AN EXPERIMENTAL INVESTIGATION INTO THE RESTORATION OF ANCIENT AND TRADITIONAL MORTARS FOR STACKWALL CONSTRUCTION

by

Randy Leslie Zapototsky

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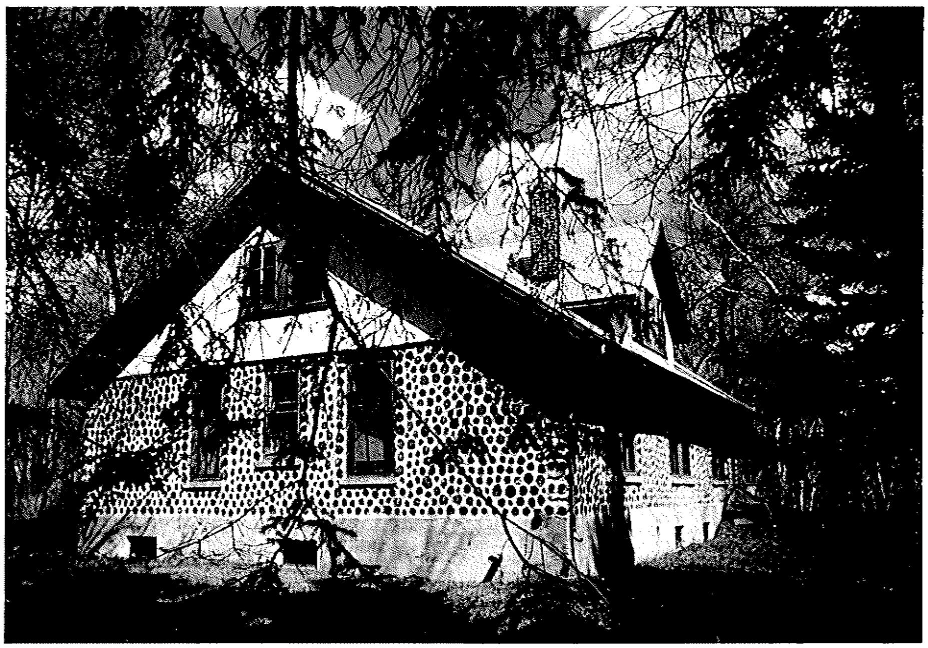

Photograph 1: Stackwall Constructed House

To

The Northern Housing Committee

of

The University of Manitoba

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	- American Association of State Highway Officials
ASTM	- American Society for Testing Materials
C_C	- coefficient of curvature (soil testing)
C_U	- coefficient of uniformity (soil testing)
CH	- inorganic clays of high plasticity, fat clays
CWC	- Canadian Wood Council
cm.	- centimetre
D	- diameter (soil testing)
D_{10}	- effective size/diameter (soil testing)
Disp.	- displacement
d/diam.	- diameter
E_m	- secant modulus of elasticity
E_o	- initial tangent modulus of elasticity
$F_{c\perp}$	- allowable unit stress in compression perpendicular to grain for the appropriate species and grade of wood
$F'_{c\perp}$	- modified allowable unit stress in compression perpendicular to grain for the appropriate species and grade of wood
F_t	- allowable unit stress in tension parallel to grain for the appropriate species and grade of wood
$F_{t\perp}$	- allowable unit stress in tension perpendicular to grain for the appropriate species and grade of wood
$f_{c\perp}$	- compressive stress perpendicular to the grain of wood
f'_m	- laboratory mortar compressive strength

f_t - tensile stress parallel to the grain of wood

$f_{t\perp}$ - tensile stress perpendicular to the grain of wood

$ft.^3$ - cubic feet

G_s - specific gravity of solid particles (soil testing)

g./gm. - gram

H_R - hydrometer reading in centimetres (soil testing)

hr. - hour

hrs. - hours

I_P - plasticity index

in. - inch

K_D - load duration modification factor for wood

K_F - treatment modification factor for wood

$K_{Sc\perp}$ - service condition modification factor for compression perpendicular to grain of wood

kg. - kilogram

L - lime

L.V.D.T. - linear voltage displacement transducer

l - length

lbs. - pounds

m_t - temperature correction (soil testing)

m.c. - moisture content

min. - minute

mins. - minutes

ml. - millilitre

mm. - millimetre

No. - number

n.a. - not applicable

n.d. - not done

P.C. - Portland cement

p. - page

pcf. - pounds per cubic foot

pp. - pages

psi. - pounds per square inch

R - remix

R^2 - coefficient of multiple determination

R_A^2 - adjusted coefficient of multiple determination

R_e - modulus of elastic resilience

R_h - hydrometer reading in specific gravity (soil testing)

S - sand

SP - poorly graded sand with little amount of fines

T - temperature/time (soil testing)

T - modulus of toughness

T' - modified modulus of toughness

t - temperature (soil testing)

Vol. - volume/volumetric

v - velocity (soil testing)

W - weight of dry soil sample (soil testing)

W_s - weight of soil solids (clay) in a moisture content sample

W_w - weight of water in a moisture content sample

w_L - liquid limit

w_P - plastic limit

xstart - experimental correction factor to x-values (computer plotting)

$yd.^3$ - cubic yard

ε	- strain
ε_e	- elastic limit strain
θ	- angle of rupture
θ_c	- angle of rupture of corner fracture
θ_p	- angle of rupture of pyramidal fracture
θ_s	- angle of rupture of splitting fracture
σ	- stress
σ_e	- elastic limit stress
ϕ	- angle of internal friction
ϕ'	- drained shear strength parameter (soils)
+	- plus/add (when used with numbers)
-	- minus/subtract (when used with numbers)
±	- plus or minus
x	- multiply (when used with numbers)
/	- divide (when used with numbers)
=	- equals
≤	- is less than or equal to
°	- degree
°C	- degree(s) centigrade
'	- foot (when used with numbers)
"	- inch (when used with numbers)
%	- percent
$	- dollars (Canadian)

LIST OF DEFINITIONS

Appearance (of Mortar): See Appendix A.

Autogenous Healing (of Mortar): See Appendix A.

Bond (of Mortar): See Appendix A.

Calcination: The act or process of heating (as inorganic materials) to a high temperature but without fusing in order to drive off volatile matter or to effect changes such as oxidation or pulverization.

Calcium Lime: A lime containing from 85 percent to 90 percent calcium oxide and five to 10 percent magnesium oxide.

Carbonization: The process of being combined with carbon.

Cement-Lime Mortar with Sawdust and/or Wood Chips: A mortar of which Portland cement, lime, sand, sawdust and/or wood chips and water are its constituents.

Clay Mortar: A mortar of which clay (usually with silt), sand, fibres, water and hydrated lime (may or may not be present) are its constituents.

Conventional Masonry: Something constructed of materials, such as concrete block/clay brick/stone together with conventional mortar (see definition), by a mason (see definition).

Conventional Mortar: Today's prevailing mortar (see definition) that consists of a mixture of Portland cement, lime, sand and water. Alternatively, an one-bag preparation of masonry cement (see definition) may be used instead of using the separate ingredients of Portland cement and lime. Conventional mortar has a flow of 105 to 115 percent in the flow test.

Durability (of Mortar): See Appendix A.

Economy (of Mortar): See Appendix A.

Efflorescence (of Mortar): See Appendix A.

Elasticity and Flexibility/Internal Accommodation (of Mortar): See Appendix A.

Flax: Flax is a plant with small, narrow leaves, blue flowers, and slender stems about two feet tall (average). Linseed oil is made from its seeds. The thread-like fibres of this plant is used to spin into linen thread.

High Calcium Lime: A lime containing at least 90 percent of calcium oxide and less than five percent magnesium oxide.

High Magnesium Lime: A lime containing not less than 85 percent of calcium and magnesium oxide, not less than 25 percent being magnesium oxide. May be referred to as dolomitic lime.

Hydrated Lime: A dry flocculent powder resulting from the treatment of quicklime (see Appendix E) with sufficient water to satisfy chemically all the calcium oxide present.

Hydraulic Lime: A lime which contains so large a percentage of lime silicate, aluminate or ferrate as to give the material the property of hardening under water, but which at the same time contains so much free lime that the burned mass will slake upon the addition of water.

Lime: Lime is the product resulting from the calcination of a limestone consisting essentially of the carbonates of calcium and magnesium, which slakes upon the addition of water.

Lime-Sand Mortar: A mortar of which lime, sand and water are its constituents.

Magnesium Lime: A lime containing from 85 percent to 90 percent of calcium and magnesium oxides, 10 percent to 25 percent being magnesium oxide.

Mason: A skilled workman who builds up by laying up units of substantial material such as stone or brick.

Masonry: Something constructed by laying up units of substantial material such as stone or brick.

Masonry Cement: An one-bag preparation containing Portland cement and pulverized limestone ($CaCO_3$) or hydrated lime ($Ca(OH)_2$) along with small amounts of soaps, oils or stearates which act as air-entraining agents and plasticizers. The majority of cement manufacturers produce masonry cement which contain approximately equal quantities of Portland cement and pulverized limestone.

Mortar: A plastic building material (example: a mixture of cement, lime, sand and water) that hardens and is used in binding building units of substantial material.

Pozzolana: A finely divided siliceous or siliceous and aluminous material that reacts chemically with slaked lime at ordinary temperature and in the presence of moisture to form a strong slow-hardening cement.

Quicklime: The first solid product that is obtained by calcining limestone (see Appendix E) and that develops great heat and becomes crumbly when treated with water.

Retempering: The restoration of mortar that has been properly mixed but not used immediately, resulting in a loss of its workability (see Appendix A) through loss of water via evaporation and absorption. Restoration is done by adding a small amount of water and throughly remixing. For a Portland cement-lime mortar, under normal conditions, the elapsed time between mixing and use should not exceed two and one-half hours.

Slake (Hydrate): To cause to heat and crumble by treatment of water to form a hydrate; a compound of complex ions formed by the combination of water with some other substance (as with lime).

Soil-Cement Mortar: A mortar of which soil, Portland cement and water are its constituents.

Strength (of Mortar): See Appendix A.

Volumetric Changes/Shrinkage (of Mortar): See Appendix A.

Water Retention (of Mortar): See Appendix A.

Workability (of Mortar): See Appendix A.

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ABSTRACT

All to often a misunderstanding exists in masonry construction in that a mortar is chosen on the basis that "the stronger the mortar is, the better it is". Due to this misunderstanding, the mortar chosen usually has a strength far beyond what is required of the masonry structure and one that is much higher in cost. In terms of strength, the correct phrase to use is <u>adequate</u> strength. Strength is not the only consideration when choosing a mortar; there are a number of other properties, some of which are even more important than strength.

The above misunderstanding is believed to exist with the mortar presently used in stackwall construction; the mortar used is a Portland cement-lime/masonry cement mortar. In order to explore this misunderstanding, an experimental investigation was carried out with 12 clay and 17 lime-sand mortar mixes. The methods used for testing followed CSA Standard A8-1970 -- Masonry Cement, wherever possible; two-inch cube specimens were used in the program.

The composition of materials found the most favourable for a clay mortar was 33.3% sand, 1.75% fibres, 3% hydrated lime, and 140% water, all proportioned by dry weight to one unit of dry clay. As for a lime-sand mortar, with both the

hydrated lime and sand measured in a dry state, the lime:sand volumetric proportion of 1:3 was suggested. Indications were that dried lime-sand mortar can be crushed and remixed. It appears that for such a mortar the ratio of sand to lime should not be greater than two to one, in order that the remixed mortar can develop similar properties to the original.

Room for improvement exists in the case of the clay mortar with respect to its workability and to reduction of its shrinkage upon drying. The high drying shrinkage experienced with the clay mortars suggests that its use in stackwall construction be restricted to the wall portion and prohibited in the corners.

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Chapter I

INTRODUCTION

The Northern Housing Committee of the University of Manitoba, Canada [51],[1] has been involved with the teaching of the construction of stackwall houses since 1975. Stackwall construction consists of short logs 10 to 36 inches in length laid perpendicular to the wall, set in three to four inches of mortar at each end of the logs, leaving a central cavity. With hydrated-lime-treated sawdust packed between the logs in this cavity, a well-insulated wall (insulation value greater than R20) can be created. Figure K-1, page 503 shows a typical cross-section of stackwall. A house constructed by the stackwall method is pictured in Photograph 1, page iv.

This type of house construction provides a labour-intensive alternative construction technique for houses in remote communities lacking development. The construction technique does not threaten the environment; the material (logs) is locally available; the cost is less than that to import graded lumber to remote places; the design layout of a house is just as flexible as a conventional house; it requires relatively unskilled labour; and it is energy effi-

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[1] The number(s) in square parenthesis indicate reference(s) used in the text.

cient during the cold winter months.

The mortar used in stackwall construction consists of the same material that are used today in brick/concrete block masonry. These materials are: Portland cement, lime, sand and water. In place of the Portland cement and lime, masonry cement is an alternative. Depending upon the area of construction, the mortar can be one of the most costly and/or unavailable materials in constructing a stackwall house. To further improve the accessibility of stackwall houses in remote communities, the idea of using a lower cost mortar and one that is more readily accessible is being explored by the Northern Housing Committee. The material used for such a mortar should be non-toxic, it should be environmentally safe to use, and it should be easy to work with for both amateur and professional builders.

This work examines the use of ancient and traditional mortars as possible alternatives in terms of local economics and availability. The two types of mortar investigated were: 1) clay mortar, and 2) lime-sand mortar. In spite of today's rapid-pace technology and vast information networks, technical information on ancient and traditional mortars, especially clay mortars, is scarce. To develop this information, this investigation was undertaken to explore variation of mortar properties as constituents were systemically varied in the laboratory. No attempt was made to evaluate clay and lime-sand mortars under field conditions.

The study starts off with a preliminary literature search on four types of mortars: 1) clay mortar; 2) lime-sand mortar; 3) soil-cement mortar; and 4) cement-lime mortar containing sawdust and/or wood chips. From this literature search, it was decided to undertake experimental work only on the first two types. This work involved 12 clay, and 17 lime-sand mortar mixes. For each of the mixes, the volumetric shrinkage, the surface characteristics and the compressive strength and failure characteristics were obtained. The investigation continues with analyses from the testing program, and concludes with a discussion of the results.

Chapter II

OBJECTIVE

Within this study, the most favourable constituents and proportions in a clay and in a lime-sand mortar mix were sought.

The essential mortar properties kept in mind throughout this search were: 1) workability, 2) water retention, 3) bond, 4) strength, 5) autogenous healing, 6) elasticity and flexibility (internal accommodation), 7) efflorescence, 8) durability, 9) volumetric changes (shrinkage), 10) economy, and 11) appearance. These properties are discussed in detail in Appendix A.

The testing of all 29 mortar mixes was done according to CSA Standard A8-1970, Masonry Cement [15], so as to use reconized experimental procedures. Deviations, however, were required, particularly when working with the non-standardized clay mortar and when obtaining the proper flow for the lime-sand mortar mixes. Omission of some tests outlined in this Standard was due to the limitations of the work and availability of equipment. All compression tests were done on two-inch cubes.

Chapter III

THE PROGRAMME

Initially, four different types of mortar were proposed for investigation towards a lower-cost and more readily accessible mortar for stackwall construction. These were: 1) clay mortar, 2) lime-sand mortar, 3) soil-cement mortar, and 4) cement-lime mortar containing sawdust and/or wood chips. A preliminary literature search was performed on each type. From this, it was decided to investigate only the clay and the lime-sand mortars. Although no experimental work was performed with the other two types of mortar, the preliminary investigative information on them is presented.

3.1 CLAY MORTAR

The term "clay mortar" as used throughout this report is defined as a mortar containing clay (usually with silt), sand, fibres, water and in some tests hydrated lime.

3.1.1 Preliminary Literature Search

A preliminary literature search directly and partially related to clay mortar was performed to provide direction for the experimental work. In particular, the materials required, the proportion of these materials and the preparatory work required was sought.

In Fathy's [34] work with mud bricks in Egypt, the four necessary components for a good mud brick were: 1) earth; 2) sand; 3) straw; and 4) water. The following material composition gave the best results: one cubic metre of earth, one-third cubic metre of sand and 45 pounds of straw. Another criterion of at least 30 percent (assumed to be in proportion by total volume) of straw is mentioned by Fathy [34]; without the straw, the bricks were noted to crack. In Egypt, the above mixture was found to give a brick that did not shrink excessively -- Egypt's earth can have a volumetric shrinkage up to 37 percent.

The above mixture of earth, sand and straw was allowed to soak and ferment in water for at least 48 hours before being formed into bricks. This fermentation produced lactic acids that made the bricks stronger and less absorbent than those more hastily made. Also during fermentation, the straw mixed with the earth so that the brick gained a highly desirable homogeneity of texture that an unfermented one did not have. To minimize the amount of shrinkage in these mud bricks, the minimal amount of water was recommended by Fathy [34].

