04	6.94E+06
46	B		1.176E-03	5.28E+06	1.005E-03	6.18E+06	8.501E-04	7.31E+06
46	C		1.217E-03	5.10E+06	1.197E-03	5.19E+06	1.154E-03	5.38E+06
53	A	Dolomite	1.456E-03	4.26E+06	3.419E-03	1.82E+06	1.291E-03	4.81E+06
53	B		1.799E-03	3.45E+06	8.645E-04	7.18E+06	1.063E-03	5.84E+06
53	C		8.112E-04	7.66E+06	9.155E-04	6.78E+06	7.899E-04	7.86E+06
55	A	Dolomite	7.447E-04	8.34E+06	1.034E-03	6.01E+06	7.581E-04	8.19E+06
55	B		8.593E-04	7.23E+06	1.110E-03	5.59E+06	1.093E-03	5.68E+06
55	C		8.994E-04	6.90E+06	8.976E-04	6.92E+06	1.041E-03	5.96E+06
56	A	Dolomite	8.325E-04	7.46E+06	8.878E-04	6.99E+06	8.273E-04	7.51E+06
56	B		9.655E-04	6.43E+06	7.801E-04	7.96E+06	8.974E-04	6.92E+06
56	C		1.656E-03	3.75E+06	9.718E-04	6.39E+06	1.606E-03	3.87E+06
57	A	Dolomite	8.877E-04	7.00E+06	9.790E-04	6.34E+06	1.205E-03	5.15E+06
57	B		1.349E-03	4.60E+06	3.722E-03	1.67E+06	1.247E-03	4.98E+06
57	C		1.013E-03	6.13E+06	8.330E-04	7.46E+06	7.933E-04	7.83E+06
58	A	Dolomite	1.021E-03	6.08E+06	9.262E-04	6.70E+06	8.317E-04	7.47E+06
58	B		1.514E-03	4.10E+06	7.753E-04	8.01E+06	8.270E-04	7.51E+06
58	C		1.614E-03	3.85E+06	1.151E-03	5.39E+06	8.109E-04	7.66E+06
60	A	Dolomite	8.971E-04	6.92E+06	7.564E-04	8.21E+06	7.914E-04	7.85E+06
60	B		8.048E-04	7.72E+06	1.294E-03	4.80E+06	1.164E-03	5.33E+06
60	C		9.783E-04	6.35E+06	9.752E-04	6.37E+06	9.959E-04	6.24E+06
65	A	Lst.	1.126E-03	5.52E+06	1.262E-03	4.92E+06	1.049E-03	5.92E+06
65	B		1.169E-03	5.31E+06	1.120E-03	5.54E+06	1.786E-03	3.48E+06
65	C		1.312E-03	4.73E+06	1.373E-03	4.52E+06	9.725E-04	6.39E+06
68	A	Lst.	8.568E-04	7.25E+06	1.116E-03	5.56E+06	9.420E-04	6.59E+06
68	B		1.507E-03	4.12E+06	9.534E-04	6.51E+06	9.864E-04	6.30E+06
68	C		1.091E-03	5.69E+06	9.703E-04	6.40E+06	9.013E-04	6.89E+06
74	A	Lst.	9.417E-04	6.59E+06	8.429E-04	7.37E+06	9.255E-04	6.71E+06
74	B		7.199E-04	8.63E+06	7.399E-04	8.39E+06	1.009E-03	6.15E+06
74	C		7.329E-04	8.47E+06	9.717E-04	6.39E+06	1.492E-03	4.16E+06
75	A	Lst.	8.451E-04	7.35E+06	9.972E-04	6.23E+06	9.776E-04	6.35E+06
75	B		1.009E-03	6.15E+06	1.926E-03	3.22E+06	9.540E-04	6.51E+06
75	C		7.764E-04	8.00E+06	1.442E-03	4.31E+06	7.904E-04	7.86E+06

Table B-2 (Cont.)

SAMPLE	EXT.	ROCK TYPE	STRAIN	MF	STRAIN	MFS	STRAIN	MFSALT
76	A	Dolomite	1.104E-03	5.63E+06	9.665E-04	6.43E+06	1.461E-03	4.25E+06
76	B		1.137E-03	5.46E+06	1.558E-03	3.99E+06	2.448E-04	2.54E+07
76	C		9.620E-04	6.46E+06	9.140E-04	6.79E+06	1.284E-03	4.84E+06
79	A	Dolomite	9.443E-04	6.58E+06	1.006E-03	6.17E+06	1.774E-03	3.50E+06
79	B		9.755E-04	6.37E+06	9.881E-04	6.28E+06	1.569E-03	3.96E+06
79	C		8.543E-04	7.27E+06	8.696E-04	7.14E+06	8.881E-04	6.99E+06
83	A	Lst.	1.022E-03	6.08E+06	1.001E-03	6.21E+06	1.141E-03	5.44E+06
83	B		1.088E-03	5.71E+06	9.022E-03	6.88E+05	9.467E-04	6.56E+06
83	C		9.343E-04	6.65E+06	1.102E-03	5.63E+06	1.038E-03	5.99E+06
90	A	Dolomite	8.710E-04	7.13E+06	8.300E-04	7.48E+06	9.809E-04	6.33E+06
90	B		7.165E-04	8.67E+06	1.140E-03	5.45E+06	9.513E-04	6.53E+06
90	C		1.133E-03	5.48E+06	1.215E-03	5.11E+06	1.050E-03	5.91E+06
93	A	Dolomite	1.313E-03	4.73E+06	1.162E-03	5.34E+06	1.085E-03	5.73E+06
93	B		1.203E-03	5.16E+06	4.990E-03	1.24E+06	1.007E-03	6.17E+06
93	C		9.221E-04	6.73E+06	1.618E-03	3.84E+06	1.178E-03	5.27E+06
94	A	Lst.	8.496E-04	7.31E+06	1.178E-03	5.27E+06	1.270E-03	4.89E+06
94	B		1.420E-03	4.37E+06	1.254E-03	4.95E+06	1.604E-03	3.87E+06
94	C		1.113E-03	5.58E+06	1.095E-03	5.67E+06	1.076E-03	5.77E+06
95	A	Dolomite	9.484E-04	6.55E+06	1.053E-03	5.90E+06	7.372E-04	8.42E+06
95	B		8.222E-04	7.55E+06	9.067E-04	6.85E+06	8.370E-04	7.42E+06
95	C		8.967E-04	6.93E+06	8.714E-04	7.13E+06	8.960E-04	6.93E+06
96	A	Lst.	9.813E-04	1.46E+06	1.187E-03	5.23E+06	8.390E-04	7.40E+06
96	B		8.652E-04	1.03E+06	2.619E-03	2.37E+06	1.155E-03	5.38E+06
96	C		9.752E-04	6.37E+06	8.759E-04	7.09E+06	1.051E-03	5.91E+06
97	A	Lst.	9.794E-04	6.34E+06	2.026E-03	3.07E+06	9.020E-04	6.88E+06
97	B		1.181E-03	5.26E+06	1.082E-03	5.74E+06	9.384E-04	6.62E+06
97	C		8.160E-04	7.61E+06	8.933E-04	6.95E+06	7.679E-04	8.09E+06
99	A	Marble	9.776E-04	6.35E+06	1.846E-03	3.36E+06	8.142E-04	7.63E+06
99	B		1.684E-03	3.69E+06	1.579E-03	3.93E+06	1.138E-03	5.46E+06
99	C		1.848E-03	3.36E+06	6.591E-04	9.42E+06	6.905E-04	8.99E+06
102	A	Sst.	1.179E-03	5.27E+06	9.314E-04	6.67E+06	1.540E-03	4.03E+06
102	B		8.784E-04	7.07E+06	8.591E-04	7.23E+06	1.140E-03	5.45E+06
102	C		8.060E-04	7.70E+06	1.420E-03	4.37E+06	1.073E-03	5.79E+06
115	A	Syenite	8.614E-04	7.21E+06	1.033E-03	6.01E+06	1.049E-03	5.92E+06
115	B		9.521E-04	6.52E+06	9.046E-04	6.86E+06	8.885E-04	6.99E+06
115	C		8.252E-04	7.53E+06	8.885E-04	6.99E+06	7.592E-04	8.18E+06
117	A	Syenite	9.140E-04	6.79E+06	9.379E-04	6.62E+06	8.463E-04	7.34E+06
117	B		1.013E-03	6.13E+06	9.403E-04	6.60E+06	8.729E-04	7.11E+06
117	C		1.550E-03	4.01E+06	9.209E-04	6.74E+06	2.308E-03	2.69E+06

TABLE B-3 Moduli of elasticity* of rocks under different conditions (kpascal)