Protection against wet-dry cycles with mud bricks was considered essential to the longevity of a building; seepage from below had to be prevented with a damp-proof course and the bricks protected by a waterproof plaster made of bitumen-stabilized earth. Fathy [34] also mentioned the use of cow dung as an ingredient of mud brick; fermented over a long period of time, the cow dung together with the straw was said to produce a brick that resisted water well. However, the use of cow dung as part of a building material may be questionable in some societies.

Fathy [34] also presented some experimental work on mud bricks that was performed by Colonel Debe at Cairo University, Egypt. In one set of experiments, four different kinds of sand were used: 1) fine, 2) small, 3) medium, and 4) large. The percentages of sand experimented with was 20, 40, 60 and 80 percent. These figures are assumed to be proportioned by weight with respect to the amount of soil used. From this set of tests, the strength of the brick decreased as one goes from the fine to the large sand and as one increased the amount of sand from 20 to 80 percent.

In a second series of tests, only one kind of sand was used at three different percentages, 5, 20 and 40 percent. Fibres in the form of straw at 1.0, 1.75, 2.5 and 5.0 percent were investigated with each of the percentages of sand. Again, both the sand and fibre were assumed to of been proportioned by weight with respect to the amount of soil used. The general trend of the strength tests was that as the proportion of sand was increased, an increase in proportion of straw fibres was needed to obtain the highest strength. At 5, 20 and 40 percent sand, the highest strength was obtained at 1.0, 1.75 and 2.5 percent straw respectively. This series of tests also indicated that if one is to add more straw fibres than the optimum level, the strength decreases. The average crushing load of mud brick samples tested at Cairo University was 425 pounds per square inch.

Ellis [61] states that lime can be used with a raw (unprocessed) clay to increase its strength and to stabilize it against shrinkage and swelling. The increase in strength, as explained by Ellis [61], is immediately attained due to an ion exchange in which calcium ions reduce the forces that hold the film of water around the clay particles. Secondary strength is gained slowly through a chemical hardening process in which hydrated calcium silicates and aluminates are formed; the calcium comes from the lime while the silica and alumina are from the clay.

Lime stabilizes the clay by reducing the plasticity index. Reduction of the plasticity index is accomplished by lowering the liquid limit and raising the plastic limit of the clay. For lime to be fully reactive with the clay, it must be pulverized. Ellis [61] advises that the optimum lime content to add to a clay is often between three and six percent. These percentages were assumed to be by weight and with respect to the weight of the clay material used.

Tallin and Raban [63] did an investigation into the use of clay mortar for stackwall construction at the University of Manitoba. In this work, five materials were used as possible components of a clay mortar. The five materials were: 1) clay, 2) sand, 3) grass fibres, 4) lime, and 5) water.

In the preparation of the materials, Tallin and Raban [63] oven dried and ground the clay to 100 percent passing the No. 4 sieve. The mortar sand was in a damp, loose state. The grass had an average diameter of one-half millimetre and was cut into one- to two-inch lengths. In the mix, the grass was allowed to ferment in the wet mix for five days in a covered container. Six different combinations of these materials were mixed by dry volumetric proportions and tested for various properties. Out of these combinations, a mix with 6 parts clay, 4 parts sand, 8 parts grass fibres, 3.6 parts water and no lime was found to be the most suitable with regard to the strength, workability and shrinkage properties.

Continuing the work of Tallin and Raban [63] at the same university, Schollenberg [58] did a further investigation into the use of a clay-based mortar for stackwall construction. With Schollenberg [58], the clay was also oven dried but it was pulverized finer -- to 100 percent passing the No. 40 sieve. The sand was in a dry loose state. The grass used as fibres was cut into one- to three-inch lengths. Instead of five days fermentation in covered containers, Schollenberg [58] allowed seven days of fermentation in the moisture room. Also using volumetric proportions of dry materials, Schollenberg [58] found that the most desirable mix to be the same as that for Tallin and Raban [63] with exception to the water; 5.1 parts of water was used instead of 3.6 parts. Schollenberg [58] also recommends that a fine sand be used for a clay mortar.

To act as a guide on how to use fibres in a clay mortar mix, a literature search on how fibres are used in fibre reinforced concrete was examined through Reference Nos. 8, 41, 42, 55 and 59. The first problem that occurred with the mixing of fibre reinforced concrete was the segregation or balling of the fibres, creating a non-uniform mix. Factors found to influence the segregation or balling of the fibres during the mixing process are:

1. the aspect ratio (length/diameter or l/d) of the fibres,
2. the volumetric percentage of fibres,
3. the coarse aggregate size and quantity,
4. the gradation of fibres,
5. the water-cement ratio, and
6. the method of mixing.

An increase in Factor Nos. 1, 2, and 3 intensifies balling tendencies.

Corresponding to the above points, for a steel fibre reinforced concrete to have a uniform mix, it was found that:

1. the aspect ratio of the steel fibres should be as low as possible and not exceed the value of 100;
2. the volumetric percentage of the steel fibres should not exceed two percent (30 percent with glass fibres); higher percentages are difficult to mix and increases the slump;
3. the size of aggregate used in a mix should be less than or equal to three-eights of an inch for workability and spacing requirements;
4. the quality of the material used as fibres should be adequate in terms of strength;
5. the water-cement ratio should be kept between 0.4 and 0.6 for the proper plasticity of the mix and the dispersion of the fibres; and
6. the steel fibres should be shaken slowly into the mix, more so if the aspect ratio is high.

From Reference No. 55 it was learned that as the steel fibre aspect ratio was reduced to decrease the balling effect, the flexural strength also reduced. To solve this problem, the fibres were bundled, increasing the diameter, with a water soluble glue. This gave a lower aspect ratio, say 30, for the initial mixing, to prevent balling of the fibres. When the mixing was finished, the individual fibres were unglued and well distributed. Since the fibres are individual in the final product, this created an increase in the aspect ratio, to say 100, and thus an increase in the flexural strength of the mix.

Steel fibres come in various types. For the straight fibres, the rate used in one study [Reference No. 55] was 140 pounds of fibres (with a l/d of 60) to one cubic yard of concrete. Assuming that the concrete weighed 150 pounds per cubic foot, this would mean that the percentage of fibres used by weight was 3.5 percent to the weight of concrete used.

The information presented in the above preliminary literature search was used to determine the kind of materials and the range of proportions to use in making a clay mortar. This information was applied to the experimental program.

3.1.2 **The Materials and their Proportions Used**

Guided by the preliminary literature search and the need to satisfy the properties for a good quality mortar listed in Appendix A, five types of materials were used in the clay mortar experimental program. The materials were: 1) clay (containing some silt), 2) sand, 3) fibres, 4) lime, and 5) water. Also through the guidance of the preliminary literature search, various combinations of these materials were mixed together so as to find what effect each type of material had. This was done by keeping all the materials but the material in study in constant proportion in any given set of mixes.

In the clay mortar program, the material quantities were proportioned by weight. The amount of material used was expressed as a percentage of the amount of clay (dry solids weight) used. In each case, the amount of clay used was taken as unity. If needed, at the completion of the tests, the recommended proportion of each type of material can be converted to an equivalent volumetric proportion. Volumetric measurement may be more applicable for field construction use. Since the degree of filling a container can differ, especially for clay and fibres, a single conversion may not be valid. Personalized conversion factors would be required.

3.1.2.1 Clay

The term clay as used throughout this investigation was taken as a soil which is mostly composed of clay with some silt. Appendix B gives more detail of the clays used in this program.

The primary intention of using clay as the main constituent of a mortar for stackwall construction was to provide a mortar that is low in cost and more readily accessible, especially in remote situations. With these characteristics, partial fulfillment of the property of economy is provided.

It is known in the field of soil mechanics that clay has the characteristics of releasing its attained moisture slowly due to its grain structure composition upon drying out. This was seen as a means of providing a supply of water for chemical reaction over a long period of time.

Clay also has the qualities of cohesion and of being able to withstand compressive loads up to a certain degree, possibly satisfying the respective properties of bond and strength (compressive, tensile and transverse). Relative to a cement mortar, clay was foreseen to have a more modest but presumably adequate strength and to be lower in density and rigidity. With these relative qualities, the clay mortar should then have adequate elasticity and flexibility for stackwall construction.

On the negative side, clay's property of high cohesiveness presents a problem of low workability in terms of mortar. Also, clay alone undergoes volumetric changes as the result of changes in moisture. An increase in clay moisture is accompanied by swelling and a decrease is accompanied by shrinkage.

Depending upon the composition of the clay used, efflorescence may or may not present a problem (see Appendix A). The mortar property of autogenous healing was presumably to be non-existant in clay alone.

The property of durability of a clay mortar is another question of importance but this question is beyond the scope of this thesis. No problems were foreseen with the property of appearance of a clay mortar.

The clay used came from the southwest part of Winnipeg, Manitoba. This material had been previously dug up about six months prior to the start of mixing and stored in sealed heavy plastic bags. Clay from two different bags had to be used to complete the volume of testing. Clay from the first bag, designated as Soil No. 1, was used for Mix Nos. 1 to 5 while the second bag, designated as Soil No. 2, was used for Mix Nos. 6 to 11.

Although the clays came from the same area and depths of 1 to a maximum of 10 feet, but from different boreholes, soil property testing was carried out on both samples. The tests showed both of the soil samples to be a silty clay with a plasticity index of approximately 50 percent. For a complete summary of the soil testing done, see Appendix B. In general, the two soils were shown to have only slight variations in the properties tested.

Clay was intended to be the main constituent of a clay mortar. The weight of clay used in each mix was always taken as unity; this weight was the weight of the dry solids only, excluding the moisture. The materials other than the clay were taken as a percentage of the dry clay weight.

3.1.2.2 Sand

Apart from the mention of sand in the preliminary literature search, the use of sand in this work was first anticipated to improve the workability of clay as a mortar. The improvement should be obtained from the fact that sand has no cohesion (little tendency to stick together) and that the particles are usually rounded or sub-angular rock fragments that may act like little ball bearings.

Sand was also introduced into the mix in the hope of improving clay's poor mortar property of large volumetric changes. In reference to conventional cement-lime mortars, the sand should be well-graded[2] to minimize shrinkage [57, p. 231]. Also, the more sand that is used in a conventional mortar, the more the initial shrinkage, the later drying shrinkage and the volume changes are reduced [68, p. 18].

Directed by the preliminary literature search for a clay mortar and by the above considerations, the finest (in terms of particle size) sand available in the laboratory was used. The sand was always in a dry state with no measurable moisture content. Soil testing done on the sand indicated that it was a poorly-graded[3] sand with little fines. For a complete summary of the testing done on the sand, see Appendix C.

In the sand study, the proportions of sand examined were 20, 33.3, 45 and 60 percent. These percentages are related to the total dry weight of clay solids in the mix. Sand was used throughout all of the mixes.

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[2] Well-graded was used in Reference 57 in the geological sense i.e. it is soil material of predominantly one size or of a range of sizes with some intermediate sizes missing.

[3] Poorly-graded is used in this thesis in terms of soil testing i.e. it is soil material predominantly of one size or a range of sizes with some intermediate sizes missing.

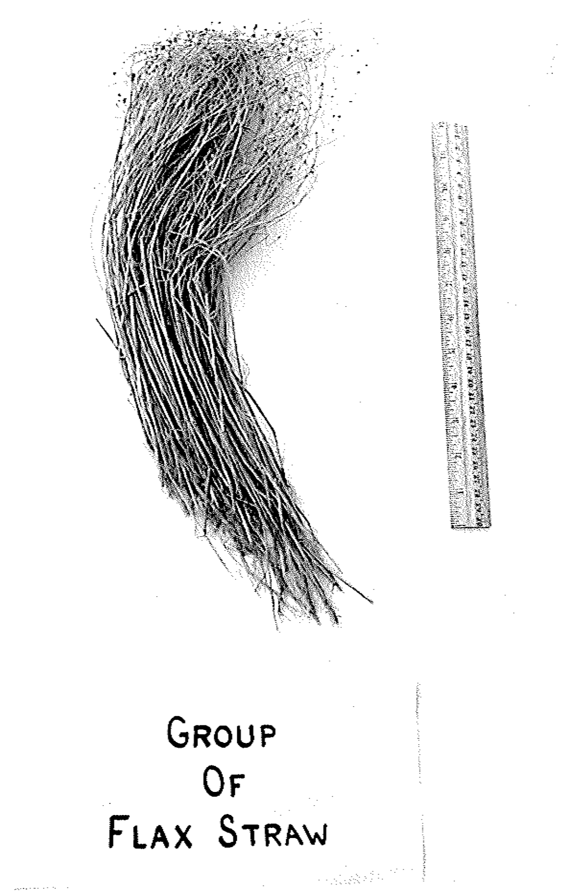
3.1.2.3 Fibres

Fibres have been used to strengthen a weaker matrix for many centuries. For clay mortar, fibre was seen to be needed as a binding agent or to act as a stabilizer for the clay with the sand. In addition it was looked upon as possibly bringing about positive changes to the properties of strength, elasticity and flexibility, durability and volumetric changes.

The possibility of improving the strength, elasticity and flexibility and durability stems from the literature [8, 41, 42, 55, 59] on fibre reinforced concrete. In addition, research [8, 41, 42, 55, 59] in fibre reinforced concrete have shown the concrete to have: 1) crack arresting properties, and 2) higher toughness (better energy absorption capacity).

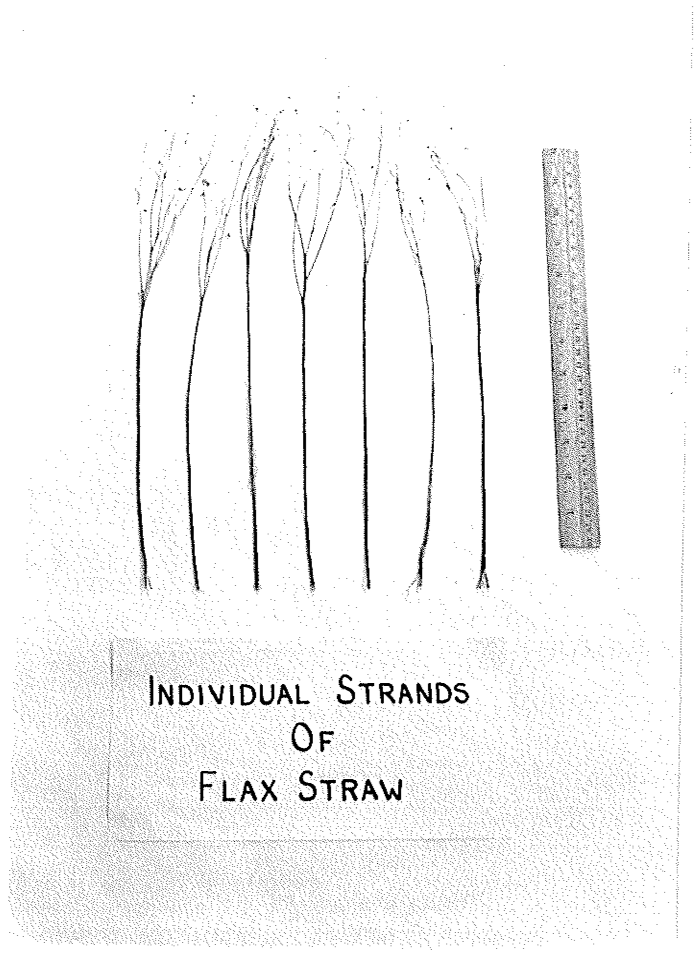
The preliminary literature search done on clay used as a building material indicated that if no form of fibres is present, excessive volumetric shrinkage along with bad cracking would take place during and after the drying process of the mortar.

Flax straw (see Definitions -- "flax") was used as the source of fibres. A group of flax straw is illustrated in Photograph 2; individual strands of flax straw composing such a group is shown in Photograph 3. Flax straw has the characteristic of not decomposing easily whereas cereal grain straw or hay (dried grass) does; this is a positive aspect with respect to the property of durability. The oilseed flax has been under cultivation from prehistoric time and is still today. Flax straw can become readily



Photograph 2: Group of Flax Straw

available wherever grain farming takes place.



Photograph 3: Individual Strands of Flax Straw

Obtainable from the flax straw, by a process known as dewetting, are threadlike fibres commercially used to make linen cloth. These fibres are remarkable for their fine texture, great strength and durability. In this thesis, the word "fibres" will be used synonymously for the term "flax straw". Appendix D takes a look at some of the characteristics of the flax straw used.

In the fibre study, the proportion of fibre (flax straw) used in the experiments was 1.0, 1.75, 2.5 and 5.0 percent. These figures are percentages of the total dry weight of clay solids in the mix. Fibres were used throughout all of the mixes.

3.1.2.4 Lime

"Tested by time" -- (National Lime Association), lime in conventional mortars has been shown to bring out the good of all the essential properties of a good quality mortar listed in Appendix A. Although the strength decreases as the amount of lime is increased, adequate strength rather than higher strength should be sought.

Lime was incorporated in the clay mortar in anticipation that it would bring out the same positive effects as it does in a conventional mortar, or at least to improve the properties that clay alone lacked as a mortar (see Article 3.1.2.1, Clay).

In particular, lime could chemically bring about the property of autogenous healing (see Appendix E). Lime's capability of chemically stabilizing clay could mean that clay mortar may become stabilized against shrinkage and swelling (volumetric changes). This chemical reaction would also harden the clay through a complex cementing reaction.

Throughout the clay mortar testing a high-calcium hydrated (slaked) lime, Brand A (see Appendix E for details) was used. In the lime study, the proportion of lime used in the experiments was 0.0, 3.0, 4.5, 6.0 and 8.0 percent. These percentages refer to the total dry weight of clay solids in the mix.

3.1.2.5 Water

The purpose of using water with the clay mortar was to improve the property of workability. At the same time, the amount of water used was to be kept to a minimum since clay expands when wetted and shrinks when it dries. From this, the mixes were stiffer (less workable) than a conventional mortar (105 to 115% flow), but to the point where it was felt to be workable enough to use in stackwall construction.

The source of water came from the cold water tap of the laboratory which in turn is supplied by the city of Winnipeg, Manitoba.

The amount of water added within each sets of tests and from set to set was so as to make the workability about the same throughout. The amount of water in the clay mixes was expressed as the moisture content (abbreviated as m.c.), reported as a percentage of the total dry weight of clay solids in the mix.

3.1.3 Procedure

In the clay mortar testing program, 11 different mixes were prepared, moulded and tested. An extra mix was created with Mix No. 5 by moulding a second set of specimens which were moisture cured; this set of specimens was counted as the twelfth mix. From these mixes, four different studies were derived. The studies were: 1) lime study, 2) sand study, 3) fibre study, and 4) moisture curing study. Based on the proportions tested, the purpose of the lime, sand and fibre studies was to determine which proportions would be most favourable for a clay mortar. The purpose of the moisture curing study was to find the effects of moisture curing a mix as compared to the same mix that was air-dried; moisture curing involved the first two weeks of drying in the moisture room and the last two weeks in the laboratory air.

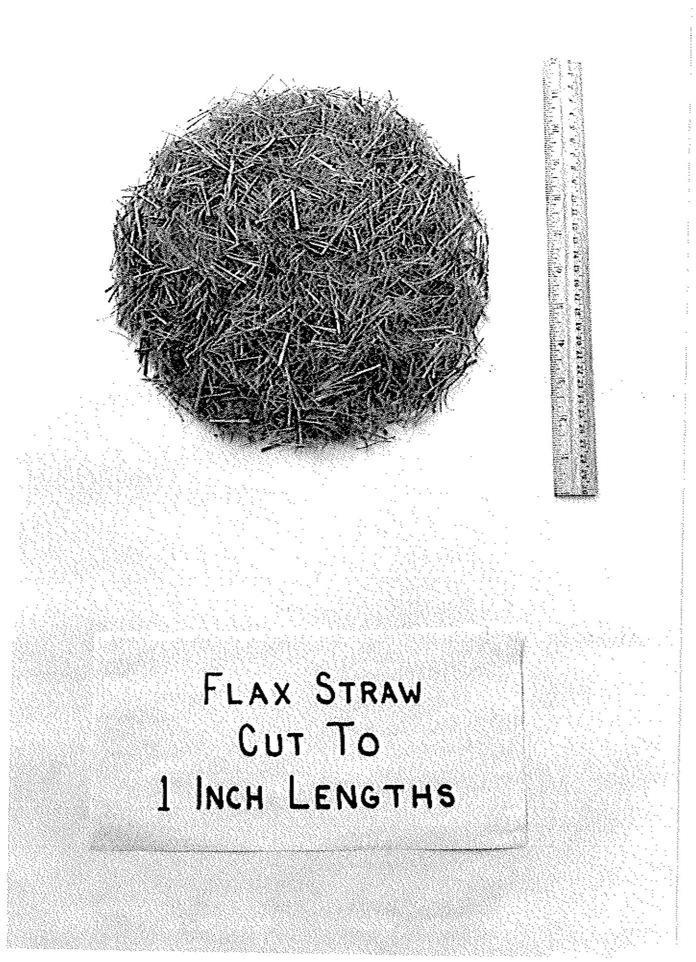
3.1.3.1 Preparation of the Materials

Since the objective of studying a clay mortar was to create an on-hand material that would be convenient to use in construction, the preparation of the materials was kept as simple as possible. This meant that as little as possible was done to the individual materials before weighing and incorporating them into the mix. The reason for this was to simulate a remote area as closely as possible and hence involve as little technical equipment as possible.

Of the five materials used to make a clay mortar, only the flax straw/fibres needed preparation before it was used in the mix. Flax straw, depending on the variety and how it is cut in the field, comes in various lengths. Assuming an average cut length of about 20 inches, this length was definitely too long to use in a mortar. In addition, the mortar test specimens were to be two-inch cubes which would indicate that the maximum allowable length should be limited to around one and one-half inches to prevent problems during the moulding procedure.

To determine what length of flax straw/fibres to use, an aspect ratio (length to diameter -- l/d) study was carried out and reported in Appendix D. From this study, it was decided to use a length of one inch, producing an average aspect ratio of 18. Hence, preparatory work was involved to cut the flax straw/fibres to one-inch lengths (Photograph 4). Of the methods tried, the most favourable method for this work was simply the use of a sharp pair of household scissors. See Appendix D for further details on the preparation of the flax straw/fibres.

The clay was used as if it had just been dug out of the ground (Photograph 5, page 26). In the laboratory situation, this was accomplished by keeping the clay in thick plastic bags to preserve the natural moisture content. The moisture content of the clay itself was taken at regular intervals so as to keep track of the initial amount of water



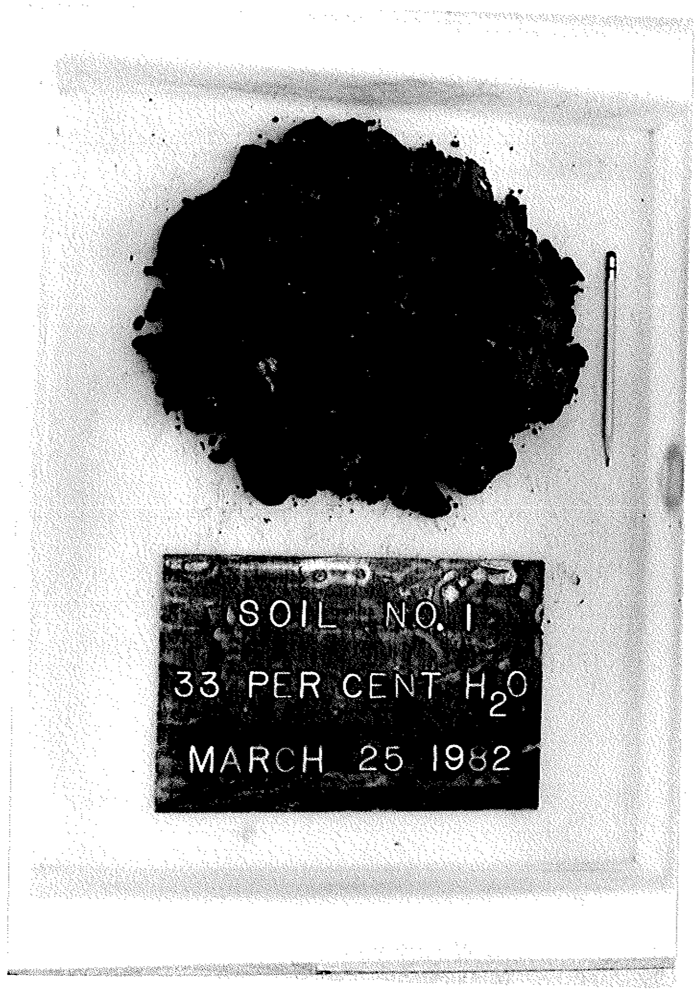
Photograph 4: Flax Straw Cut to One-Inch Lengths

in a mix. It was foreseen to be beneficial to prevent the clay from drying out as it would become very stiff, making it difficult to form into a workable paste with the other components. The sand, lime and water were also used in the mixes without any preparation.

3.1.3.2 Mixing and Moulding

The procedure used in mixing and moulding the clay mortar test specimens was followed closely from mix to mix. Following are the steps used:

1. Set up the mixing apparatus, which consisted of a plastic mixing tray, a cast iron pestle (one used in soil testing for breaking up the aggregations of soil particles -- see Photograph B-1, page 297), a mortar trowel and a metal scraper to do the mixing.
2. Weigh enough proportioned materials (clay, sand, fibres and estimated water) to make approximately five, two-inch cube specimens (two more than required).
3. Start out mixing by placing all of the measured clay into the mixing pan (Photograph 5, shows Clay No. 1 at this stage; Clay No. 2 was similar in appearance).
4. Gradually mix in all of the dry sand with enough water to blend it with the clay.
5. Ram the mixture in Step No. 4 throughly three times with the pestle to make it free of soil aggregations.
6. Gradually mix in the fibres (flax straw) along with more water. The mix at this stage, which is to be fermented later, was allowed to be stiff; while mixing, adequate workability at this point was determined when furrowing with the mortar trowel was possible with about three times the effort as it is with



Photograph 5: Soil (Clay No. 1) as it was Introduced into a Clay Mortar Mix

a conventional mortar[4] (see Definitions). In this study, the moisture content at this point was between 90 and 110 percent.

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[4] Conventional mortar has a flow of 105 to 115 percent in the flow test.

7. Mix throughly the mixture with the pestle and/or mortar trowel for 10 minutes to make the mix uniform and to help break down the individual fibres from the flax straw (Photograph 6, shows clay mortar Mix No. 2

Photograph 6: Clay Mortar Mix No. 2 without Lime Prior to Fermentation

at this stage).

8. Let the mixture in Step No. 7 ferment in a sealed plastic container for at least 48 hours, room temperature.

9. Repeat Step No. 1.

10. If no lime were to be added to the mix, proceed to Step No. 12.
11. Weigh out the required proportion of lime and an estimated amount of water that would be needed to blend the dry lime with the fermented mix.
12. Put the fermented mix into the plastic mixing tray.
13. If no lime were to be added to the mix, proceed to Step No. 15.
14. Gradually add all of the lime to the fermented mix; at the same time, enough water is added so that at the end, furrowing with the mortar trowel was possible with about twice the effort as it is with a conventional mortar (see Definitions).
15. Finish mixing the mixture throughly with the mortar trowel and/or pestle for 10 minutes (Photograph 7, shows clay mortar Mix No. 2 furrowed at this stage).
16. Proceed with the flow test (Photograph 8, shows clay mortar Mix No. 2 with a resultant flow of 53 percent). The flow test was done following the procedure given in CSA Standard A8-1970, Masonry Cement, Section 7.9, Determination of Flow of Mortars [15]. Given the laboratory facilities, however, some deviations were necessary; these changes are discussed later.
17. Mould 3 two-inch cube test specimens following the procedure specified in CSA Standard A8-1970, Masonry Cement, Section 7.11, Determination of Compressive

Photograph 7: Clay Mortar Mix No. 2 with Lime After Being Furrowed

Strength, Subsections 7.11.1 to 7.11.5 [15]. Due to the nature of the clay mortar however, some deviations were made; these changes are discussed later.

Step No. 8 specified the mixture should ferment for at least 48 hours. Actual fermentation period of each mix is listed in Table I. Mix No. 8 had the shortest fermentation period at 59 hours while Mix No. 6 had the longest at 117 hours. The average fermentation period of all the clay mortar mixes was 79 hours or approximately three days.

Photograph 8: Clay Mortar Mix No. 2 with Lime After Flow Test -- 53% Flow

With respect to Step No. 16, compromising changes were made to the flow test since the flow table and the accessory apparatus for testing the flow of mortar were not available in the laboratory. Instead, the flow table used in concrete testing was utilized. The basic difference between the two tables is that the mortar flow table has a table top diameter of 10 inches and a thickness of 0.3 inch while the concrete flow table has a top diameter of 30 inches and a measured thickness of 0.34 inch. From the difference in size, it was assumed that the concrete flow table also weighed

Table I

Fermentation Period of Clay Mortar Mixes

Mix No.	Fermentation Period (hours)
1	72
2	71
3	70
4	67
5	84
6	117
7	60
8	59
9	77
10	89
11	98
Average	79

more than the required nine-pound mortar flow table. Also, the top of the concrete flow table did not have scribe lines or meet the requirement of being free of surface defects.

Also not available, was the mortar flow table mould detailed in Subsection 7.9.2 of CSA Standard A8-1970, Masonry Cement [15]. The mould used instead was the top part of a Proctor compaction unit that is used in soil testing laboratories for compaction tests. Detail dimensions of this mould is shown in Figure 1. The dimensions of the two moulds are similar except the non-standard mould used does not taper to the top dimension of 2.75 inches. Instead the diameter of the mould remains constant at 4.0 inches. Height of the non-standard mould is also one-eighth of an inch higher than the standard mould.

Also, the standard mould is made of bronze or brass and the weight is specified to be less than two pounds in Subsection 7.9.2 of CSA A8-1970 [15] and at the same time is shown to have a minimum weight of two pounds [15, p. 31]. With the non-standard mould, the material was steel and it weighed 2.45 pounds. To measure the flow, a ruler marked in sixteenths of an inch was used in place of the flow table caliper stipulated in Subsection 7.9.3 of CSA A8-1970 [15]. Photograph 9 shows the flow test table and equipment with the non-standard mould.

With respect to Articles 7.9.5.1 and 7.9.5.2 of CSA A8-1970 [15], each of the two layers of mortar placed in the flow table mould should be tamped 20 times. Due to the designed lower workability of the clay mortar, the larger top area of the mould and the possible formation of a two-planed packed mass [63, p. 3], each layer was instead tamped 80 times so as to ensure uniform filling of the mould. After the second layer was tamped, the excess mortar was cut off to a plane surface; this was accomplished by moving a piece of Plexiglas (sized so as to fit the slot on top of the mould -- see Figure 1, page 33) in a circular motion. As mentioned earlier, procedure was varied from Articles 7.9.5.3 and 7.9.5.4 of CSA A8-1970 [15], in that flow was