SAMPLE	ROCK TYPE	Grain Size **	RA	R98H	RS	RSALT	RF	RFS	RFSALT
4	L	Aphanitic	8.12E+09	7.02E+09	5.23E+09	5.70E+09	7.48E+09	5.44E+09	5.87E+09
8	D	Aphanitic	8.57E+09	8.15E+09	8.14E+09	7.22E+09	1.00E+10	6.64E+09	7.85E+09
16	D	Medium	9.75E+09	7.53E+09	8.71E+09	8.95E+09	8.76E+09	1.07E+10	8.02E+09
18	D	Fine	8.56E+09	8.46E+09	6.18E+09	6.40E+09	1.09E+10	8.43E+09	5.93E+09
19	D	Aphanitic	8.36E+09	9.06E+09	8.98E+09	1.01E+10	1.19E+10	1.07E+10	7.41E+09
21	D	Fine	1.01E+10	9.81E+09	7.71E+09	8.43E+09	1.20E+10	7.05E+09	7.01E+09
22	D	Fine	8.78E+09	8.23E+09	7.20E+09	7.95E+09	9.45E+09	8.80E+09	7.45E+09
23	D	.	7.91E+09	7.63E+09	5.73E+09	6.92E+09	7.43E+09	6.48E+09	7.79E+09
24	D	.	9.86E+09	9.41E+09	1.11E+10	6.62E+09	1.01E+10	8.21E+09	9.74E+09
26	D	.	9.80E+09	8.83E+09	8.22E+09	8.16E+09	1.08E+10	7.94E+09	8.10E+09
34	D	Aphanitic	1.02E+10	9.97E+09	7.17E+09	7.09E+09	1.07E+10	7.44E+09	8.11E+09
37	D	Fine	5.84E+09	4.57E+09	4.34E+09	5.11E+09	5.83E+09	4.83E+09	3.86E+09
39	L	.	9.71E+09	8.40E+09	9.53E+09	8.21E+09	8.92E+09	7.26E+09	7.16E+09
40	L	.	3.76E+09	2.98E+09	2.21E+09	4.56E+09	.	.	.
41	D	Aphanitic	7.75E+09	7.55E+09	6.33E+09	6.73E+09	8.38E+09	6.10E+09	5.31E+09
46	D	.	5.86E+09	5.72E+09	5.46E+09	6.71E+09	6.04E+09	7.32E+09	8.12E+09
53	D	.	8.59E+09	9.10E+09	1.05E+10	8.18E+09	1.26E+10	8.52E+09	7.48E+09
55	D	Aphanitic	7.68E+09	7.70E+09	7.96E+09	5.74E+09	8.18E+09	6.40E+09	7.22E+09
56	D	Aphanitic	1.06E+10	9.46E+09	7.55E+09	7.89E+09	9.53E+09	7.45E+09	6.57E+09
57	D	.	.	.	.	.	.	.	.
58	D	Fine	.	.	.	.	.	.	.
60	D	Fine .	7.12E+09	7.47E+09	6.18E+09	6.71E+09	6.94E+09	6.50E+09	5.28E+09
65	L	.	5.85E+09	5.37E+09	6.05E+09	5.76E+09	6.43E+09	4.51E+09	4.54E+09
68	L	.	6.37E+09	8.51E+09	8.87E+09	7.98E+09	7.21E+09	1.03E+10	5.61E+09
74	L	Fine	1.24E+10	9.67E+09	1.19E+10	1.04E+10	1.24E+10	1.13E+10	8.55E+09
75	L	Aphanitic	9.12E+09	1.10E+10	9.36E+09	8.60E+09	1.10E+10	1.06E+10	8.59E+09
76	D	Fine	1.16E+09	1.21E+09	9.44E+08	1.05E+09	9.44E+08	1.07E+09	1.10E+09
79	D	.	5.69E+09	5.81E+09	5.67E+09	.	6.64E+09	6.08E+09	.
83	L	Fine	9.09E+09	9.43E+09	8.47E+09	8.76E+09	1.13E+10	7.95E+09	7.42E+09
90	D	.	.	.	.	.	.	.	.
93	D	.	7.05E+09	5.56E+09	4.20E+09	4.32E+09	6.89E+09	4.05E+09	3.63E+09
94	L	.	6.15E+09	6.16E+09	4.07E+09	4.27E+09	7.27E+09	3.97E+09	3.65E+09

TABLE B-3 (Cont.)

SAMPLE	ROCK TYPE	Grain Size **	RA	R98H	RS	RSALT	RF	RFS	RFSALT
95	D	.	7.35E+09	7.49E+09	8.49E+09	8.35E+09	8.56E+09	8.54E+09	7.92E+09
96	L	Medium	6.85E+09	5.43E+09	5.03E+09	6.13E+09	6.38E+09	6.49E+09	6.80E+09
97	L	.	6.19E+09	5.33E+09	5.29E+09	4.92E+09	6.14E+09	5.29E+09	5.32E+09
99	M	Fine	5.78E+09	6.07E+09	6.10E+09	8.20E+09	6.08E+09	6.66E+09	6.28E+09
102	SSt	Coarse	4.69E+09	4.15E+09	4.43E+09	4.72E+09	4.96E+09	4.55E+09	5.59E+09
115	SY	Phaneritic	6.76E+09	6.07E+09	7.01E+09	6.99E+09	6.87E+09	7.59E+09	6.87E+09
117	SY	Phaneritic	6.42E+09	7.01E+09	8.04E+09	6.80E+09	7.74E+09	6.68E+09	5.09E+09

RA= Ambient
R98=98%Relative Humidity
RS=Saturated
RSALT=Brine Saturated
RF=Frozen
RFS=Frozen Saturated
RFSALT=Frozen Brine Saturated

L=Limestone
D=Dolomite
SSt=Sandstone
SY=Syenite
M=Marble

* Elasticity of rocks are calculated based on Pour Molk Ara (In progress) data
** Grain Size data have been copied from Dananaj(2001)

TABLE B-4 Moduli of elasticity of mortars under different conditions (kpascal)

SAMPLE	TYPE OF AGGREGATE	MA	MH98	MS	MSALT	MF	MFS	MFSALT
4	L	5.575E+06	5.781E+06	7.615E+06	6.371E+06	3.807E+06	3.673E+06	5.477E+06
8	D	5.810E+06	5.586E+06	6.455E+06	5.696E+06	6.052E+06	5.379E+06	4.923E+06
16	D	8.332E+06	8.695E+06	7.691E+06	7.407E+06	8.888E+06	8.332E+06	4.651E+06
18	D	7.591E+06	6.706E+06	7.059E+06	6.287E+06	8.211E+06	6.819E+06	4.470E+06
19	D	6.561E+06	5.726E+06	6.846E+06	5.832E+06	7.324E+06	6.056E+06	9.263E+06
21	D	6.240E+06	5.265E+06	6.739E+06	5.911E+06	7.487E+06	6.607E+06	6.017E+06
22	D	9.644E+06	7.144E+06	9.644E+06	8.573E+06	7.014E+06	6.651E+06	8.037E+06
23	D	7.110E+06	9.094E+06	7.668E+06	6.861E+06	5.925E+06	6.307E+06	7.242E+06
24	D	7.681E+06	7.201E+06	7.514E+06	7.054E+06	9.096E+06	6.172E+06	7.856E+06
26	D	6.251E+06	7.213E+06	7.501E+06	7.814E+06	6.819E+06	6.357E+06	7.501E+06
34	D	6.154E+06	6.782E+06	7.071E+06	5.632E+06	7.224E+06	5.830E+06	7.728E+06
37	D	4.158E+06	3.201E+06	4.019E+06	4.307E+06	4.065E+06	6.577E+06	3.445E+06
39	L	6.074E+06	5.486E+06	6.299E+06	6.184E+06	5.765E+06	6.669E+06	7.394E+06
40	L	7.048E+06	6.197E+06	8.767E+06	7.489E+06	5.706E+06	5.991E+06	8.558E+06
41	D	8.038E+06	6.746E+06	6.628E+06	5.105E+06	2.159E+06	3.740E+06	6.403E+06
46	D	5.720E+06	6.196E+06	6.196E+06	6.466E+06	5.948E+06	5.832E+06	7.081E+06
53	D	3.078E+06	3.969E+06	5.291E+06	4.788E+06	4.022E+06	5.800E+06	5.027E+06
55	D	7.034E+06	6.064E+06	7.327E+06	6.513E+06	7.327E+06	6.064E+06	5.961E+06
56	D	6.173E+06	6.073E+06	7.241E+06	6.382E+06	5.705E+06	7.241E+06	5.793E+06
57	D	6.176E+06	6.738E+06	6.445E+06	7.231E+06	6.738E+06	6.738E+06	7.058E+06
58	D	5.236E+06	5.984E+06	6.093E+06	6.093E+06	6.839E+06	6.839E+06	7.616E+06
60	D	5.342E+06	5.441E+06	7.732E+06	6.251E+06	4.897E+06	7.166E+06	5.441E+06
65	L	6.656E+06	4.941E+06	5.528E+06	5.260E+06	5.017E+06	5.260E+06	6.039E+06
68	L	6.983E+06	5.502E+06	7.262E+06	7.120E+06	5.674E+06	6.484E+06	6.725E+06
74	L	8.370E+06	6.175E+06	8.188E+06	8.188E+06	8.560E+06	7.386E+06	6.278E+06
75	L	5.999E+06	6.352E+06	7.363E+06	5.585E+06	6.352E+06	5.890E+06	6.479E+06
76	D	7.046E+06	4.336E+06	5.636E+06	5.033E+06	6.554E+06	4.944E+06	4.336E+06
79	D	7.698E+06	6.415E+06	7.370E+06	7.698E+06	6.298E+06	6.536E+06	3.571E+06
83	L	5.652E+06	7.194E+06	6.087E+06	6.595E+06	6.331E+06	6.735E+06	5.553E+06
90	D	7.300E+06	5.996E+06	7.144E+06	6.457E+06	7.631E+06	6.584E+06	6.457E+06
93	D	4.304E+06	6.171E+06	4.740E+06	3.989E+06	5.451E+06	4.480E+06	5.841E+06
94	L	4.643E+06	5.542E+06	6.248E+06	4.707E+06	5.053E+06	4.980E+06	3.950E+06
95	D	8.073E+06	6.986E+06	7.568E+06	8.256E+06	6.986E+06	6.854E+06	7.568E+06

TABLE B-4(Cont.)