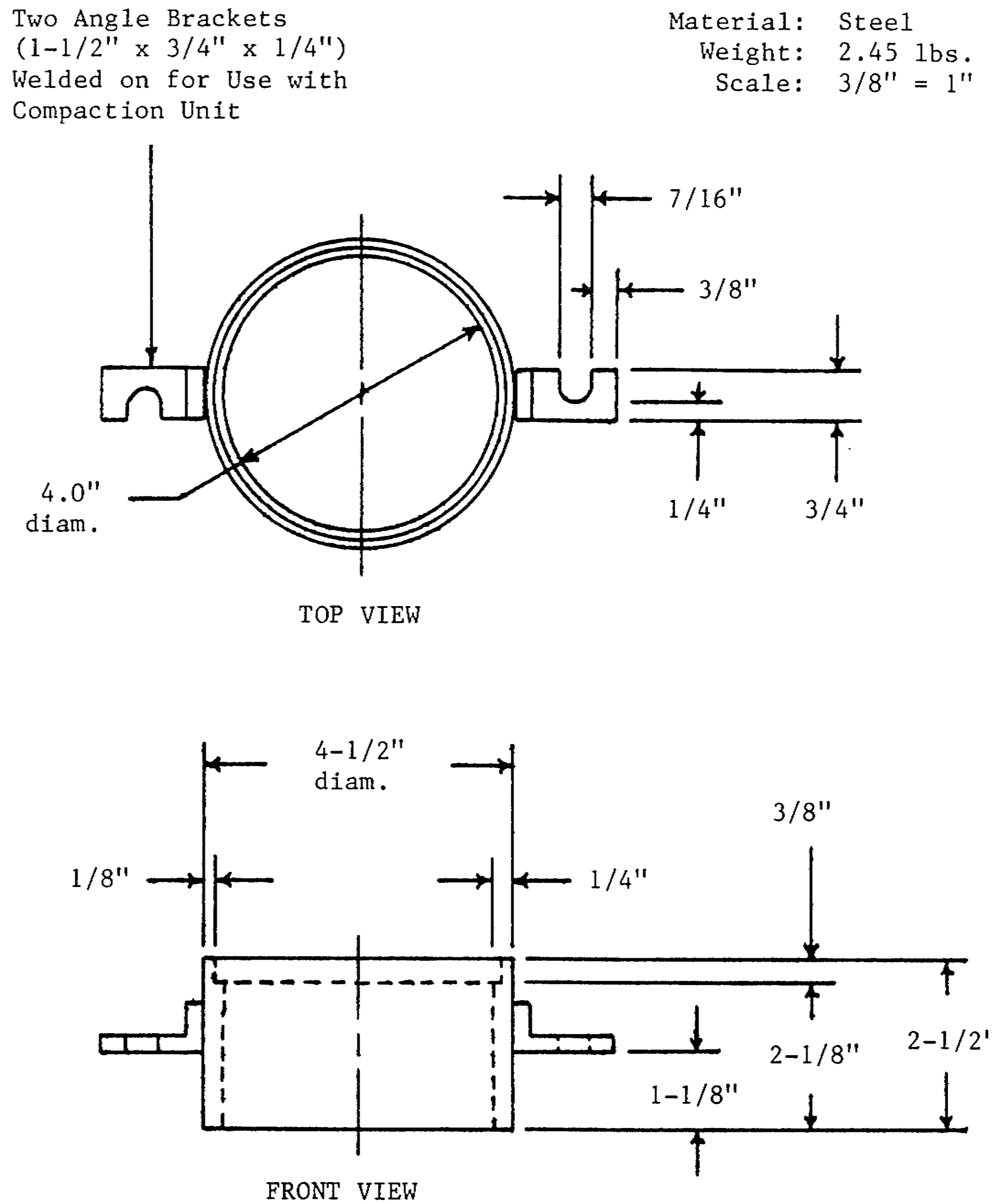
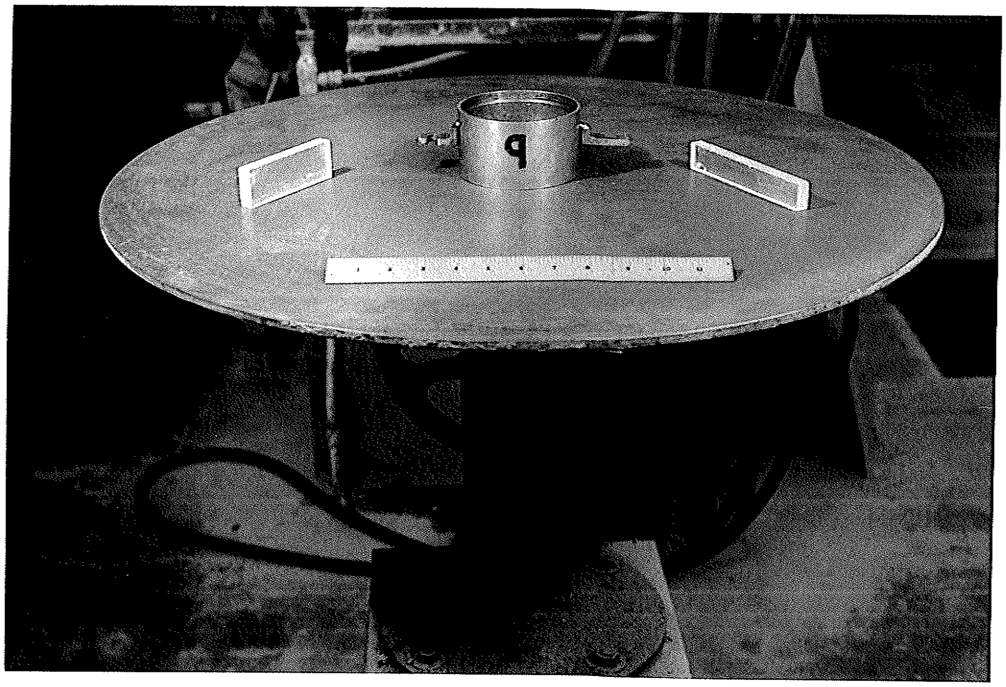


Figure 1: Non-Standard Mortar Flow Table Mould



Photograph 9: Flow Test Table and Equipment with Non-Standard Mould

considered adequate at about half the workability of conventional mortars and the mortar was remixed by hand, not machine, after the flow test.

With reference to Step No. 17, the changes made to CSA A8-1970 [15] were with respect to Articles 7.11.3.2, 7.11.4.1, and Subsection 7.11.5. It is specified in Article 7.11.3.2 that the outside contact line of the moulds and base plate be made water-tight by the application of a mixture of paraffin and rosin or paraffin alone. This was not done as it was assumed that the moulds with the interior faces coated with oil provided an adequate seal.

Article 7.11.4.1 states that the time between completion of first mixing and start of moulding should not exceed three and one-half minutes. In the actual laboratory work it was found difficult not to exceed this time limit.

Subsection 7.11.5 specifies that the test specimens are to be stored continuously under moist conditions. However, to simulate the as-used conditions more precisely, the clay mortar specimens were air-dried under laboratory conditions with no period of moist curing (with one exception -- Mix No. 5). With Mix No. 5, a second set of three specimens were moulded and moist-cured for about 15 days to investigate if any difference(s) would occur in the mortar properties. The air-dried specimens were removed from their moulds at the approximate age of three days while the moist-cured set was removed after eight days.

Overall, Step Nos. 3 to 7 inclusive can be classified as the pre-fermentation mixing period with Step Nos. 12 to 15 inclusive as the post-fermentation mixing period. Shown in Table II, is the time of mixing for each mix. The total mixing time shown in this table is the addition of the above two mixing periods. Mix Nos. 1 to 5 can be classified as a learning period in which initial experience was gained in mixing a clay mortar; evidence of this is shown in the higher total mixing times for these mixes.

Table II

Mixing Time of Clay Mortar Mixes

Mix No.	Pre-Fermentation Mixing Period (minutes)	Post-Fermentation Mixing Period (minutes)	Total Mixing Time (minutes)
1	55	10	65
2	50	25	75
3	65	35	100
4	65	30	95
5	60	30	90
6	40	25	65
7	40	20	60
8	35	20	55
9	35	15	50
10	40	15	55
11	25	20	45
Average	46	22	69

The highest and lowest pre-fermentation mixing period and total mixing time took place with Mix Nos. 3 and 11 respectively; the highest and lowest post-fermentation mixing period took place with Mix Nos. 3 and 1 respectively. Based on all of the 11 clay mortar mixes, the average pre-fermentation mixing period, post-fermentation mixing period and the total mixing time were 46, 22, and 69 minutes respectively.

In addition to the total mixing time of a clay mortar mix, is the testing and moulding time. The testing time is the time it took to perform the flow and moisture content tests while the moulding time was the time it took to mould three two-inch cube specimens. Summation of the total mixing time and the testing and moulding time was called the "total preparation time" of a mix. The total preparation time along with its components for each clay mortar mix is

Table III

Total Preparation Time[1] of Clay Mortar Mixes

Mix No.	Total Mixing Time[2] (minutes)	Testing[3] and Moulding Time (minutes)	Total Preparation Time[1] (minutes)
1	65	135	200
2	75	70	145
3	100	70	170
4	95	70	165
5	90	60	150
6	65	55	120
7	60	60	120
8	55	35	90
9	50	60	110
10	55	50	105
11	45	50	95
Average	69	65	134

[1]The time required to mix, perform the flow test, obtain moisture content samples and to mould three two-inch cube specimens.

[2]Obtained from Table II, page 36.

[3]Flow and moisture content tests.

listed in Table III.

As with the total mixing time, the initial mixes required a longer testing and moulding time until some experience was gained. This is evident with Mix No. 1 having the largest testing and moulding time of 135 minutes while the later Mix No. 8 took the least time of all mixes at 35 minutes. The average total preparation time of all the 11 clay mortar mixes was 134 minutes.

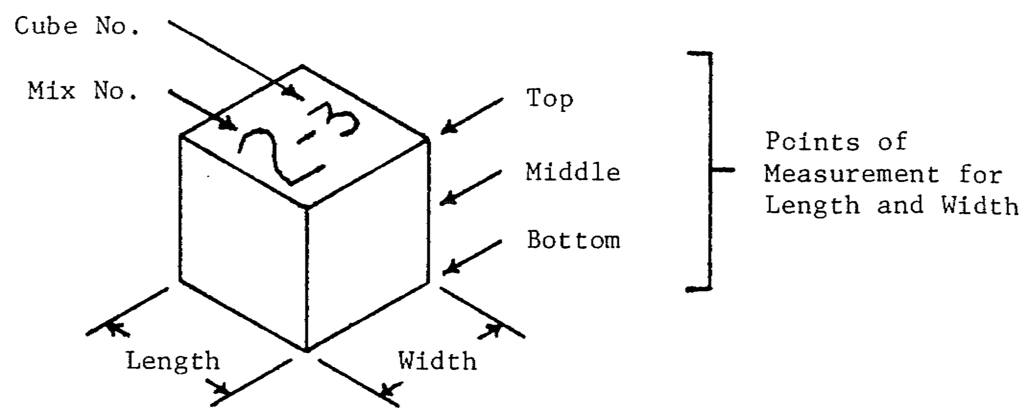
Throughout the mixing and moulding procedure, moisture contents were taken. The stages at which measurement of moisture content took place were: 1) before fermentation; 2) after fermentation, but before the addition of lime; 3) after the addition of lime, but before the flow test and moulding; and 4) after the flow test and moulding. Moisture content measurements at Stages Nos. 1, 2, and 3 were not taken for every mix. The purpose of these three measurements was to determine the efficiency of the sealed containers (plastic ice cream pails with double plastic wrap and the pail's lid placed on top) used for the fermentation stage along with the moisture content loss at the various stages of mixing and moulding. The moisture content at Stage No. 4 was taken for every mix to determine the total moisture loss from the start of mixing, and to report the moisture content of the mix.

3.1.3.3 Pre-Testing Measurements and Preparation

From the day of moulding to the day of testing, a careful watch on each of the mix's specimens took place. The primary concern with the clay mortar was shrinkage. To monitor the shrinkage, volumetric measurements were taken for all of the specimens at the approximate drying ages of 1/2, 1, 2, 3, and 4 weeks.

Volume of each cube was obtained by multiplying the average length, width, and height. The average length and width were each based on three measurements taken at the top, middle and bottom of the cube while the average height was based on three measurements taken at the left, middle and right hand side of the cube. See Figure 2 for details of these measurements. To identify the specimens, the mix and cube number were painted on the original top surface. The specimen number was painted smaller than the mix number for distinguishing purposes. Measurement was made with a set of calipers capable of measuring to the nearest thousandth of an inch. Time required to perform the nine measurements on each cube was approximately five minutes.

During the volumetric shrinkage measurements, it was observed that upon drying, the surfaces of the cubes rarely remained flat. The surfaces usually became concave, convex or bumpy. With surfaces of this kind, a significant error in volume measurement was seen when using calipers, as the calipers could not follow the irregular surface area pre-



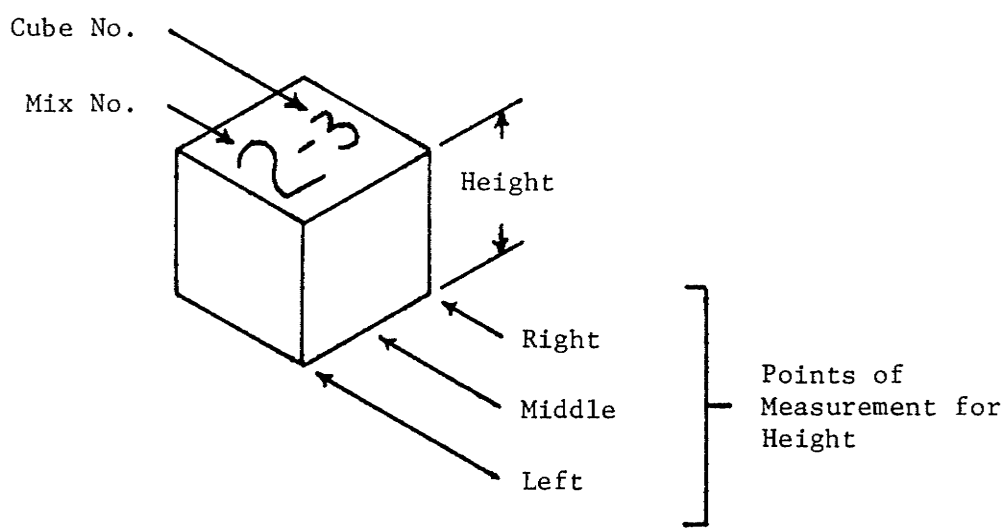


Figure 2: Numbering System and Points of Measurement of Mortar Cube Specimens

cisely. In spite of this, calipers were used throughout with a correction factor applied later. The correction factor was derived from a more precise but time-consuming method of water displacement.

During the water displacement procedure it was desirable not to get the specimens wet. To prevent this, each specimen was wrapped up tightly in aluminum foil and then sealed with a coat of wax. The aluminum foil not only provided a partial seal from the water but also gave an easy and quick way of unwrapping the wax from the specimen. Finally, the volume of the aluminum foil and wax (also measured by water displacement) was subtracted to get the volume of the specimen alone.

The equipment used to measure the water displacement was a 1,000 or 2,000 millilitre (ml.) graduated cylinder plus a 100 ml. graduated cylinder. Graduations on each of the cylinders were 10, 20, and 1 ml. respectively. The larger cylinders were used as the displacement containers. When the specimen did not fit in the 1,000 ml. cylinder, the 2,000 ml. cylinder was used. The 100 ml. cylinder was used to bring the final water level of the larger cylinder up to the nearest 10 or 20 ml. division respectively. This way the 100 ml. cylinder gave volume readings to the nearest millilitre.

As stated earlier, during the drying stage, the specimens did not remain in a perfect cube shape with planar sides. Instead, they developed sides that were either concave, convex or rough with bumps. Since these kinds of surfaces would create an uneven stress distribution during the compression test and to comply with Subsection 7.11.8 of CSA A8-1970 [15], it was necessary to sand the specimens just prior to testing. Sanding was done so as to make the: 1) loading surfaces (original moulded top and bottom) plane; 2) top loading surface parallel to the bottom loading surface; and 3) top loading area equal to the bottom loading area.

The sanding was done so as to minimize the amount of material removed. Sanding was performed with a motorized belt and disc table sander. Table IV shows the amount of time spent in sanding per mix; each mix had a set of three specimens. The amount of time spent in sanding was proportional firstly to the hardness of the material and secondly to the experience with the procedure. This is evident with Mix No. 1 which was a very hard material to sand and was the first set of specimens sanded down; it had a sanding time of 390 minutes. Photograph 10 shows the specimens of clay mortar Mix No. 1 after being sanded. Towards Mix No. 11, the sanding time decreased due to the material being considerably easier to sand down and due to the familiarity in the sanding procedure. Numerically, this trend can be seen in Table IV; the lowest recorded sanding times (33 and 35 minutes) occurred with Mix Nos. 9, 10, and 11 which were sanded

Table IV

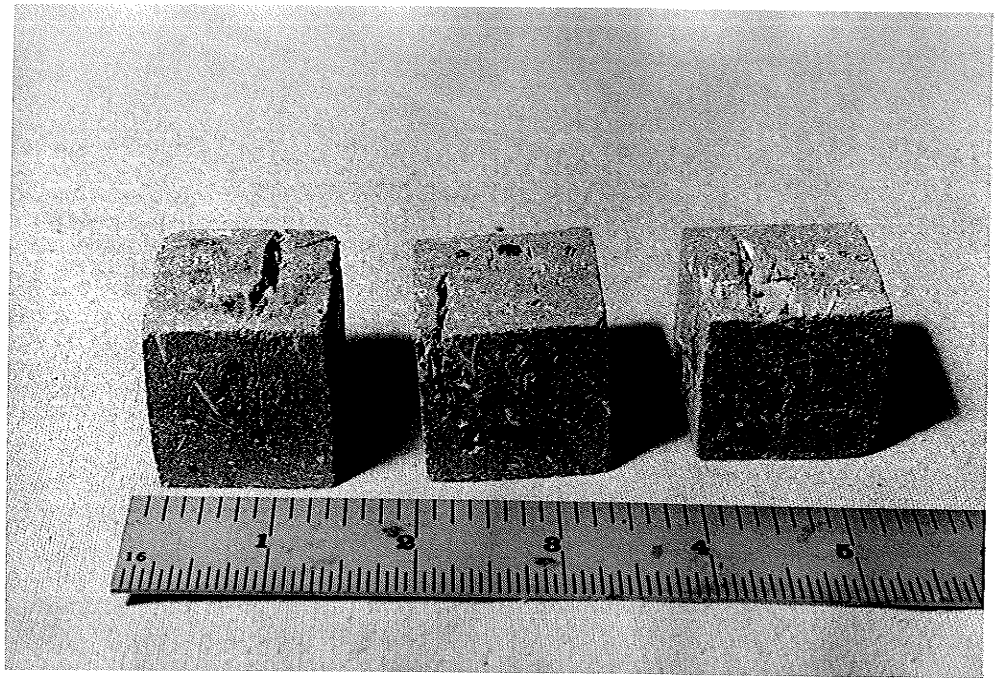
Time Spent in Sanding Clay Mortar Specimens

Mix No.	Time (minutes)
1	390
2	80
3	80
4	80
5A	45
5B	45
6	45
7	45
8	45
9	33
10	33
11	35

last.