SAMPLE	TYPE OF AGGREGATE	MA	MH98	MS	MSALT	MF	MFS	MFSALT
96	L	6.224E+06	6.346E+06	7.192E+06	6.224E+06	1.371E+06	3.763E+06	5.485E+06
97	L	6.034E+06	5.857E+06	7.659E+06	7.241E+06	5.857E+06	6.866E+06	6.750E+06
99	M	8.335E+06	7.145E+06	6.365E+06	8.977E+06	3.432E+06	6.365E+06	7.780E+06
102	SSt	5.018E+06	6.690E+06	7.084E+06	5.827E+06	7.373E+06	6.123E+06	5.558E+06
115	SY	6.324E+06	6.033E+06	6.535E+06	7.842E+06	7.002E+06	6.646E+06	7.129E+06
117	SY	4.838E+06	5.805E+06	6.140E+06	6.025E+06	5.322E+06	6.652E+06	7.257E+06

MA= Ambient
M98=98%Relative Humidity
MS=Saturated
MSALT=Brine Saturated
MF=Frozen
MFS=Frozen Saturated
MFSALT=Frozen Brine Saturated

L=Limestone
D=Dolomite
SSt=Sandstone
SY=Syenite
M=Marble

TABLE B_5 Additional Data of Rock and Mortar

SAMPLE	Mortar Absorption%	Mortar Adsorption%	Rock Absorption%	Rock Adsorption%	Mag. Test of Rocks %	Ultimate Strength of Mortars(Kpascal)
4	4.69	1.35	0.99	0.53	0.65	1.731E+04
8	6.02	2.97	0.49	0.15	92	2.009E+04
16	5.51	2.28	0.23	0.03	0.85	1.652E+04
18	6.3	2.67	0.98	0.31	4.2	1.756E+04
19	4.47	1.6	1.15	0.17	8.3	1.790E+04
21	7	3.58	0.68	0.09	0.7	1.290E+04
22	5.86	1.88	0.84	0.06	1.65	2.086E+04
23	5.09	1.44	1.8	0.03	1.5	1.911E+04
24	4.87	1.64	0.38	0.03	2.65	1.825E+04
26	5.26	1.82	3.13	0.17	12.75	1.585E+04
34	4.31	1.34	1.13	0.31	2.7	1.547E+04
37	6.47	2.74	0.75	0.6	10	1.625E+04
39	6.14	1.82	0.24	0.13	5.35	1.494E+04
40	5.15	1.79	0.69	0.4	7.8	1.575E+04
41	5	1.84	2.72	0.12	8.5	1.962E+04
46	6.53	2.46	3.78	0.13	27.15	1.237E+04
53	5.67	2.17	3.31	0.06	5.15	1.500E+04
55	5.23	1.79	1.86	0.02	2.65	1.701E+04
56	5.85	2.28	0.07	0.03	1.4	1.159E+04
57	5.18	2.31	0.51	0.04	1.35	1.913E+04
58	6.32	3.03	1.41	0.13	12.8	1.637E+04
60	5.26	2.08	1.38	0.07	4.5	1.439E+04
65	5.51	1.54	0.34	0.14	12.9	1.507E+04
68	5.17	1.56	0.24	0.16	9.2	1.915E+04
74	5.94	2.5	0.24	0.15	1.9	1.915E+04
75	4.71	1.3	0.52	0.16	4.35	1.560E+04
76	5.91	2.5	1.83	0.01	2	1.705E+04
79	5.41	1.86	1.63	0.03	7.85	1.687E+04
83	5.73	1.86	0.26	0.17	0.55	1.672E+04
90	5.68	2.25	1.14	0.52	20.3	2.058E+04
93	6.1	2.48	2.49	0.7	31.9	1.485E+04

TABLE B_5 Additional Data of Rock and Mortar

SAMPLE	Mortar Absorption%	Mortar Adsorption%	Rock Absorption%	Rock Adsorption%	Mag. Test of Rocks %	Ultimate Strength of Mortars(Kpascal)
94	6.45	2.46	1.92	0.6	28.5	1.540E+04
95	5.14	1.71	1.73	0.04	-	1.847E+04
96	5.67	2.13	1.5	0.17	8.95	1.087E+04
97	5.95	2.59	0.88	0.1	11.35	2.239E+04
99	4.18	1.62	0.17	0	3.45	2.081E+04
102	4.84	1.96	2.9	0.05	95	1.913E+04
115	5.2	1.84	0.13	0.01	2.2	1.663E+04
117	4.96	1.74	0.13	0.01	1.1	1.764E+04

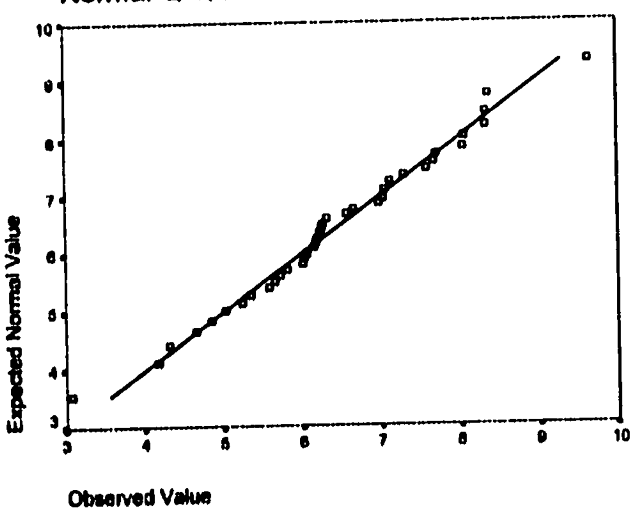
APPENDIX C

Statistical Analysis

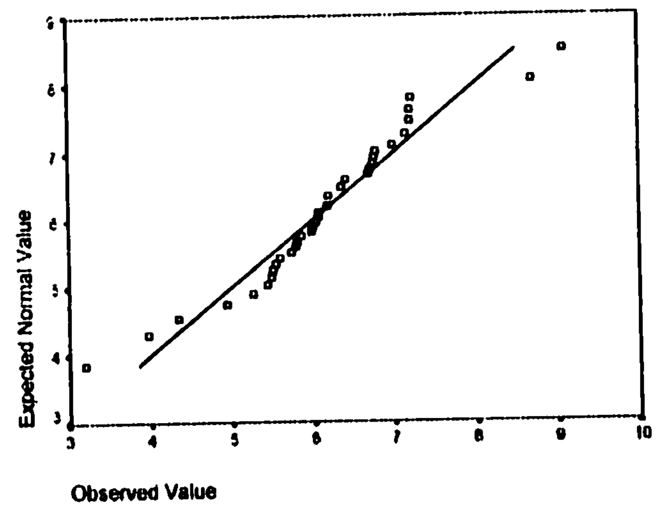
- **Normality Plots**
- **Paired *t*-test**
- **Group *t*-test**
- **Factor Analysis**
- **Backward Regression**