3.1.3.4 Compression Testing Equipment

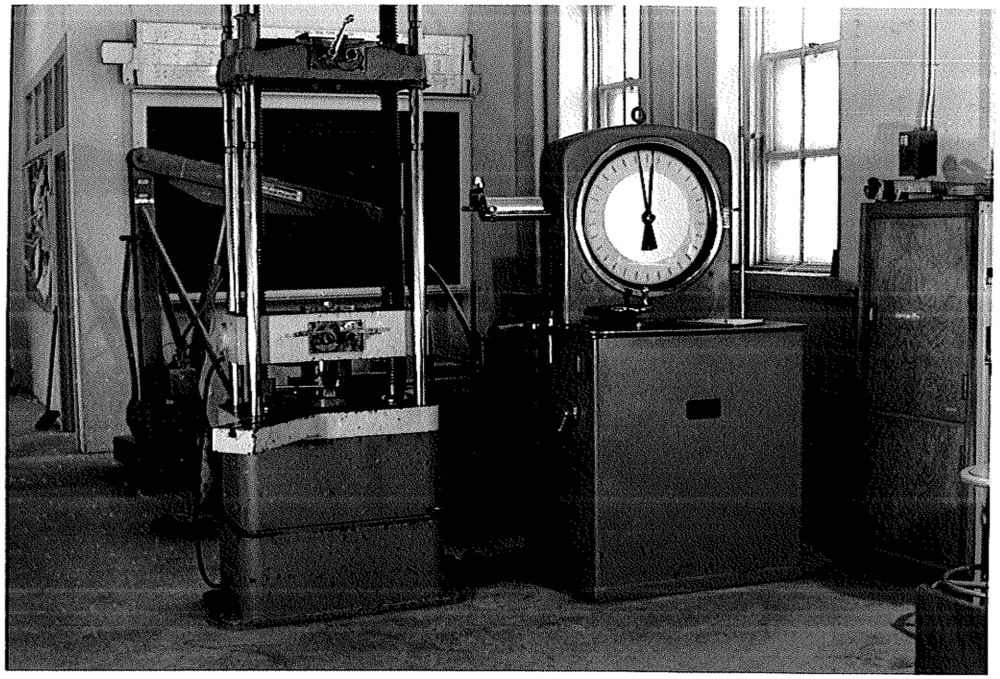
The testing machine used for loading the clay mortar specimens in compression was a Riehle universal screw-gear type, with a total loading capacity of 60,000 pounds (Photograph 11). This machine met the specifications of CSA Standard A8-1970, Masonry Cement, Subsection 7.11.6, Testing Machine [15]. To assure the accuracy of the indicated load of ±1.0 percent called for in Article 7.11.6.2 of CSA A8-1970 [15],



Photograph 10: Clay Mortar Mix No. 1 Specimens After Being Sanded

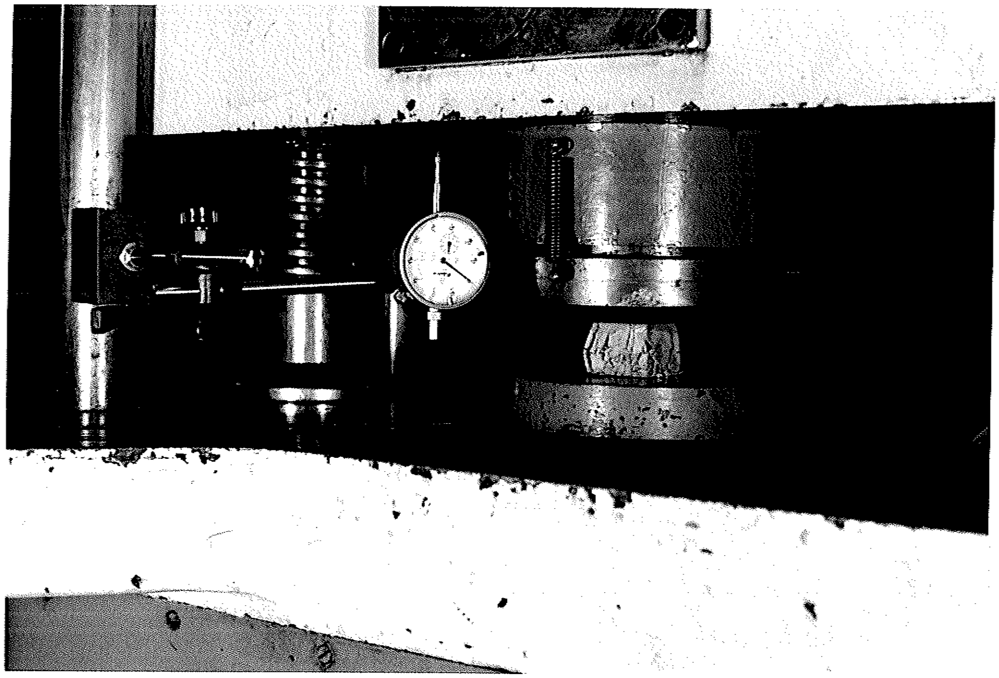
the loading range of the testing machine was set at the lowest range of 3,000 pounds, with a scale division reading of 5 pounds. This range proved satisfactory with the highest load occurring at 2,137 pounds, therefore using 71 percent of the scale.

To measure the deformation, a standard Mitutoyo deformation gauge was placed between the load insensitive table (lower part of the testing machine) and the load-sensitive crosshead (Photograph 12) or above the load-sensitive



Photograph 11: Riehle Testing Machine (60,000 Pounds Capacity) Used to Test the Clay Mortar Specimens

crosshead (Photograph 16, page 70). For any given test, the gauge used had either Imperial or metric units of measurement. The respective scale divisions on these gauges were 0.001 inch and 0.01 millimetre. Deformation readings between the divisions were further estimated to the next decimal place.



Photograph 12: Apparatus for Loading and Deformation Measurement (Dial Gauge) of Clay Mortar Specimens

3.1.3.5 Compression Testing Procedure

Subsection 7.11.7 of CSA A8-1970 [15] states that a set of tests are to be taken at the age of seven and 28 days. In the clay mortar study, only the 28-day test was sought. Since the final pre-testing measurements and preparation started around the 28-day age, the actual testing took place after 28 days. The age at the time of testing for each mix was recorded with the respective results.

With the cube specimens prepared as described in Article 3.1.3.3 above, every cube was carefully placed in the testing machine at the centre of the upper and lower bearing block (Photograph 12). No cushioning or bedding material was used. The original moulded top faced the load-sensitive crosshead (after the completion of the testing however, it was discovered that a misunderstanding of Subsection 7.11.9, Testing Operations, of CSA A8-1970 [15] took place). Subsection 7.11.9 of CSA A8-1970 [15] states that the load shall be applied to the cube faces that were in contact with the true plane surfaces of the mould. This means that the load should of been applied to two of the original sides of the cubes, not the top and bottom.

The rate of loading was applied at a rate which the deformation readings could be taken conveniently throughout. This rate was considerably slower than the 4,000 pounds per square inch per minute rate stated in Subsection 7.11.9 of CSA A8-1970 [15]. The actual time spent in testing each cube is recorded with its respective results.

In the actual testing, two people were involved; one person operated the testing machine and at the same time calling for deformation readings at a regular increment of loading. Recording of the data was done by the person operating the testing machine.

3.1.3.6 Error Analysis

The three areas of error analysis investigated were: 1) weighed materials, 2) volumetric measurements (shrinkage), and 3) compression testing.

1. **Weighed Materials**

All of the materials used as components of the mixes were proportioned by weights with the use of a weigh scale with gradations of 0.01 gram. The same kind of scale was used for the determination of moisture contents and in the soil testing. This was the least sensitive scale used throughout all of the testing. Assuming a maximum weighing error of ±0.005 gram and relative to the smallest quantity of material weighed (flax straw) which was 5.04 grams, this represents a maximum error of ±0.1 percent. From the above discussion on the accuracy of the weighed materials, requirements of Subsection 7.2.2, Accuracy of Scales and Weights, of CSA A8-1970 [15] were met.

2. **Volumetric Measurements (Shrinkage)**

To measure the volume of the specimens, two methods were used: 1) calipers, and 2) water displacement. Although a high error was foreseen in using calipers (for reason, see Article 3.1.3.3 above), this error was corrected by taking a final volume reading with both of the methods to form a correction factor. The correction factor was calculated by assuming the volume obtained by water displacement to be accurate to the true volume. This correction factor was then applied to all of the previous caliper measurements of the given mix.

Volumes obtained through the water displacement method were always lower than that through the caliper method. The lowest and highest differences measured were seven and 23 percent respectively.

The volume obtained through the water displacement method was recorded to the nearest millilitre (see Article 3.1.3.3 above). However, due to the largeness of the displacement containers (1,000 and 2,000 ml. cylinders), accuracy of ±2 ml. was assumed. With the lowest volume of a specimen measured at 62 millilitres, this represents a maximum error of ±3.2 percent.

3. Compression Testing

With the load indicator dial of the testing machine having a scale division of 5 pounds, it was assumed that the load readings were accurate to ±1 pound. The lowest load applied with failure was 684 pounds while the lowest division of load applied between deformation readings was 25 pounds. With respect to these figures, the respective maximum percentage of error are ±0.15 and ±4.0 percent.

The Imperial and metric deformation gauges used had scale divisions of 0.001 inch and 0.01 millimetre respectively. Correspondingly, the readings were taken to the nearest 0.0001 inch and 0.001 millimetre. Accuracy of these readings though were assumed as ±0.0005 inch and ±0.005 millimetre. The lowest deformations at failure with respect to each gauge were 0.0430 inch and 0.96 millimetre. From the assumed accuracy of the readings and these deformations, this represents a maximum error of ±1.2 and ±0.52 percent respectively.

3.2 LIME-SAND MORTAR

The term "lime-sand mortar" as used throughout this report is defined as a mortar of which lime, sand and water are its constituents.

3.2.1 Preliminary Literature Search

A preliminary literature search on lime-sand mortar was performed to find what course to take in the experimental program. Searched for were the kinds of lime that could be used and the possible proportions of lime and sand. This information was attained through Reference Nos. 24, 33, 36, 37, 44, 45 and 56.

It was established that lime of various compositions are available on the market -- high-calcium lime, calcium lime, magnesium lime, high-magnesium lime and hydraulic lime. The lime can be purchased in the quicklime (unslaked) or in the hydrated (slaked) form. For the description of any of these terms, see Definitions and/or Appendix E. Depending on the kind of lime that is used, different effects on the mortar properties (see Appendix A) can take place. This is especially true if the mortars are proportioned by volume and not by the available lime content. In practice, the great majority of the lime produced is usually either of the high-calcium or the high-magnesium type [33, p. 120]; this stems from the limestone's natural composition and not the manufacturing process.

The volumetric proportion of lime to sand found published in the above mentioned references ranged from 1:2 to 1:12. However, most of the lime mortars discussed and dealt with centred around the proportion of 1:3. Reference 36 showed favor to an interpolated proportion of 1:3.65; at this ratio, it was observed when testing at a standard consistency that the water content decreased to a minimum which is simultaneously the approximate point of maximum packing. Also indicated from the above references is that as the amount of lime is increased in a mix, the workability and the water retention capability of the mortar is increased and the amount of shrinkage is decreased.

Reference 33 [Tables 43 and 48, pp. 125 and 130] has tabulated results of tensile tests (a common test performed in the early 1920's) performed with quicklime and hydrated lime mortars. In these tests, two types of lime were used, high-calcium and magnesium lime. Tests were conducted at various ages up to one year. The proportion of lime to sand (by weight) used in these tests was 1:2.

From the tensile tests stated above, little difference in the tensile strength was noted between using the quick-lime and the hydrated lime. Differences were however, noted to exist when comparing the results between the two types of lime. The differences are as follows:

1. At the 28-day age, the high-calcium lime mortar tensile strength exceeded that of the magnesium lime, by almost four times in the case of the hydrated lime (30 psi. for the high-calcium and 8 psi. for the magnesium lime).
2. After the 28-day age, both the magnesium and the high-calcium lime mortars continued to gain more strength but the gain for the magnesium lime mortars was much more rapid.
3. At the age of four months, the tensile strength of the magnesium lime mortar exceeded that of the high-calcium lime.
4. At the age of one year, the magnesium lime mortar developed a tensile strength about double that of the high-calcium lime.
5. In the case of the hydrated lime mortars, from the age of 28 days to the age of six months, the magne-

sium lime gain in strength was 938 percent while the gain for the calcium lime was 66 percent.

It is believed [33, 45] that the strength of lime mortar is due primarily from the hardening process of carbonization (see Appendix E) of the outer layer. Since this layer is nearly impervious, it retards the process of carbonization deeper into the mortar. For the process of carbonization to take place effectively some moisture is essential as carbon dioxide does not react with dry lime [45, p. 252]. At the same time, the moisture level or relative humidity should not be kept at 100 percent as the pores of the mortar become filled with water and slows the carbonization process; a large proportion of the water in the mortar should be allowed to evaporate [45, p. 252].

A secondary claim for the hardening of the lime-sand mortars, although not fully proven, is the chemical action or combination of the lime with the silica of the sand, forming a silicate of lime or "lime-silicate". This is specifically claimed to occur when ground quicklime with sand is subjected to either superheated or high-pressure steam, which slakes the lime and causes it to attack the silica. After the slaking process is completed, the material is then moulded and heavily compressed. While it may be true that the above chemical activity may take place to some degree, it is on the most hopeful possible basis that at most only 15 percent of the material would have any binding properties, the remainder being merely uncombined and inert sand [33, pp. 135 to 136, assuming lime to be eight percent of the mass and forming the richest possible silicate, calcic silicate -- $CaO-SiO_2$].

The information presented in the above preliminary literature search was used to determine the kind of materials and range of proportions to use in a lime-sand mortar. This information was then applied to the experimental program.

3.2.2 The Materials and their Proportions Used

Directed by the preliminary literature search, the three materials used throughout all of the mixes in the lime-sand mortar experimental program were: 1) lime, 2) sand, and 3) water. It was assumed that these three basic materials would satisfy the properties of a good quality mortar (see Appendix A).

In the lime-sand mortar experimental program, the material quantities were proportioned on a volumetric basis. However, when measuring out the quantity of materials for the mixes, weights were used. The proportioning by volume and using weights in the laboratory was accomplished by assuming the average apparent densities of the hydrated lime and dry sand to be 35 and 100 pounds per cubic foot [45, p. 361] respectively. These density weights can be taken for materials placed in the container with gentle shaking. By using weights, the uncertainty in the degree of packing created by volumetric measurement is eliminated. Throughout the text dealing with the lime-sand mortar, mixes are presented with respect to their equivalent volumetric proportions.

3.2.2.1 Lime

The purpose of using lime as the only cementitious material in a mortar was to lower the initial cost relative to a conventional mortar (see Definitions). Since Portland cement, which is often higher-priced than lime, is not used in the mortar, an economic benefit would be realized. Elimination of the Portland cement would also make the mortar more accessible since there is one less component to obtain; in addition to this, on a world-wide basis, lime is a more readily available material than Portland cement.

"Tested by time" -- (National Lime Association) and from evidence in the literature, lime in mortar has been credited with providing all of the essential properties of a good quality mortar (see Appendix A). Although a straight lime mortar may be found to have only a modest compressive strength, an adequate strength rather than high strength is what is sought.

The form of lime used throughout the experimental program was the hydrated (slaked) form. Quicklime (unslaked) requires knowledge to slake and can be dangerous to use because of the high heat upon contact with moisture during the slaking process. Due to these facts quicklime was foreseen to be unfavourable for stackwall construction.

Initially it was set out to test one set of lime-sand mortar mixtures using a high-magnesium lime and a second set using using a high-calcium lime. However, it was discovered that after all of the mixes were mixed and moulded that an oversight had taken place. What was thought to be a high-magnesium lime turned out to be a high-calcium lime. Instead of comparing the proposed results of a high-magnesium and a high-calcium lime, the tests resulted in comparing two brands names of high-calcium lime (see Appendix E).

The volumetric proportion of lime in each mix was considered unity in each case. The weight of lime used in each mix was varied accordingly so as to change the volumetric proportion of sand from mix to mix.

3.2.2.2 Sand

The purpose of adding sand to a lime mortar is to minimize shrinkage, for lime used alone as a binding material shrinks greatly upon drying/hardening and would produce cracks [33, p. 124]. In the carbonization process of a lime mortar (see Appendix E), the sand takes no active part, it is merely an inert material, added solely in order to prevent shrinkage and consequent cracking [33, p. 124]. The sand may also be looked upon as a material that is low in cost relative to the cementitious materials (lime, cement) thus acting as a low-cost filling material in the mortar.

The sand used throughout the lime-sand mortar mixes was the same as that used for the clay mortar mixes. For information on this sand, see Article 3.1.2.2, Sand. Complete test results of the sand are in Appendix C.

With respect to a lime volumetric proportion of unity, the volumetric proportions of sand tested were 2.0, 3.0, 3.65, 4.5, 5.0 and 6.0. These proportions were achieved by changing the quantity of lime in the mix, not the sand. The volume of sand used in each mix was calculated to be enough to mould 30 two-inch cubes.

3.2.2.3 Water

The purpose of the water in the lime-sand mortar was to bring about the property of workability. Sufficient water was added to the mortar to create a flow of 105 to 115 percent in the flow test performed. To get a preliminary indication to the amount of water that would be needed for each mix, reference was made to Table 10, page 100 of Gillard and Lee [36].

As with the clay mortar mixes, the source of water came from the cold water tap of the laboratory which in turn comes from the city of Winnipeg, Manitoba. The amount of water in the lime-sand mixes is expressed as the moisture content (abbreviated as m.c.), reported as a percentage. These percentages are referred to the total dry weight of the mortar (lime and sand).

3.2.3 Procedure

In the lime-sand mortar testing program, six different volumetric ratios of lime-sand were tested. For each volumetric ratio, two different brands of lime were employed, Brands A and B (see Appendix E). From each mix, two sets of two-inch cubes were moulded with each set consisting of three cubes; sets one and two were respectively for the seven- and 28-day compressive strength tests. On selected mixes, left-over dried mortar was broken up to sand size particles, remixed and moulded as with the original mixes; these mixes were termed as remix mixes.

With the above mixes, four different sets of studies were undertaken. The sets were: 1) lime-sand ratio studies, 2) remix strength studies, 3) seven- and 28-day strength studies, and 4) lime brand studies. The purpose of the lime-sand ratio studies was to compare the compressive strength and failure characteristics as the lime-sand ratio changed. To economize, the highest possible volume of sand that could be accommodated by a unit volume of lime was sought. The remix strength studies provided a comparative look at the compressive strength and failure characteristics between a remix mix and its original mix counterpart. To ensure compatibility, a remix mix which behaves similarly to the original mix is the most desirable. The seven- and 28-day strength studies provided a comparison of the compressive strength and failure characteristics between the seven- and 28-day tests of any given mix. For each lime-sand ratio, lime-brand studies were performed to determine if any differences exist in the compressive strength and failure characteristics between lime Brands A and B (see Appendix E).

3.2.3.1 Preparation of the Materials

For the reasons mentioned in the article on the clay mortar materials, the preparation of the lime-sand mortar materials was also kept minimal. Lime, sand and water -- (the three components of the original lime-sand mortar mixes) were all incorporated into the mix without initial preparation.

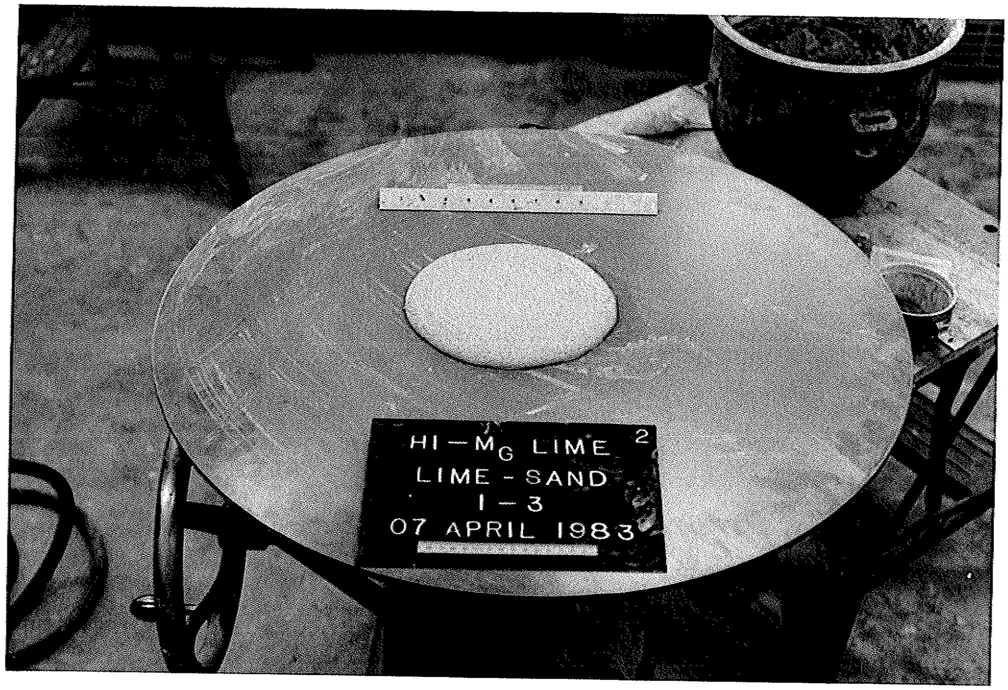
A form of preparation did however take place with the remix mixes. The hardened mortar, which was in the form of a round cake, was broken up with a hand held pestle [as used in soil testing -- Reference 1, page 109] (Photograph B-1, page 297). The degree of crushing was considered satisfactory when 100 percent of the material passed the No. 10 sieve. If individual solid pebbles were retained on the No. 10 sieve, they were also used in the mix, as was the case in the original mixes.

3.2.3.2 Mixing and Moulding

Used to mix the lime-sand mortar mixes, was the mechanical mixing apparatus detailed in Subsection 7.8.6 of CSA Standard A8-1970, Masonry Cement [15]. Obtained from the same Standard, Subsection 7.8.8, was the mixing procedure for the mixes. All of the steps of this mixing procedure were followed closely except when it came to the addition of the dry material in the remix mixes and the addition of water to all of the mixes.

For the remix mixes, the difference in the mixing procedure resulted from the fact that the lime and sand were already combined together. So as to be similar, the total time spent to add and mix the lime-sand dry mixture in the remix mixes and the total time spent in adding and mixing the individual lime and sand material in the original mixes, were both made equal.

From the above mixing procedure it is specified in the first step to place all of the mixing water in the mixing bowl. In the actual mixing this was not done due to an uncertainty in knowing how much water to add to create a mix with a flow of 105 to 115 percent in the flow test. Instead, about 70 to 80 percent of the total water added was used in the first step while the remaining was added after all of the sand was in the mix. The quantity of water was adjusted until the correct consistency was obtained in the flow test. This usually involved going through the flow test more than once; on average, two or three times were required. Photograph 13 shows lime-sand mortar Mix No. 16



Photograph 13: Lime-Sand Mortar Mix No. 16 After Flow Test -- 107% Flow

with a satisfactory flow of 107 percent.

The flow test was performed on each mix following the procedure given in CSA A8-1970, Section 7.9, Determination of Flow of Mortars [15]. However, due to the limitations of the laboratory facilities, compromising changes from the Standard were made with respect to the equipment (flow table, flow table mould and flow table calipers) used in the flow test. These equipment changes were discussed in Article 3.1.3.2, Mixing and Moulding. Changes were also made with respect to Article 7.9.5.2 of CSA A8-1970 [15].

Rather than discarding the mortar mix and starting with a fresh mix as stated by Article 7.9.5.2 of CSA A8-1970 [15], the quantity of water was altered if the mix did not satisfy the flow requirement of 105 to 115 percent. If the mixture was too dry, additional water was added and the mixture was remixed for about three minutes. In the case where the mixture was too wet, the mixture was remixed at medium speed for a period of time (actual time ranged from 2.5 to 11 minutes) so as to allow the energy of the mixing paddle to assumably expel the moisture, reducing the flow. With each additional trial of the flow test, the time required to complete a mix was increased.

The moulding of the test specimens was carried out following the procedure specified in CSA A8-1970, Subsection 7.11, Determination of Compressive Strength, Subsections 7.11.1 to 7.11.5 [15]. However, Articles 7.11.3.2, 7.11.4.1 and Subsection 7.11.5 were not enforced for the same reasons as mentioned in Article 3.1.3.2, Mixing and Moulding. It was foreseen to be advantageous though to allow the freshly moulded specimens to be placed in a moisture room for a 24 hour period so as to obtain consistent and reproducible results [36, p. 94]. This satisfies the first part of Subsection 7.11.5 but not the second part which requires the specimens to be immersed and stored in water until tested; after 24 hours the specimens were air dried. The specimens were removed from the moulds at the approximate age of three days.

The time required to mix, perform the flow test(s), obtain moisture content samples and to mould six two-inch cube specimens (three for the seven-day test and three for the 28-day test) was classified as the "total preparation time". Not included in the total preparation time was the time required to measure out the proportioned quantity of lime and sand. Shown in Table V is the total preparation time for each of the lime-sand mortar mixes. The lowest and highest total preparation time was 30 and 120 minutes for Mix Nos. 23 and 17 respectively.

Although the quantity of water added to a mix was recorded, moisture content sampling was performed immediately after the flow test that gave the correct flow. The sampling method value was recorded as the moisture content of the mix. This procedure accounted for any moisture loss that may of taken place during the mixing process.

A modified Vicat test was performed for Mix Nos. 14 and 17. The purpose of this test was to get an indication of the time of setting. Normally the Gillmore method [see Reference 15, pages 22 to 24] would be used, but this apparatus was not available.

Table V

Total Preparation Time[1] of Lime-Sand Mortar Mixes

Lime Brand	Mix No.	Total Preparation Time[1] (minutes)
A	12	60
	13	60
	14	70
	15	85
	16	65
	17	120
	17-R	90
B	18	60
	19	50
	20	50
	20-R	90
	21	60
	21-R	60
	22	80
	22-R	75
	23	30
	23-R	60
Average		69

[1]The time required to mix, perform the flow test(s), obtain moisture content samples and to mould six two-inch cube specimens.

The general procedure of the modified Vicat test was obtained from Section 7.4 of CSA A8-1970 [15]. Modifications were done to Article 7.4.3.3, Subsection 7.4.4 and in general a lime-sand mortar was used instead of a cement paste. Article 7.4.3.3 is said to be satisfied if the rod [see Reference 15, page 17] settles 10 millimetres within 30 seconds after being released; in the modified test, the time at which this settlement occurred was sought. Subsection 7.4.4 states that the water content shall be calculated as the percentage by weight of dry cement; the moisture content of the mix as predetermined by the flow test is the percentage by weight of the dry lime and sand.

3.2.3.3 Pre-Testing Measurements and Preparation

To distinguish between the mixes and the cubes, the mix and cube numbers were painted on the original top surface of the specimens. A larger number represented the mix number while the smaller number indicated the cube number. This numbering system is illustrated in Figure 2, page 40.

The lime-sand mortar test specimens displayed small volumetric shrinkage and sides that remained plane with exception to the top which developed a slight concave shape. Shrinkage occurred primarily in the initial drying stage, remaining relatively stable thereafter up to the testing ages of seven and 28 days. Due to this stable behaviour, it was decided unnecessary to perform scheduled volumetric measurements as performed for the clay mortar test specimens. Instead, a single pre-testing measurement served as the final volumetric measurement as well as providing the dimensional information required for the compression test results. The volumetric measurements gave an indication of the degree of shrinkage.

The above measurements were performed with the use of calipers capable of measuring to the nearest thousandth of an inch. Little error in volume measurements was seen in using calipers, as the surfaces were flat and regular, with exception to the original top surface.

With the surface in the above mentioned state and with the allowance of some curvature given by CSA A8-1970 [15], Subsection 7.11.8, the lime-sand mortar test specimens were used as-is, with no sanding or other form of preparation.

3.2.3.4 Compression Testing Equipment

The testing machine used in loading the lime-sand mortar specimens in compression was a Baldwin universal screw-gear type, with a total loading capacity of 30,000 pounds (Photograph 14). This machine met the specifications of CSA Standard A8-1970, Masonry Cement, Subsection 7.11.6, Testing Machine [15], with an exception to Article 7.11.6.3. In this article it is partially stated that the upper bearing of the testing machine shall be spherically seated.

At the beginning of the compressive tests, Mix No. 13[5] at the seven-day strength, the top and bottom loading platens were parallel to each other with no spherical seats. Concern for providing a spherical seat occurred during this early testing as it was noted that local failure at the corners and sides took place.

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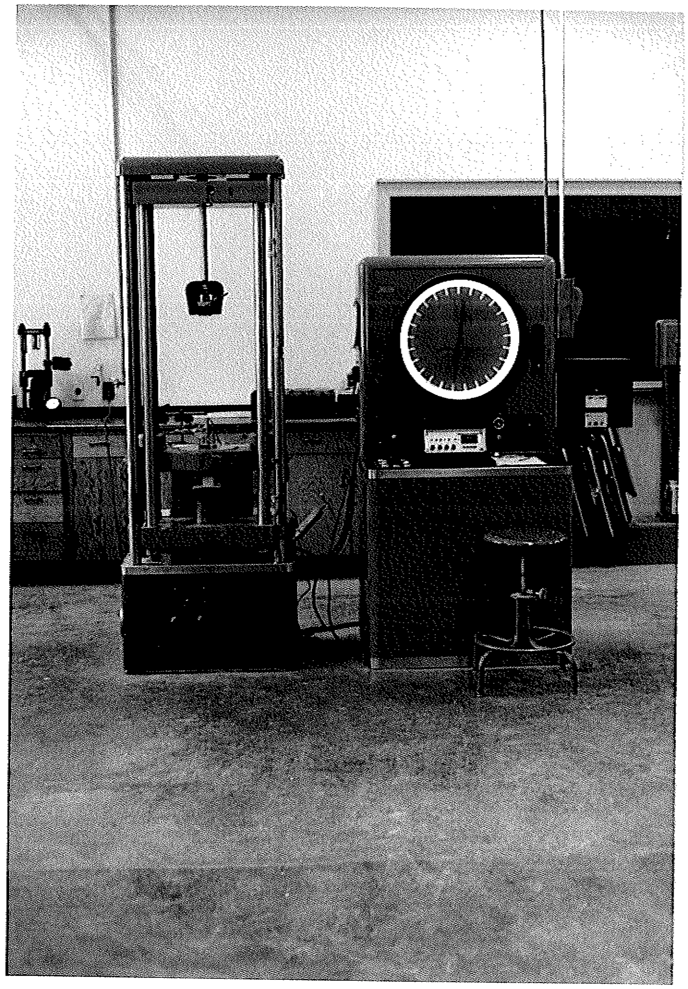
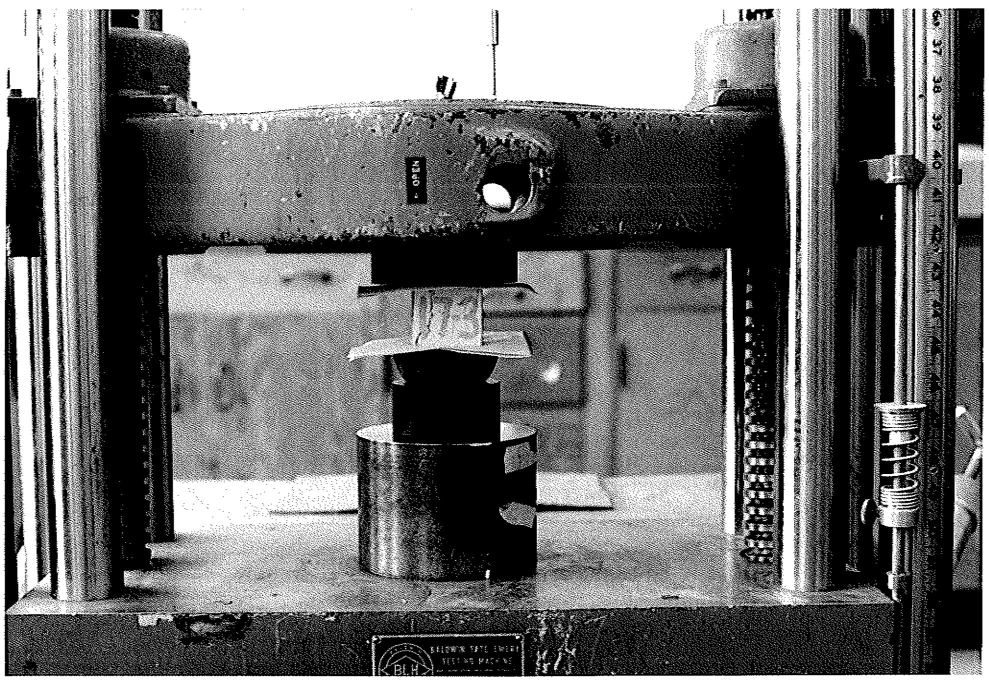
[5] Mix No. 12 was mixed after Mix No. 17.