Normality plots

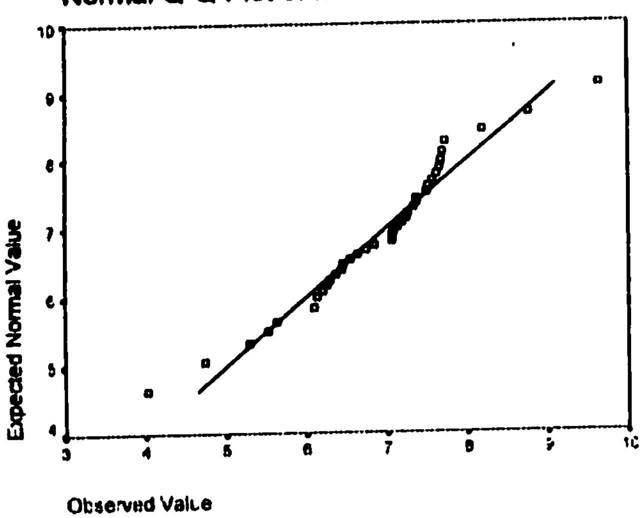
Normal Q-Q Plot of MA



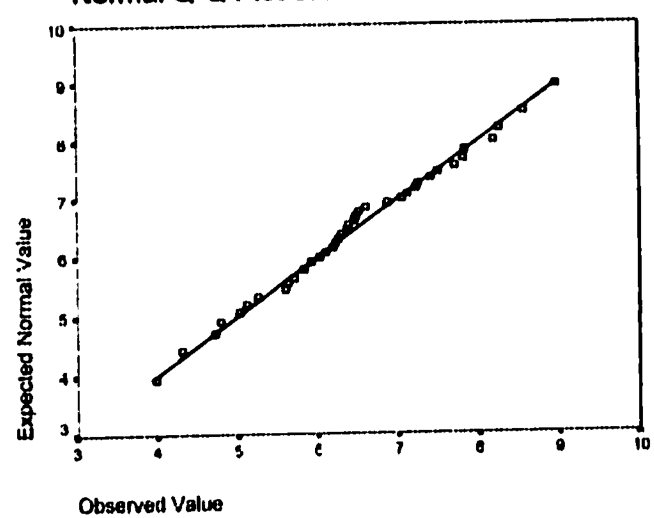
Normal Q-Q Plot of MH98



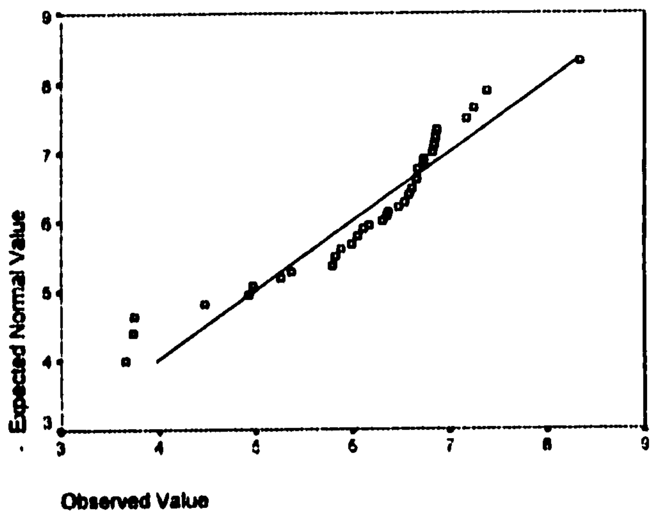
Normal Q-Q Plot of MS



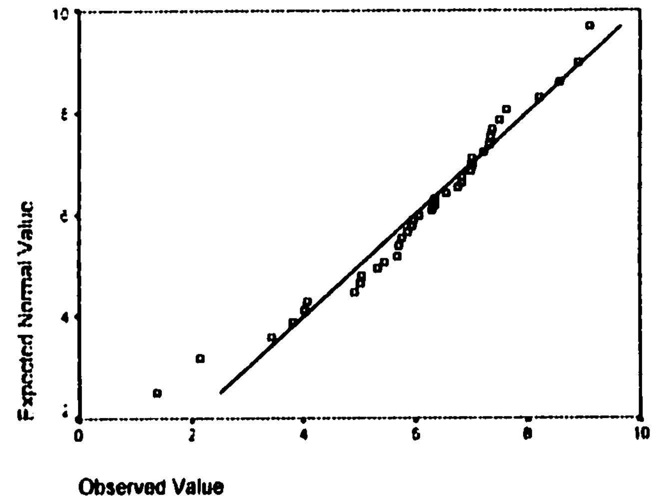
Normal Q-Q Plot of MSALT



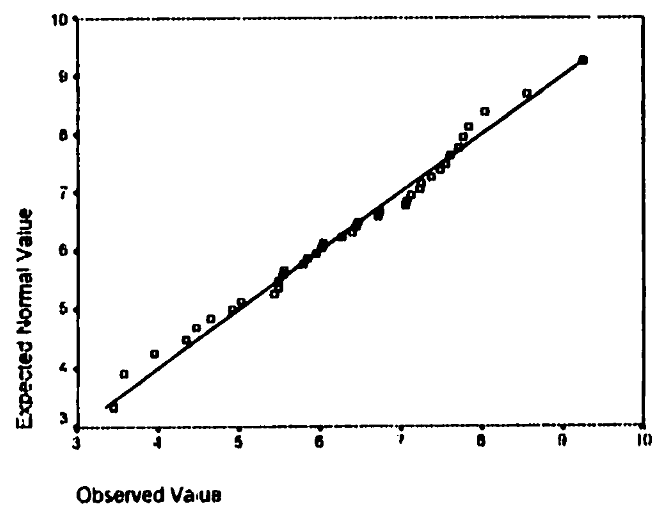
Normal Q-Q Plot of MFS



Normal Q-Q Plot of MF



Normal Q-Q Plot of MFSALT



Paired samples t test on RA vs RH98 with 36 cases

Mean RA	=	7.607			
Mean RH98	=	7.259			
Mean Difference =	0.348	95.00% CI =	0.025 to	0.671	
SD Difference =	0.955	t =	2.185		
	df = 35	Prob =	0.036		

Paired samples t test on RA vs RS with 36 cases

Mean RA	=	7.607			
Mean RS	=	6.899			
Mean Difference =	0.708	95.00% CI =	0.222 to	1.194	
SD Difference =	1.438	t =	2.955		
	df = 35	Prob =	0.006		

Paired samples t test on RH98 vs RS with 36 cases

Mean RH98	=	7.259			
Mean RS	=	6.899			
Mean Difference =	0.360	95.00% CI =	-0.063 to	0.783	
SD Difference =	1.251	t =	1.728		
	df = 35	Prob =	0.093		

Paired samples t test on RA vs RSALT with 35 cases

Mean RA	=	7.661			
Mean RSALT	=	6.875			
Mean Difference =	0.786	95.00% CI =	0.310 to	1.263	
SD Difference =	1.388	t =	3.352		
	df = 34	Prob =	0.002		

Paired samples t test on RH98 vs RSALT with 35 cases

Mean RH98	=	7.300			
Mean RSALT	=	6.875			
Mean Difference =	0.425	95.00% CI =	-0.009 to	0.859	
SD Difference =	1.264	t =	1.990		
	df = 34	Prob =	0.055		

Paired samples t test on RS vs RSALT with 35 cases

Mean RS	=	6.934			
Mean RSALT	=	6.875			
Mean Difference =	0.059	95.00% CI =	-0.384 to	0.501	
SD Difference =	1.288	t =	0.270		
	df = 34	Prob =	0.789		

Paired samples t test on RA vs RF with 35 cases

Mean RA	=	7.717			
Mean RF	=	8.364			
Mean Difference =	-0.648	95.00% CI =	-1.048 to	-0.247	
SD Difference =	1.166	t =	-3.288		
	df = 34	Prob =	0.002		

Paired samples t test on RH98 vs RF with 35 cases

Mean RH98	=	7.381
Mean RF	=	8.364

Mean Difference =	-0.983	95.00% CI =	-1.327 to	-0.640	
SD Difference =	1.000	t =	-5.816		
	df = 34	Prob =	0.000		

Paired samples t test on RS vs RF with 35 cases

Mean RS =	7.033			
Mean RF =	8.364			
Mean Difference =	-1.332	95.00% CI =	-1.842 to	-0.821
SD Difference =	1.485	t =	-5.304	
	df = 34	Prob =	0.000	

Paired samples t test on RSALT vs RF with 34 cases

Mean RSALT =	6.943			
Mean RF =	8.415			
Mean Difference =	-1.472	95.00% CI =	-2.017 to	-0.927
SD Difference =	1.562	t =	-5.496	
	df = 33	Prob =	0.000	

Paired samples t test on RA vs RFS with 35 cases

Mean RA =	7.717			
Mean RFS =	7.081			
Mean Difference =	0.635	95.00% CI =	0.071 to	1.200
SD Difference =	1.644	t =	2.287	
	df = 34	Prob =	0.029	

Paired samples t test on RH98 vs RFS with 35 cases

Mean RH98 =	7.381			
Mean RFS =	7.081			
Mean Difference =	0.300	95.00% CI =	-0.181 to	0.781
SD Difference =	1.399	t =	1.268	
	df = 34	Prob =	0.213	

Paired samples t test on RS vs RFS with 35 cases

Mean RS =	7.033			
Mean RFS =	7.081			
Mean Difference =	-0.048	95.00% CI =	-0.478 to	0.381
SD Difference =	1.249	t =	-0.229	
	df = 34	Prob =	0.820	

Paired samples t test on RSALT vs RFS with 34 cases

Mean RSALT =	6.943			
Mean RFS =	7.111			
Mean Difference =	-0.167	95.00% CI =	-0.504 to	0.169
SD Difference =	0.965	t =	-1.012	
	df = 33	Prob =	0.319	

Paired samples t test on RF vs RFS with 35 cases

Mean RF =	8.364			
Mean RFS =	7.081			
Mean Difference =	1.283	95.00% CI =	0.693 to	1.873
SD Difference =	1.717	t =	4.421	
	df = 34	Prob =	0.000	

Paired samples t test on RA vs RFSALT with 34 cases

Mean RA =	7.776			
Mean RFSALT =	6.507			
Mean Difference =	1.269	95.00% CI =	0.780 to	1.758
SD Difference =	1.402	t =	5.279	

df = 33 Prob = 0.000

Paired samples t test on RH98 vs RFSALT with 34 cases

Mean RH98 = 7.427
Mean RFSALT = 6.507
Mean Difference = 0.920 95.00% CI = 0.442 to 1.399
SD Difference = 1.372 t = 3.911
df = 33 Prob = 0.000

Paired samples t test on RS vs RFSALT with 34 cases

Mean RS = 7.073
Mean RFSALT = 6.507
Mean Difference = 0.566 95.00% CI = 0.074 to 1.057
SD Difference = 1.409 t = 2.342
df = 33 Prob = 0.025

Paired samples t test on RSALT vs RFSALT with 34 cases

Mean RSALT = 6.943
Mean RFSALT = 6.507
Mean Difference = 0.436 95.00% CI = 0.004 to 0.868
SD Difference = 1.238 t = 2.054
df = 33 Prob = 0.048

Paired samples t test on RF vs RFSALT with 34 cases

Mean RF = 8.415
Mean RFSALT = 6.507
Mean Difference = 1.908 95.00% CI = 1.284 to 2.532
SD Difference = 1.789 t = 6.217
df = 33 Prob = 0.000

Paired samples t test on RFS vs RFSALT with 34 cases

Mean RFS = 7.111
Mean RFSALT = 6.507
Mean Difference = 0.604 95.00% CI = 0.114 to 1.093
SD Difference = 1.404 t = 2.507
df = 33 Prob = 0.017

Paired samples t test on MA vs MH98 with 39 cases

Mean MA = 6.423
Mean MH98 = 6.173
Mean Difference = 0.250 95.00% CI = -0.131 to 0.630
SD Difference = 1.174 t = 1.328
df = 38 Prob = 0.192

Paired samples t test on MA vs MS with 39 cases

Mean MA = 6.423
Mean MS = 6.871
Mean Difference = -0.448 95.00% CI = -0.782 to -0.113
SD Difference = 1.032 t = -2.709
df = 38 Prob = 0.010

Paired samples t test on MH98 vs MS with 39 cases

Mean MH98 = 6.173
Mean MS = 6.871
Mean Difference = -0.697 95.00% CI = -1.021 to -0.374

SD Difference = 0.998 t = -4.363
df = 38 Prob = 0.000

Paired samples t test on MA vs MSALT with 39 cases

Mean MA = 6.423
Mean MSALT = 6.443
Mean Difference = -0.020 95.00% CI = -0.342 to 0.303
SD Difference = 0.995 t = -0.124
df = 38 Prob = 0.902

Paired samples t test on MH98 vs MSALT with 39 cases

Mean MH98 = 6.173
Mean MSALT = 6.443
Mean Difference = -0.269 95.00% CI = -0.614 to 0.075
SD Difference = 1.064 t = -1.582
df = 38 Prob = 0.122

Paired samples t test on MS vs MSALT with 39 cases

Mean MS = 6.871
Mean MSALT = 6.443
Mean Difference = 0.428 95.00% CI = 0.144 to 0.712
SD Difference = 0.876 t = 3.050
df = 38 Prob = 0.004

Paired samples t test on MA vs MF with 39 cases

Mean MA = 6.423
Mean MF = 6.084
Mean Difference = 0.339 95.00% CI = -0.232 to 0.910
SD Difference = 1.762 t = 1.201
df = 38 Prob = 0.237

Paired samples t test on MH98 vs MF with 39 cases

Mean MH98 = 6.173
Mean MF = 6.084
Mean Difference = 0.089 95.00% CI = -0.456 to 0.634
SD Difference = 1.682 t = 0.331
df = 38 Prob = 0.742

Paired samples t test on MS vs MF with 39 cases

Mean MS = 6.871
Mean MF = 6.084
Mean Difference = 0.787 95.00% CI = 0.249 to 1.324
SD Difference = 1.658 t = 2.962
df = 38 Prob = 0.005

Paired samples t test on MSALT vs MF with 39 cases

Mean MSALT = 6.443
Mean MF = 6.084
Mean Difference = 0.359 95.00% CI = -0.198 to 0.916
SD Difference = 1.718 t = 1.304
df = 38 Prob = 0.200

Paired samples t test on MA vs MFS with 39 cases

Mean MA = 6.423
Mean MFS = 6.138
Mean Difference = 0.285 95.00% CI = -0.193 to 0.763
SD Difference = 1.475 t = 1.206
df = 38 Prob = 0.235

Paired samples t test on MH98 vs MFS with 39 cases

Mean MH98 = 6.173
Mean MFS = 6.138
Mean Difference = 0.035 95.00% CI = -0.387 to 0.457
SD Difference = 1.301 t = 0.169
df = 38 Prob = 0.867

Paired samples t test on MS vs MFS with 39 cases

Mean MS = 6.871
Mean MFS = 6.138
Mean Difference = 0.733 95.00% CI = 0.328 to 1.137
SD Difference = 1.248 t = 3.665
df = 38 Prob = 0.001

Paired samples t test on MSALT vs MFS with 39 cases

Mean MSALT = 6.443
Mean MFS = 6.138
Mean Difference = 0.305 95.00% CI = -0.051 to 0.660
SD Difference = 1.096 t = 1.736
df = 38 Prob = 0.091

Paired samples t test on MF vs MFS with 39 cases

Mean MF = 6.084
Mean MFS = 6.138
Mean Difference = -0.054 95.00% CI = -0.475 to 0.367
SD Difference = 1.298 t = -0.260
df = 38 Prob = 0.796

Paired samples t test on MA vs MFSALT with 39 cases

Mean MA = 6.423
Mean MFSALT = 6.301
Mean Difference = 0.123 95.00% CI = -0.402 to 0.647
SD Difference = 1.618 t = 0.473
df = 38 Prob = 0.639

Paired samples t test on MH98 vs MFSALT with 39 cases

Mean MH98 = 6.173
Mean MFSALT = 6.301
Mean Difference = -0.127 95.00% CI = -0.589 to 0.335
SD Difference = 1.426 t = -0.557
df = 38 Prob = 0.581

Paired samples t test on MS vs MFSALT with 39 cases

Mean MS = 6.871
Mean MFSALT = 6.301
Mean Difference = 0.570 95.00% CI = 0.123 to 1.017
SD Difference = 1.378 t = 2.584
df = 38 Prob = 0.014

Paired samples t test on MSALT vs MFSALT with 39 cases

Mean MSALT = 6.443
Mean MFSALT = 6.301
Mean Difference = 0.142 95.00% CI = -0.300 to 0.584
SD Difference = 1.364 t = 0.652
df = 38 Prob = 0.518

Paired samples t test on MF vs MFSALT with 39 cases

Mean MF	=	6.084			
Mean MFSALT	=	6.301			
Mean Difference =		-0.216	95.00% CI =	-0.853 to	0.420
SD Difference =		1.964	t =	-0.688	
		df = 38	Prob =	0.496	

Paired samples t test on MFS vs MFSALT with 39 cases

Mean MFS	=	6.138			
Mean MFSALT	=	6.301			
Mean Difference =		-0.162	95.00% CI =	-0.680 to	0.355
SD Difference =		1.596	t =	-0.635	
		df = 38	Prob =	0.529	

Paired samples t test on RADS vs RABS with 39 cases

Mean RADS	=	0.170			
Mean RABS	=	1.194			
Mean Difference =		-1.024	95.00% CI =	-1.344 to	-0.704
SD Difference =		0.987	t =	-6.477	
		df = 38	Prob =	0.000	

Paired samples t test on MABS vs MADS with 39 cases

Mean MABS	=	5.506			
Mean MADS	=	2.071			
Mean Difference =		3.435	95.00% CI =	3.318 to	3.552
SD Difference =		0.361	t =	59.455	
		df = 38	Prob =	0.000	

SYSTAT Rectangular file C:\WINDOWS\Desktop\2\2 divided.SYD,
created Wed Apr 04, 2001 at 01:00:54, contains variables:

SAMPLE$	TYPE$	RA	RH98	RS	RSALT
RF	RFS	RFSALT	MA	MH98	MS
MSALT	MF	MFS	MFSALT	MABS	MADS
RABS	RADS	MAGTES	MODU	ULTI	

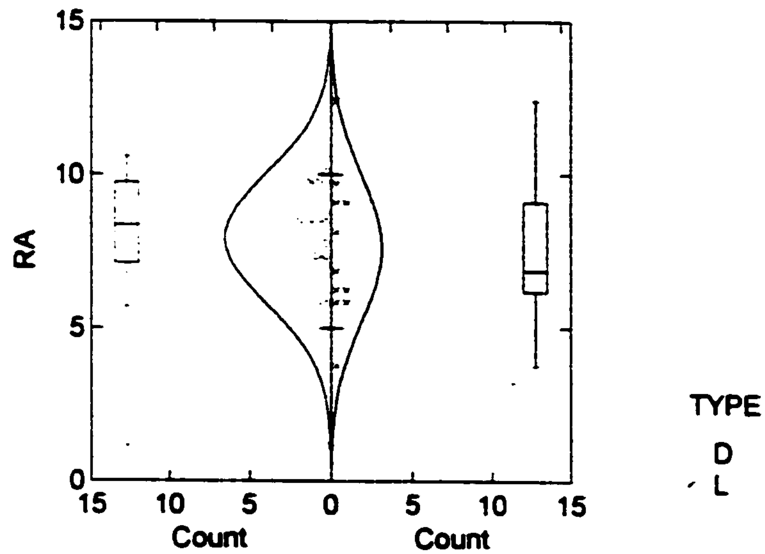
The grouping variable has more than two distinct values.
Only the first two values encountered in the data will be used.

Two-sample t test on RA grouped by TYPE$

Group	N	Mean	SD
D	21	7.932	2.134
L	11	7.601	2.372

Separate Variance t = 0.388 df = 18.6 Prob = 0.702
Difference in Means = 0.331 95.00% CI = -1.457 to 2.120

Pooled Variance t = 0.402 df = 30 Prob = 0.691
Difference in Means = 0.331 95.00% CI = -1.353 to 2.016

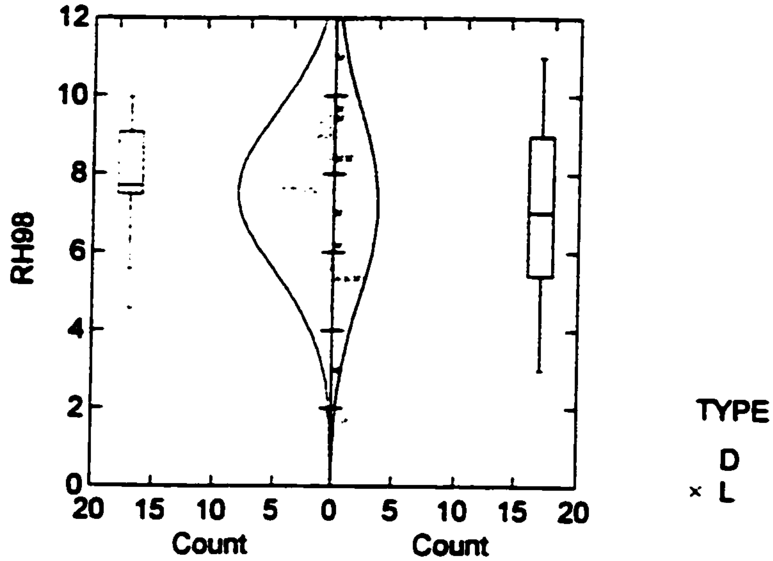


Two-sample t test on RH98 grouped by TYPE$

Group	N	Mean	SD
D	21	7.558	2.068
L	11	7.209	2.399

Separate Variance t = 0.409 df = 17.9 Prob = 0.687
Difference in Means = 0.349 95.00% CI = -1.443 to 2.141