Photograph 14: Baldwin Testing Machine (30,000 Pounds Capacity) Used to Test the Lime-Sand Mortar Specimens

It was not until Specimen No. 3 of Mix No. 14, at the seven-day test, that a spherical bottom seat was used as illustrated in Photograph 15; also in this photograph, take note of the paper towel on the loading surfaces and the displacement dial gauge pointer above the top loading platen. To minimize the friction during any levelling movement, the ball joint of this seat was sprayed with a silicone spray. This seat was effective in compensating, when necessary, slight differences in the height of specimens. With the use of the spherical bottom seat, the mode of fail-



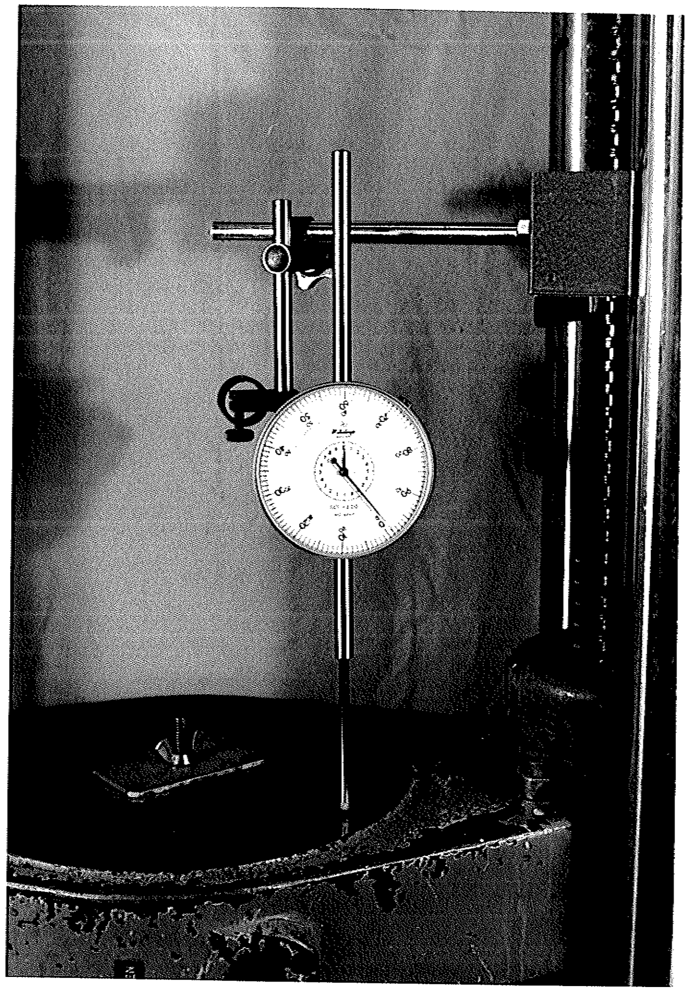
Photograph 15: Loading Apparatus for Lime-Sand Mortar Mixes

ure became more dominantly internal instead of local.

To assure the accuracy of the indicated load of ±1.0 percent stated in Article 7.11.6.2 of CSA A8-1970 [15], the loading range of the testing machine was set at the range of 1,200 pounds with a scale division of 1 pound. This range proved satisfactory with the highest loading occurring at 618 pounds, therefore using 52 percent of the scale.

To measure the deformation of the specimens, two different methods were used. The first method employed was the use of a standard Mitutoyo deformation gauge. This method was used for all of the seven-day tests of the original mixes and Remix No. 17, plus the 28-day tests of Mix Nos. 12 to 17 (both original and remix). To obtain the deformations, the gauge was placed between the load-insensitive table (lower part of the testing machine) and the load-sensitive crosshead (Photograph 12, page 46) or above the load-sensitive crosshead (Photograph 16). Units on the gauge were Imperial with scale divisions of 0.001 inch. Deformation readings between the divisions were further estimated to the next decimal place.

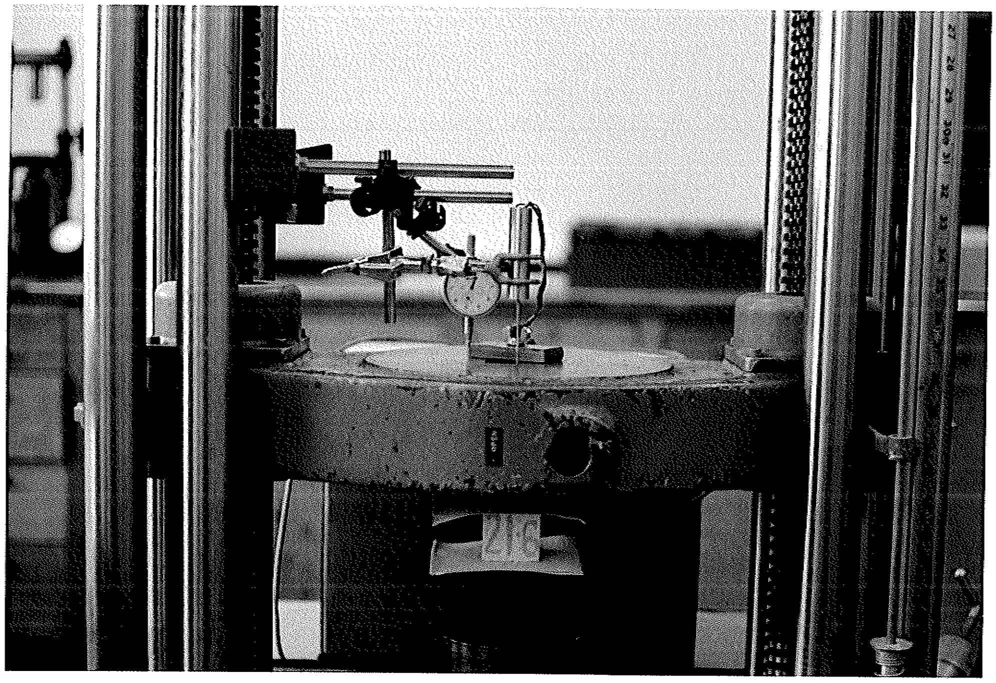
The second method used in obtaining deformation readings was through the use of an electronic setup using a linear voltage displacement transducer (L.V.D.T.), (Photograph 17). Incremental electronic digital readouts of 0.001 millimetre were obtained with this setup (Photograph 18). This method was used for all of the 28-day tests starting at Mix No. 18 and ending with Mix No. 23 of the original mixes, and also for all of the seven- and 28-day tests of Remix Nos. 20 to 23.



Photograph 16: Dial Gauge Setup for Deformation Measurements of Lime-Sand Mortar Specimens

3.2.3.5 Compression Testing Procedure

Complying with Subsection 7.11.7 of CSA A8-1970 [15], for each lime-sand mortar mix, a set of three cubes were tested at the age of seven and 28 days. The time allowance in performing the seven- and 28-day test, as specified by CSA



Photograph 17: Linear Voltage Displacement Transducer (L.V.D.T.) Above the Top Loading Platen to Measure Deformation of Lime-Sand Mortar Specimens -- Neighbouring Deformation Dial Gauge Used for Determining Error of L.V.D.T.

A8-1970 [15], is ±3 and ±6 hours respectively. For the minority of the tests this was not possible due to scheduling problems of the testing machine or secondly the hours of operation of the laboratory. The exact age at the time of testing for each mix was recorded with the respective results.

Also stated in Subsection 7.11.7 of CSA A8-1970 [15] is that the specimens shall be removed from the storage water

Photograph 18: Linear Voltage Displacement Transducer (L.V.D.T.) Electronic Digital Readout -- 0.001 mm.

and immediately tested. Since the specimens were air-dried (with exception to the first 24 hours), this was not applicable.

When preparing the lime-sand mortar specimens for the compression test, specifications given by Subsection 7.11.8 of CSA A8-1970 [15] were followed.

For the actual testing operation of the specimens, Subsection 7.11.9 of CSA A8-1970 [15] was used as a guide with some changes. Continuing on from the clay mortar mixes, the lime-sand mortar specimens at the start were mistakenly tested in the position as they moulded; the moulded top faced upwards and the moulded bottom faced downwards. With the testing started at Mix No. 13,[6] it was not until the second specimen of Mix No. 15 at the seven-day test that the specimens were positioned correctly. The correct position was with the load applied to the specimen faces that were in contact with the true plane surfaces of the mould; this meant applying the load to a pair of the original sides of a specimen. This correction was deemed necessary as the slight concave shape of the original top surface caused local failure along the top perimeter of the specimen.

At the initial part of testing, as directed by Subsection 7.11.9 of CSA A8-1970 [15], no crushing or bedding material was used on the loaded surfaces of the specimens. This took place at the start of testing at Mix No. 13[6] until the second specimen of Mix No. 15 at the seven-day test. At this point it was advised by the laboratory technician that a paper towel should be used on both of the loading surfaces when testing mortar specimens; this procedure was followed for the remaining specimens.

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[6] Mix No. 12 was mixed after Mix No. 17.

The rate of loading was such that the deformation readings could be taken at a convenient rate throughout. Similar to the clay mortar project, this rate turned out to be considerably slower than that called for by CSA A8-1970 [15], Subsection 7.11.9. The actual time spent in testing each specimen is recorded with their respective results.

When the testing involved the use of the deformation gauge, two people were involved as described for the clay mortar testing. Only one person was required however, when using the electronic setup using L.V.D.T. readouts. This was possible since the deformation information was fed to an electronic digital readout box which was situated at the controls of the loading machine.

3.2.3.6 Error Analysis

The three areas of error analysis investigated were: 1) weighed materials, 2) volumetric measurements (shrinkage), and 3) compression testing.

1. Weighed Materials

In mixing the lime-sand mortar mixes, the lime and sand were proportioned by weight. The weigh scale used had weight graduations of one gram. Assuming a maximum weigh error of ±0.5 gram and relating this to the smallest quantity of material weighed (lime) which was 368 grams, this represents a maximum error of ±0.1 percent.

When performing the moisture content tests, a weigh scale with gradations of 0.01 gram was used. It is assumed that this scale had a maximum error of ±0.005 gram. With respect to the smallest measured weight of 18.15 grams obtained in the moisture content tests, this yields a maximum error of ±0.03 percent.

From the above discussion on the accuracy of the weighed materials, requirements of Subsection 7.2.2, Accuracy of Scales and Weights, of CSA A8-1970 [15] were met.

2. Volumetric Measurements (Shrinkage)

Calipers were used to measure indirectly the volumetric shrinkage of each lime-sand mortar specimen. Measurement capability of the calipers was to the nearest thousandth of an inch. Little error was anticipated in these measurements as the surfaces of the specimens were flat and regular with exception to the original top surface, which was slightly concaved. It was assumed that the error created by the original top surface was very small. With this assumption, a calibration check with the more time consuming but precise water displacement method was not performed.

3. Compression Testing

With the load indicator dial of the testing machine having a scale division of 1 pound, it was felt that the load readings were accurate to ±0.5 pound. The lowest load applied with failure was 198 pounds while the lowest division of load applied between deformation readings was 25 pounds. With respect to these figures, the respective maximum percentage of error are ±0.3 and ±2.0 percent.

Deformations taken by the deformation gauge had divisions of 0.001 inch. Although readings were taken to the nearest 0.0001 inch, accuracy was assumed to be ±0.0005 inch. With respect to the lowest deformation read at failure, 0.0243 inch, this represents a maximum error of ±2.1 percent.

In the second method of obtaining deformations, where an electronic setup using a L.V.D.T. was used, the apparatus was calibrated each day that tests were performed. The calibration employed the use of a deformation dial gauge (Photograph 17, page 71). By operating the testing machine to register a given deformation on the dial gauge and then by comparing it to the deformation registered on the electronic digital readout, the range of error was acquired. The error was taken as the difference between these two readings. Varying with the sets of tests, the error ranged from ±0.006 to ±0.012 millimetre. With the maximum reading error at ±0.012 millimetre, the lowest deformation at failure while using the L.V.D.T. setup was 0.733 millimetre. From this reading, the maximum error in the total deformation of a specimen at failure was ±1.6 percent.

3.3 SOIL-CEMENT MORTAR

The term "soil-cement mortar" as used throughout this report is defined as a mortar for which soil, Portland cement and water are its constituents. Unless otherwise stated, when the cement content in a soil-cement mortar is stated, it is to be taken as the proportion by weight.

3.3.1 Preliminary Literature Search

Reference 54, the Soil-Cement Laboratory Handbook gives detailed instructions on how to design a soil-cement. The three properties of soil-cement of major concern in this publication, in order of importance, are: 1) adequate weatherability (durability), 2) adequate strength, and 3) economy. Although there are more properties (see Appendix A) to be concerned about when designing a mortar, one could presumably use Reference 54 as a basis for developing a soil-cement mortar.

It is reported [54, p. 12] that 85 percent of all soils likely to be used for soil-cement can be adequately hardened by the addition of 14 percent cement or less. Also reported is that 50 percent of all the soils so far tested for soil-cement require only 10 percent cement or less for adequate hardening. A general rule is that the cement requirement of soils increases as the silt and clay content increases. Nonplastic or moderately plastic silty soils generally require about 10 percent cement and plastic clay soils require about 13 percent or more.

In cases where the amount of material passing the No. 200 sieve is more than 50 percent and the clay fraction is more than about 30 percent, with a corresponding plasticity index of more than about 20 and a liquid limit of more than about 45, special effort will generally be required to obtain adequate pulverization [54, p. 34]. Adequate pulverization is met when 80 percent of the soil-cement mixture passes the No. 4 sieve and 100 percent passes the one inch sieve, exclusive of gravel or stone retained on these sieves [53, p. 13].

Detailed in the Soil-Cement Laboratory Handbook [54] are three different laboratory procedures for determining: 1) the quantity of cement required, 2) the quantity of water required, and 3) the degree of compaction required to produce a satisfactory compacted soil-cement for a given soil. The three laboratory procedures are as follows: 1) ASTM-AASHO (American Society for Testing Materials -- American Association of State Highway Officials) Test Methods, 2) Short-Cut Test Procedures for Sandy Soils, and 3) Rapid Test Procedure.

The ASTM-AASHO test method is used for major projects of high cost relative to the testing costs; it is used so as to obtain the minimum cement content required for adequate hardness. A laboratory testing facility is required to perform the ASTM-AASHO test method. Testing involves moisture-density tests, freeze-thaw, and wet-dry tests. The approximate time to perform these tests is one month. Complete details of this procedure can be found in Chapter 3 of the Soil-Cement Laboratory Handbook [54].

The short-cut test procedure can be used to determine adequate cement contents for sandy soils only. Sandy soils here are classified as soils containing less than 50 percent material smaller than 0.05 mm. (silt and clay), less than 20 percent material smaller than 0.005 mm. (clay), and less than 45 percent material retained on the No. 4 sieve. Also, the material retained on the No. 4 sieve must not have a bulk specific gravity less than 2.45.

The only laboratory tests required for the short-cut test procedure are a grain-size analysis, a moisture-density test and seven-day compressive strength tests. With these tests, the procedure involves the use of data and charts developed from previous tests of similar soils. Thus, this eliminates a number of tests and greatly reduces the amount of work required compared to using the ASTM-AASHO test method. Overall, the short-cut test procedure does not always give the minimum amount of cement that can be used.

Rather, it provides a safe cement factor generally close to that indicated by the standard ASTM-AASHO wet-dry and freeze-thaw tests. Complete details of this procedure can be found in Chapter 6 of the Soil-Cement Laboratory Handbook [54].

The rapid test method is used for emergency construction and for very small projects where laboratory testing facilities are not available or detailed testing is not feasible or practical. This method is quick and has a very simple test procedure that involves moulding and visual inspection of specimens that cover a wide range of cement contents. Depending upon the soil, the cement content can range from six to 18 percent. The rapid test method provides a safe cement factor, but one that may be appreciably higher than the minimum for adequate hardness that would be obtained using the ASTM-AASHO test method.

Visual inspection of the specimens in the rapid test method is performed after at least a day or two of hardening. After a four-hour soaking, inspection is performed by "picking" with a relatively sharp-pointed instrument and by sharp "clicking" of each specimen against a hardened object such as concrete to determine the relative hardness. If a specimen cannot be penetrated more than 1/8 to 1/4 inch by picking and if it produces a clear or solid tone upon clicking, an adequate cement factor is indicated [54, p. 10]. Complete details of the rapid test method can be found in Chapter 7 of Reference 54.

Chapter 9 of Reference 54 discusses the testing of plastic soil-cement. To have a consistency of that of plastering mortar at the time of placing, a soil-cement should be plastic in nature. To form a plastic soil-cement mixture, the mix usually requires cement contents to be four percentage points higher than those used with soil-cement compacted with optimum moisture to maximum density. In addition to this, it may be advantageous to increase the water content so that the placement of the soil-cement can be easily facilitated.

Soils that contain more than about 30 percent material passing the No. 200 sieve are generally not used: they are difficult to pulverize and because of their stickiness, they are difficult to mix and place in a plastic condition [54, p. 44]. Laboratory testing procedure for a plastic soil-cement differs slightly from that of compacted soil-cement. This procedure is discussed in Chapter 9 of Reference 54. For a plastic soil-cement to have a surface that is more resistant to water erosion it is recommended [54, p. 45] that the cement content be increased by two percentage points above that indicated by tests.