Pooled Variance t = 0.429 df = 30 Prob = 0.671
Difference in Means = 0.349 95.00% CI = -1.311 to 2.009

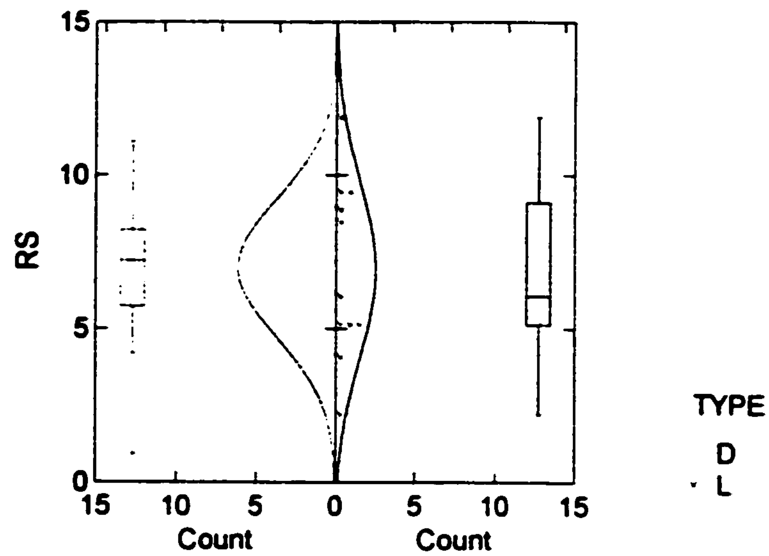


Two-sample t test on RS grouped by TYPE$

Group	N	Mean	SD
D	21	6.989	2.257
L	11	6.910	2.897

Separate Variance t = 0.079 df = 16.5 Prob = 0.938
Difference in Means = 0.079 95.00% CI = -2.041 to 2.199

Pooled Variance t = 0.085 df = 30 Prob = 0.933
Difference in Means = 0.079 95.00% CI = -1.813 to 1.970

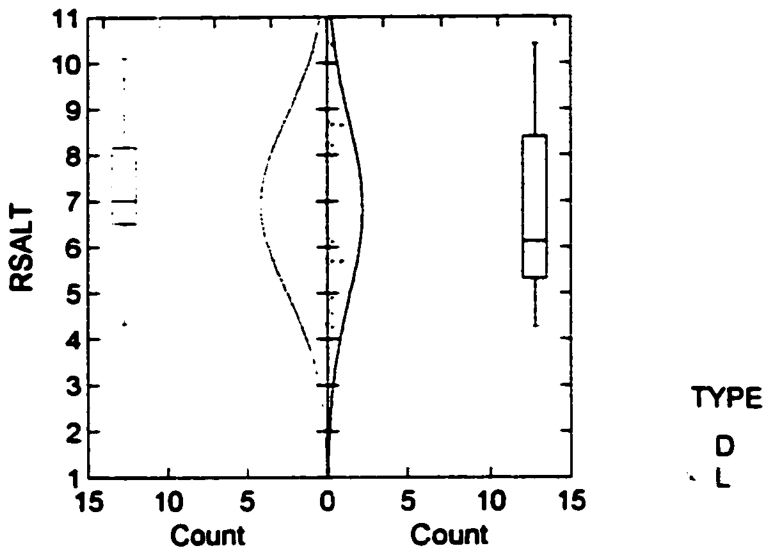


Two-sample t test on RSALT grouped by TYPE$

Group	N	Mean	SD
D	20	6.931	1.922
L	11	6.845	2.027

Separate Variance t = 0.116 df = 19.8 Prob = 0.909
Difference in Means = 0.087 95.00% CI = -1.473 to 1.647

Pooled Variance t = 0.118 df = 29 Prob = 0.907
Difference in Means = 0.087 95.00% CI = -1.417 to 1.591

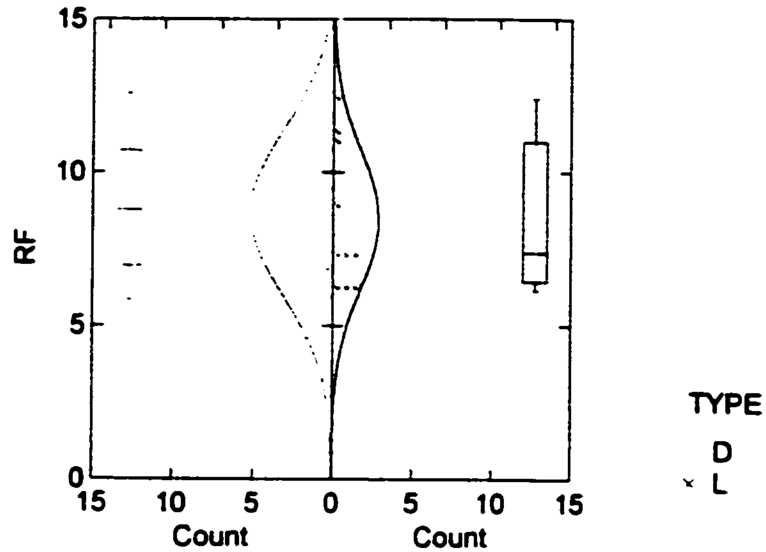


Two-sample t test on RF grouped by TYPE$

Group	N	Mean	SD
D	21	8.694	2.670
L	10	8.453	2.310

Separate Variance t = 0.258 df = 20.4 Prob = 0.799
Difference in Means = 0.241 95.00% CI = -1.706 to 2.188

Pooled Variance t = 0.245 df = 29 Prob = 0.808
Difference in Means = 0.241 95.00% CI = -1.774 to 2.256

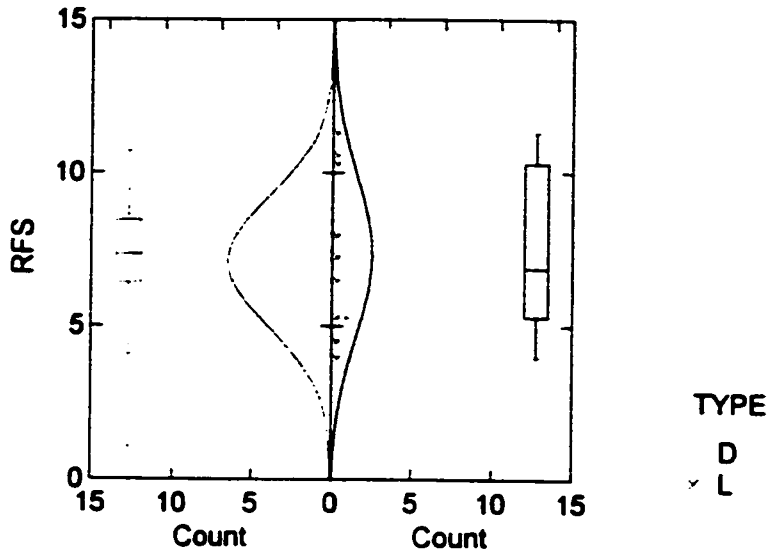


Two-sample t test on RFS grouped by TYPE$

Group	N	Mean	SD
D	21	7.107	2.135
L	10	7.311	2.653

Separate Variance t = -0.212 df = 14.8 Prob = 0.835
Difference in Means = -0.204 95.00% CI = -2.252 to 1.844

Pooled Variance t = -0.230 df = 29 Prob = 0.820
Difference in Means = -0.204 95.00% CI = -2.018 to 1.610

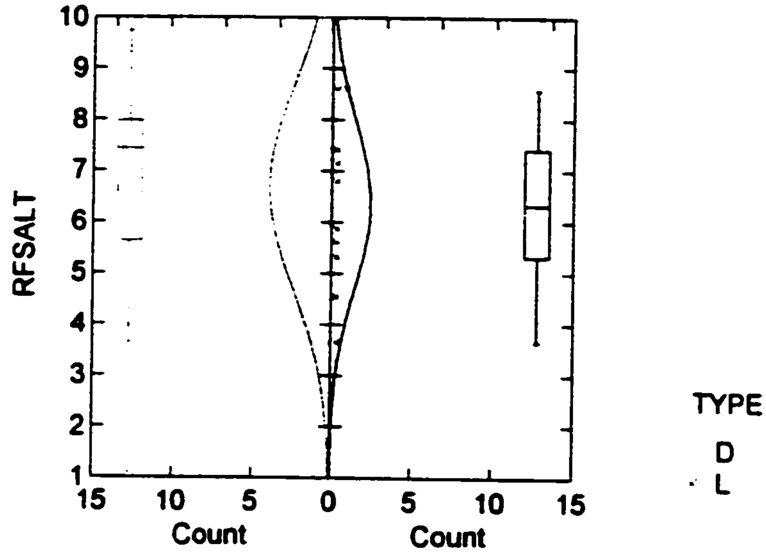


Two-sample t test on RFSALT grouped by TYPE$

Group	N	Mean	SD
D	20	6.695	2.005
L	10	6.351	1.642

Separate Variance t = 0.501 df = 21.7 Prob = 0.621
Difference in Means = 0.344 95.00% CI = -1.080 to 1.768

Pooled Variance t = 0.468 df = 28 Prob = 0.643
Difference in Means = 0.344 95.00% CI = -1.160 to 1.848



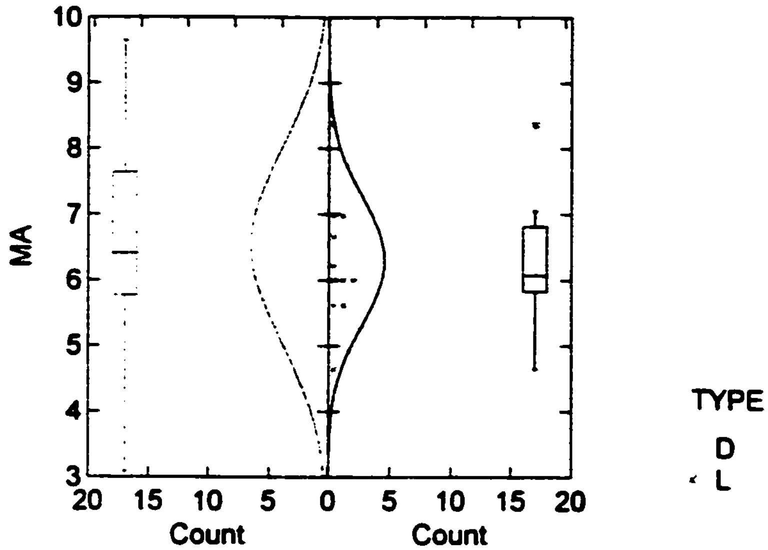
The grouping variable has more than two distinct values.
Only the first two values encountered in the data will be used.

Two-sample t test on MA grouped by TYPE$

Group	N	Mean	SD
D	24	6.531	1.476
L	11	6.295	0.968

Separate Variance t = 0.563 df = 28.6 Prob = 0.578
Difference in Means = 0.236 95.00% CI = -0.622 to 1.095

Pooled Variance t = 0.483 df = 33 Prob = 0.632
Difference in Means = 0.236 95.00% CI = -0.758 to 1.231

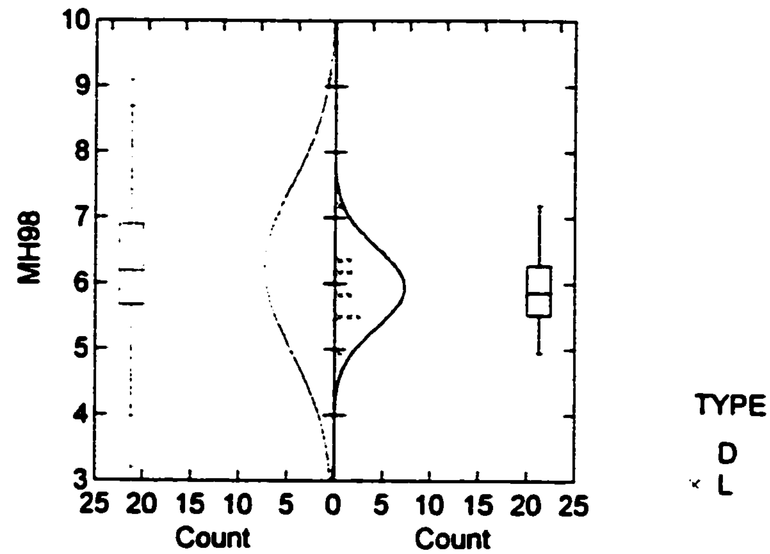


Two-sample t test on MH98 grouped by TYPE$

Group	N	Mean	SD
D	24	6.238	1.300
L	11	5.943	0.601

Separate Variance t = 0.920 df = 33.0 Prob = 0.364
Difference in Means = 0.296 95.00% CI = -0.358 to 0.949

Pooled Variance t = 0.715 df = 33 Prob = 0.479
Difference in Means = 0.296 95.00% CI = -0.545 to 1.136

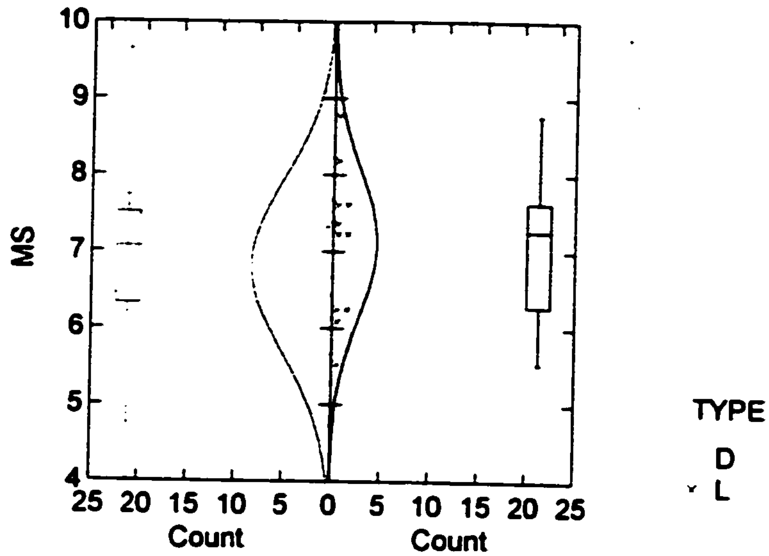


Two-sample t test on MS grouped by TYPE$

Group	N	Mean	SD
D	24	6.817	1.139
L	11	7.110	0.975

Separate Variance t = -0.781 df = 22.6 Prob = 0.443
Difference in Means = -0.293 95.00% CI = -1.068 to 0.483

Pooled Variance t = -0.736 df = 33 Prob = 0.467
Difference in Means = -0.293 95.00% CI = -1.101 to 0.516

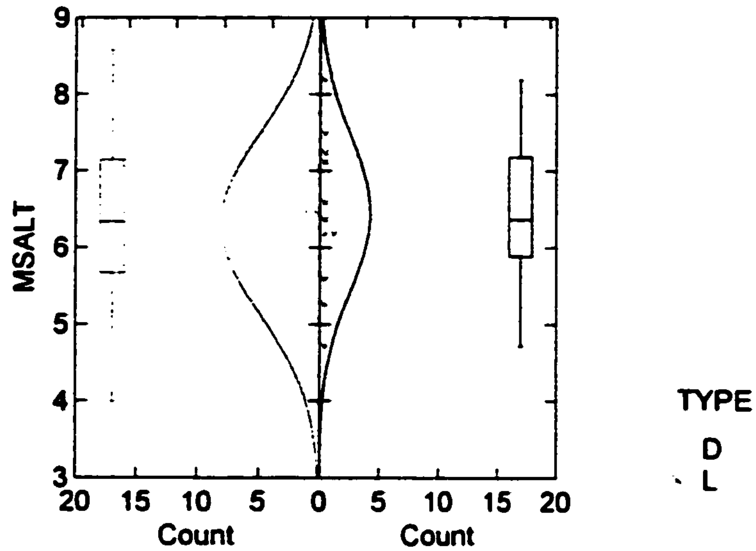


Two-sample t test on MSALT grouped by TYPE$

Group	N	Mean	SD
D	24	6.318	1.182
L	11	6.451	1.026

Separate Variance t = -0.338 df = 22.3 Prob = 0.739
Difference in Means = -0.133 95.00% CI = -0.945 to 0.680

Pooled Variance t = -0.320 df = 33 Prob = 0.751
Difference in Means = -0.133 95.00% CI = -0.975 to 0.710

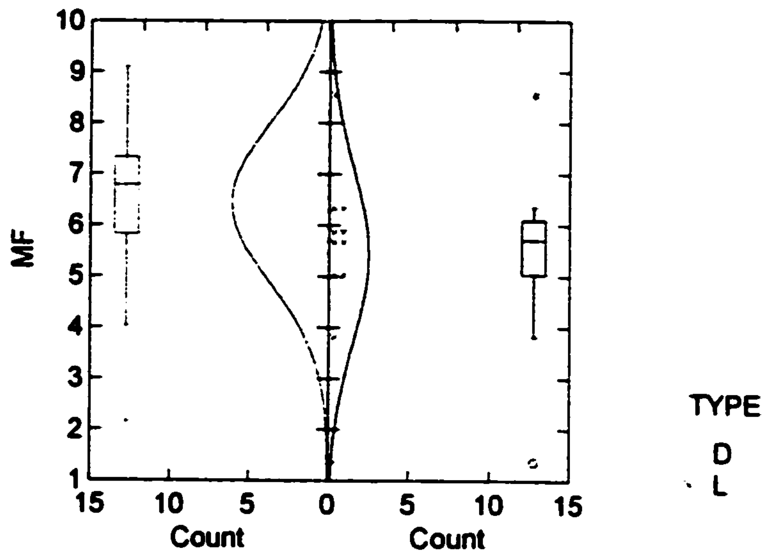


Two-sample t test on MF grouped by TYPE$

Group	N	Mean	SD
D	24	6.445	1.565
L	11	5.408	1.769

Separate Variance t = 1.667 df = 17.5 Prob = 0.113
Difference in Means = 1.036 95.00% CI = -0.273 to 2.345

Pooled Variance t = 1.747 df = 33 Prob = 0.090
Difference in Means = 1.036 95.00% CI = -0.171 to 2.244

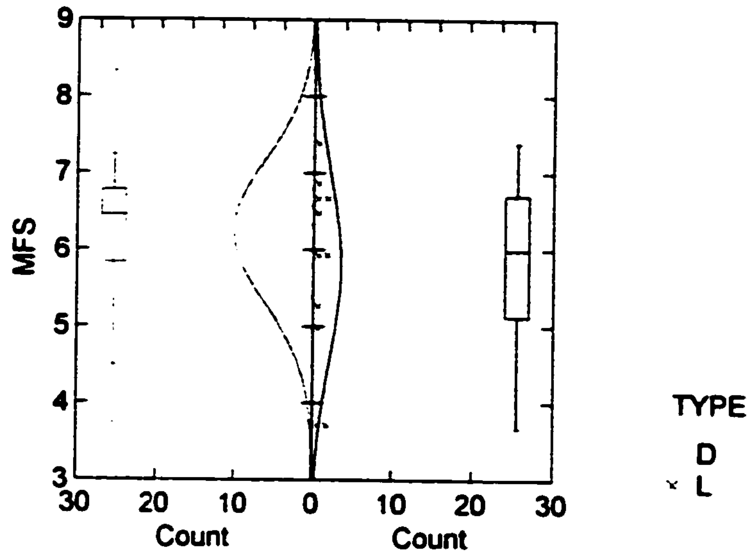


Two-sample t test on MFS grouped by TYPE$

Group	N	Mean	SD
D	24	6.246	0.946
L	11	5.790	1.243

Separate Variance t = 1.082 df = 15.5 Prob = 0.296
Difference in Means = 0.456 95.00% CI = -0.440 to 1.352

Pooled Variance t = 1.199 df = 33 Prob = 0.239
Difference in Means = 0.456 95.00% CI = -0.318 to 1.230

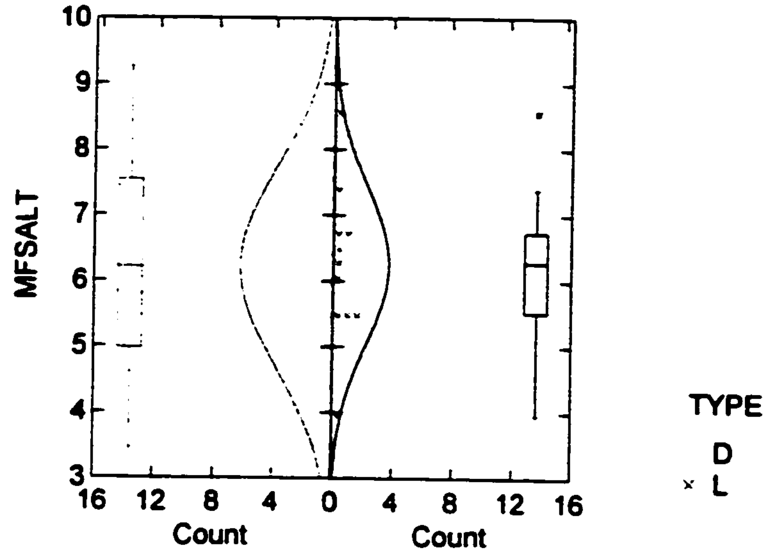


Two-sample t test on MFSALT grouped by TYPE$

Group	N	Mean	SD
D	24	6.221	1.524
L	11	6.245	1.190

Separate Variance t = -0.050 df = 24.6 Prob = 0.961
Difference in Means = -0.024 95.00% CI = -1.002 to 0.955

Pooled Variance t = -0.046 df = 33 Prob = 0.964
Difference in Means = -0.024 95.00% CI = -1.084 to 1.036



10
9
8
7
6
5
4
3
MFSALT
16
12
8
4
0
4
8
12
16
Count
Count
TYPE
D
L

Factor Analysis

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.434	40.163	40.163	8.434	40.163	40.163	6.007	28.604	28.604
2	3.175	15.117	55.280	3.175	15.117	55.280	4.053	19.301	47.905
3	2.075	9.879	65.159	2.075	9.879	65.159	2.546	12.122	60.027
4	1.381	6.574	71.733	1.381	6.574	71.733	2.221	10.577	70.604
5	1.190	5.667	77.400	1.190	5.667	77.400	1.427	6.796	77.400
6	.926	4.411	81.811						
7	.820	3.903	85.714						
8	.586	2.788	88.502						
9	.462	2.202	90.704						
10	.414	1.974	92.678						
11	.371	1.767	94.445						
12	.273	1.298	95.743						
13	.231	1.098	96.841						
14	.223	1.062	97.903						
15	.126	.601	98.504						
16	9.302E-02	.443	98.947						
17	7.756E-02	.369	99.316						
18	7.198E-02	.343	99.659						
19	3.904E-02	.186	99.845						
20	2.347E-02	.112	99.957						
21	9.111E-03	4.339E-02	100.000						

Extraction Method: Principal Component Analysis

Rotated Component Matrix[a]

	Component				
	Aggregate strength	Mortar strength	Mortar porosity	Aggregate porosity	Durability
RA	.909				
RH98	.935				
RS	.876				
RSALT	.852				
RF	.959				
RFS	.814				
RFSALT	.806				
MA		.739			
MH98		.832			
MS		.741			
MSALT		.660		.514	
MF		.429			
MFS				.680	
MFSALT			-.641		
MABS			.895		
MADS			.877		
RABS				-.685	
RADS				-.613	
MAG.TEST					.892
MODULUS		.650			-.478
ULTIMATE		.790			

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

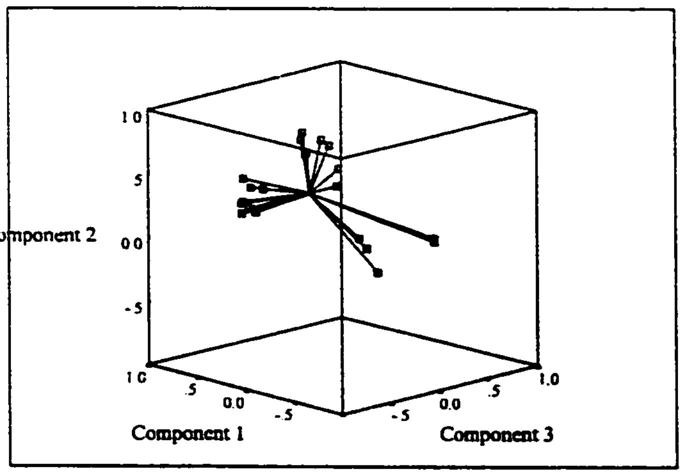
a. Rotation converged in 8 iterations.

Component Transformation Matrix

Component	Aggregate strength	Mortar strength	Mortar porosity	Aggregate strength	Durability
Aggregate strength	.743	.526	-.235	.316	-.128
Mortar strength	.630	-.610	.469	-.095	.050
Mortar porosity	-.187	.324	.763	.514	.115
Aggregate strength	.130	.377	.128	-.542	.729
Durability	.014	.323	.355	-.577	-.661

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Component Plot in Rotated Space



Backward Regression

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	MODULUS, RABS, MABS, RADS, MAG.TEST, MADS[a]	.	Enter
2	.	MABS	Backward (criterion: Probability of F-to-remove >= .100).
3	.	RADS	Backward (criterion: Probability of F-to-remove >= .100).

a. All requested variables entered.

b. Dependent Variable: ULTIMATE

ANOVA[d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.104	6	.184	2.711	.031[a]
	Residual	2.104	31	6.786E-02		
	Total	3.207	37			
2	Regression	1.103	5	.221	3.354	.015[b]
	Residual	2.105	32	6.577E-02		
	Total	3.207	37			
3	Regression	1.088	4	.272	4.237	.007[c]
	Residual	2.119	33	6.421E-02		
	Total	3.207	37			

a. Predictors: (Constant), MODULUS, RABS, MABS, RADS, MAG.TEST, MADS

b. Predictors: (Constant), MODULUS, RABS, RADS, MAG.TEST, MADS

c. Predictors: (Constant), MODULUS, RABS, MAG.TEST, MADS

d. Dependent Variable: ULTIMATE

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.062	.544		1.953	.060
	MABS	-1.551E-02	.125	-.035	-.124	.902
	MADS	-.131	.161	-.232	-.817	.420
	RABS	-8.335E-02	.046	-.283	-1.801	.081
	RADS	-.101	.244	-.065	-.415	.681
	MAG.TEST	5.556E-03	.003	.396	2.197	.036
	MODULUS	.132	.047	.480	2.789	.009
2	(Constant)	1.014	.373		2.715	.011
	MADS	-.148	.086	-.261	-1.733	.093
	RABS	-8.407E-02	.045	-.285	-1.860	.072
	RADS	-.109	.232	-.070	-.469	.643
	MAG.TEST	5.624E-03	.002	.401	2.314	.027
	MODULUS	.132	.046	.479	2.831	.008
3	(Constant)	.978	.361		2.709	.011
	MADS	-.151	.084	-.265	-1.787	.083
	RABS	-8.633E-02	.044	-.293	-1.944	.060
	MAG.TEST	5.637E-03	.002	.402	2.347	.025
	MODULUS	.136	.045	.494	3.009	.005

a. Dependent Variable: ULTIMATE

Excluded Variables[c]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
2	MABS	-.035[a]	-.124	.902	-.022	.268
3	MABS	-.064[b]	-.240	.812	-.042	.287
	RADS	-.070[b]	-.469	.643	-.083	.932

a. Predictors in the Model: (Constant), MODULUS, RABS, RADS, MAG.TEST, MADS

b. Predictors in the Model: (Constant), MODULUS, RABS, MAG.TEST, MADS

c. Dependent Variable: ULTIMATE

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.0585	1.8528	1.4637	.1715	38
Residual	-.4514	.5448	6.077E-16	.2393	38
Std. Predicted Value	-2.362	2.269	.000	1.000	38
Std. Residual	-1.782	2.150	.000	.944	38

a. Dependent Variable: ULTIMATE

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