Testing data and properties of the two soils available for the experimental program are given in Appendix B. Results in this Appendix indicate that both of the soils were found to be plastic silty clays. For such a soil, adequate pulverization, as detailed earlier, may be a problem.

So as to meet the pulverization requirements and to bring them about with more ease, an addition of larger-grained material, such as sand, may provide improvement. Gillard and Lee [36, pp. 67 to 81] mention a combination of such a mix containing Portland cement, clay and sand with a volumetric proportion of 1:1:4.5 respectively. With the soil as is, an estimated cement requirement [54, p. 12] for the ASTM-AASHO test method is about 13 percent or more, as compared to the 13 percent of cement in the above mix containing sand (assuming average dry density weights of Portland cement, clay and sand to be 85, 110 and 100 pounds per cubic foot respectively [45, p. 361; 26]).

Most stackwall buildings are considered relatively small projects. Therefore the rapid test method usually would be used to determine the adequate amount of cement required. Since this method gives an appreciably higher cement content than the ASTM-AASHO test method, the required cement content would probably be greater than the 13 percent estimated above. There may be room for an empirical adjustment factor (downwards) to the cement content derived from the rapid-test method.

To obtain a plastic soil-cement, which is more suitable for mortar, the preliminary literature search indicates that an additional four percent of cement is required over that required for the three criteria discussed above. In addition to this, an additional two percent is required for the plastic soil-cement to be water erosion resistant.

Summing up, the plastic silty clay soils available for the experimental program would require a cement content of 19 percent or more. The cost of a soil-cement mortar with such a high cement content would not be economical. Little or no benefit was seen in such a mortar relative to a conventional mortar [see Definitions and/or Reference 51, page 20] presently used for stackwall construction. Due to the above, soil-cement mortar was not proceeded any further.

3.4 CEMENT-LIME MORTAR WITH SAWDUST AND/OR WOOD CHIPS

The phrase "cement-lime mortar with sawdust and/or wood chips" as used throughout this report is defined as a mortar in which Portland cement, lime, sand, sawdust and/or wood chips and water are its constituents.

3.4.1 Preliminary Literature Search

The initial intention of using wood by-products (sawdust and/or wood chips) was to act as an inexpensive filler thereby extending the use of a given volume of cement-lime mortar. Since sawdust and/or wood chips are readily available at little or no cost and the unit volume of the cement-lime mortar would increase, the unit cost of the mortar should decrease.

The second intention of using sawdust and/or wood chips was to possibly increase the insulation value of the mortar. This comes from the fact that wood is a much better insulator than cement-lime mortar alone. Insulation may also increase due to a possibility of the sawdust and/or wood chips creating a more porous mortar.

Although it was expected that the compressive strength of such a modified mortar would be reduced, an adequate strength rather than high strength was sought. A preliminary literature search into the use of sawdust and/or wood chips in a cement-lime mortar was carried out through Reference Nos. 33 and 57.

Reference 33 [pp. 71 to 72] discusses the use of sawdust in plasters to serve as a retarder -- to increase the time required for the plaster to set. Eckel [33] states that any organic material or any uncrystallized material will act as a retarder. As the amount of retarder is increased, there is a general trend that the compressive strength of plasters will decrease. An example where a retarder in a mortar would be very helpful is in the case where very high temperatures exist at a building site.

Opposite to a retarder is an accelerator which decreases the time to which plaster will set. Materials which act as accelerators are inorganic and of the crystallized nature such as salts. An example of slow setting plaster is when impure lime is used and takes one to two hours to set. To accelerate the setting time in this case, an amount of pure plaster of Paris can be used. Alone, a pure plaster of Paris takes five to 15 minutes to set.

Sahlin [57, p. 21] points out that if additives must be added to mortar, most of them should be added in very small amounts. While a correct dose of an additive may improve the mortar, it is almost certain that an overdose will harm it [57, p. 21].

Although the preliminary literature search gave some positive indications for a cement-lime mortar with sawdust and/or wood chips, an experimental program was not performed. This decision came mainly from the fact that relative to the other two types of mortars set out to experiment with, clay and lime-sand mortar, the economic advantage appeared to be less. The relative economics seemed less favourable since the purchase of both the Portland cement and lime still must be made. In addition to this, the quantity of sawdust and/or wood chips that could be added to a cement-lime mortar seems somewhat minimal as indicated by the preliminary literature search. Through possible experimental research at a later date, this assumption may however prove to be untrue.

Chapter IV

RESULTS

4.1 CLAY MORTAR

4.1.1 Constituent Data Results

Clay soils have the characteristic of being lumpy when dug up. This was the case with the soils available for the mixing of the clay mortar mixes. As the number and size of these lumps increased in the sample being mixed by hand, the effort required to produce a uniform mix increased. Mixing was further retarded if the lumps were drier as was the case of Soil No. 1 which was drier than Soil No. 2. The softer and higher-moisture-content Clay No. 2 was faster and easier to mix into a mortar paste than Clay No. 1.

The mixing of the sand with water into the soil assisted the breaking down of the lumps present in the soil and in general improved the workability (see Appendix A) of the mixture. Water was required when mixing in the sand since the sand was in a dry state. As the sand and water content of the clay mortar mix was increased, it was easier to get the clay into a workable paste and the mortar became less sticky in the mixing pan.

When the dry flax straw was added to the clay and sand mixture, additional water was required in the mix to maintain adequate workability. It was found that a good mixing in of the flax straw got the thread-like fibres surrounding the straw core (see Appendix D) to separate into individual fibres. Since the thread-like fibres have a smaller diameter than the flax straw itself, a fibre with a higher aspect ratio was created in the mix: a higher aspect ratio implies a higher strength. This phenomenon is similar to that of the bundled steel fibres discussed in the preliminary literature search on clay mortar.

With the addition of the dry hydrated lime to the clay, sand and flax straw mixture, additional water was again required in the mix to maintain adequate workability. It was noted that the lime in a clay mortar brought about a noticeably smoother consistency and improved workability.

In the overall mixing of the clay mortar mixes, the cast iron pestle that is used in soil testing worked fairly well in mixing the components of a clay mortar together. In particular, the pestle was useful in getting the lumps of clay combined with the remaining components of the mix.

After the mixing of the clay mortar was completed, a flow test was performed. The resultant flow of each mix is listed in Table VI. After the flow test, moulding of the specimens took place and then a final moisture content measurement was taken immediately after. This final moisture content was taken as the moisture content of the mix. Table VII lists these final moisture contents of each clay mortar mix along with the moisture contents at the various stages of each mix. The final moisture content of each mix is listed in the second last column of this table under the

Table VI

Flow Test Results of Clay Mortar Mixes

Mix No.	Flow (%)
1	10
2	53
3	65
4	55
5	48
6	53
7	60
8	56
9	49
10	48
11	50

heading "Measured m.c. -- After Testing and Moulding -- %".

Also included in Table VII is the total loss of moisture content (last column) of each mix. This is the loss in moisture content from the theoretical total moisture content to the measured moisture content after testing and moulding. The total loss of moisture content ranged from a low of four

Table VII

Moisture Content Record of Clay Mortar Mixes

Mix No.	Theoretical m.c.		Measured m.c.				Total Loss of m.c. (%)
	Mix's Theoretical Total m.c. (%)	Theoretical m.c. Before Fermentation (%)	Before Fermentation (%)	After Fermentation, Before Lime Added (%)	After Lime Added, Before Testing and Moulding (%)	After Testing and Moulding (%)	
1	95	95	n.d.	n.a.	n.a.	83	12
2	150	112	n.d.	n.d.	n.d.	140	10
3	153	110	n.d.	n.d.	n.d.	142	11
4	156	110	n.d.	n.d.	n.d.	144	12
5	160	110	105	103	154	147	13
6	138	90	88	n.d.	n.d.	130	8
7	148	88	83	82	143	141	7
8	144	90	85	82	139	136	8
9	132	90	86	86	128	124	8
10	142	90	88	88	141	138	4
11	155	100	96	94	151	148	7

Table VII

(Continued)

Notes:
1) m.c. indicates moisture content;
2) n.a. indicates not applicable;
3) n.d. indicates not done;
4) Moisture contents are expressed as follows:

$$m.c. = \frac{W_w}{W_s} \times 100\%$$

where: W_w = weight of water in a moisture content sample
W_s = weight of original soil solids (clay) in a moisture content sample, not including the added materials (sand, flax straw, lime);

5) Moisture content sample sizes were minimized before lime was added so as to minimize the error in calculating the percentage of soil solids (clay) in the moisture content sample after the lime was added;

6) Theoretical moisture content is the water originally in the soil plus the water added to the mix;

7) Total loss of m.c. = (mix's theoretical total m.c.) minus (mix's measured m.c. after testing and moulding).

percent for Mix No. 10 to a high of 13 percent for Mix No. 5. Summation of the losses in moisture content from stage to stage do not add up exactly to the total loss of moisture content due to the individual moisture contents' being reported only to the nearest whole percentage point. The loss of moisture can be attributed primarily due to evaporation during the mixing stages and secondarily due to the fermentation containers retaining some moisture.

At the initial stage of the clay mortar program there was concern about whether a pungent odor would result from the mixes after the fermentation period. Out of all the 11 mixes, only Mix No. 6 had a slight odor after the fermentation period. The length of fermentation of Mix No. 6 was the longest at 117 hours (see Table I, page 31) or about five days. The next lowest fermentation period was 98 hours (see Table I, page 31) or about four days for Mix No. 11. This would indicate that a maximum of four days should be allowed for the fermentation period if odor is of a concern.

In the moisture curing study of Mix No. 5, the moist-cured specimens were taken out of the moisture room at the approximate age of 15 days. At this stage, no shrinkage was apparent; the specimens were wet and appeared to be only slightly hardened to the touch. Though the moist-cured cubes did not shrink up to this point, once exposed to the laboratory air, hardening and shrinkage took place as it did for the air-dried specimens.

Shrinkage data for each set of specimens of every clay mortar mix are tabulated in Tables F-I to F-XII in Appendix F, pages 339 to 350. All of these shrinkage data were combined together to form Figure 3 using Computer Program No. 1 of Appendix G. In this figure the data are plotted as "% of Original Volume" versus "Age -- Days". The values of "% of Original Volume" were obtained by subtracting the Adjusted Volumetric Shrinkage percentage values in the tables of Appendix F from 100.

From the plot of the data points of Figure 3, it can be seen that the volumetric shrinkage of the specimens behaved in a bilinear form. At the beginning, the specimens shrank at a steady rate up to the approximate age of 10 days. After this age, the volume of the specimens remained approximately the same with no further volumetric shrinkage.

The equation of the sloped part of the curve in Figure 3 was arrived at using a Tektronix computer. The program used was Volume No. 1, Tape No. 1 of the statistics package -- "Simple Regression". In getting this slope, all of the shrinkage data points from the age of zero day to the approximate age of stabilization (no further shrinkage) was used. Stabilization occurred before 10 days. If the first shrinkage measurement of a set of specimens was taken after 10 days, the data point was not used in determining the slope of the curve, since it would not lie on the first part of the bilinear curve.

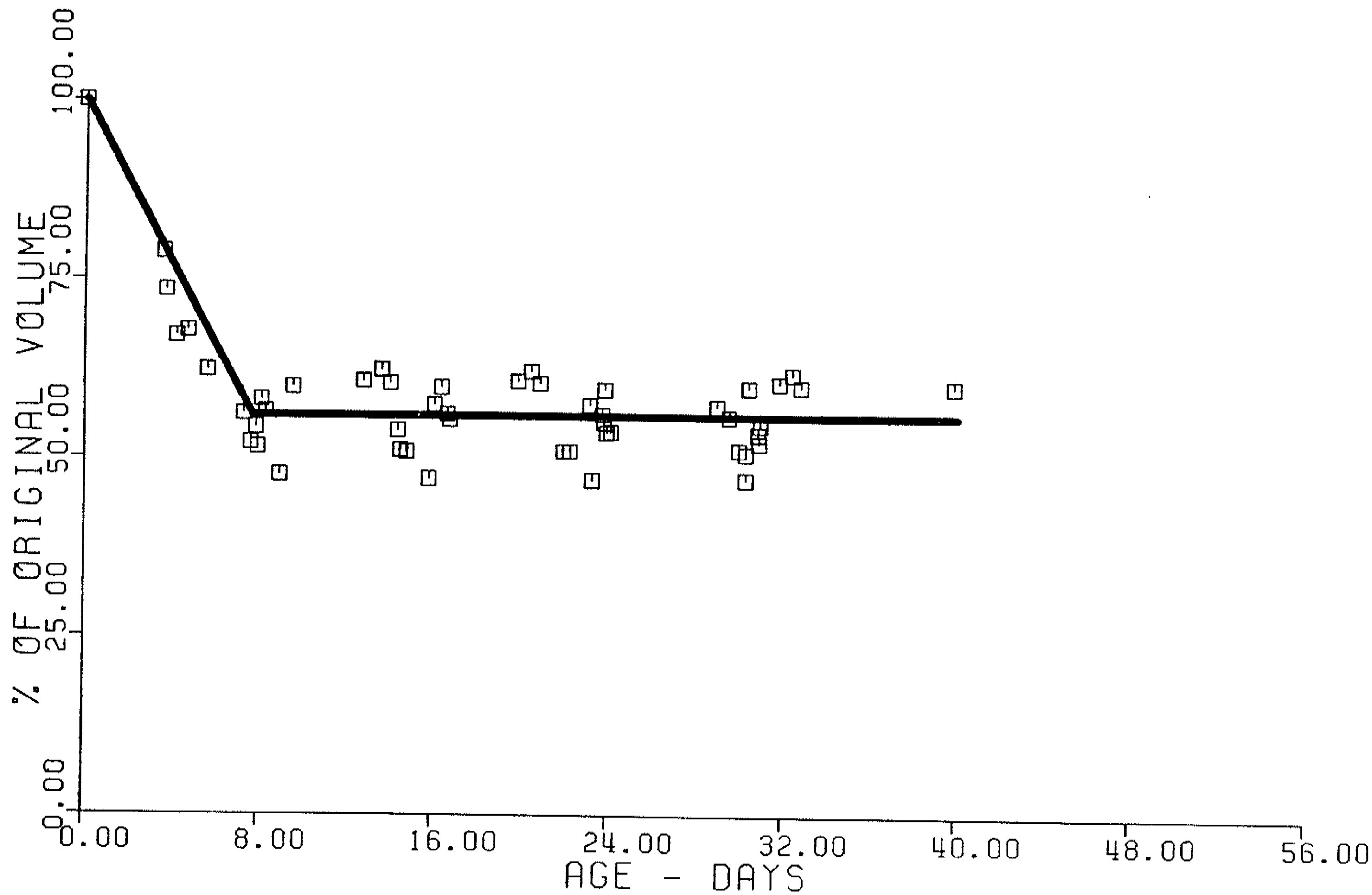


Figure 3: Shrinkage Behaviour of Clay Mortar Mixes

The resultant equation of the sloped line in Figure 3 is:

$$y = 100 - 5.685(x)$$

where x = Age in Days

y = % of Original Volume

The statistical value of R-squared (coefficient of multiple determination) for this equation relative to the data points, as determined by the computer program, is 0.96. This sloped line starts at x = zero day and ends at a day where it meets the horizontal line representing that shrinkage has stopped. Position of this horizontal line was determined by first calculating the average stabilized volumetric shrinkage. This value was then subtracted from 100 to get the percent of original volume value of y = 56 percent.

In Figure 3, the point at which the sloped and the horizontal lines meet is at x = 7.74 days and y = 56% of original volume. This would indicate that one can expect the volumetric shrinkage of clay mortar to cease at the age of 7.74 days or approximately eight days and with an approximate volumetric shrinkage of 44 percent.

During the initial drying stage of Mix No. 1, all of the three specimens, in their moulds, formed a chip on one of the bottom corners. This chip became more apparent once the pre-testing preparation was started. The cause of this phenomenon is believed to be due to one bottom corner sticking to the side of the mould while the rest of the specimen shrank away. So as to make the specimens acceptable for testing purposes (see Article 3.1.3.3, Pre-Testing Measurements and Preparation) sanding was required resulting in relatively high material loss compared to the rest of the clay mortar mixes.

The 10 remaining clay mortar mixes also required sanding of the specimens, but to a lesser degree. Sanding in this case was not due to chipping but rather due to irregularities in the surfaces such as convexity, concavity and bumps formed during drying. The degree of material sanded can be detected from the testing size of the specimens for each mix (see Table H-V, pages 454 to 455 of Appendix H). Specimens of Mix No. 8 required the least amount of sanding as all of the sides had very little distortion except for the top which was slightly concave shaped.

4.1.2 Testing Data

Prior to the sanding of the clay mortar specimens, in preparation for the compression test, notes were taken on the colour, shape, surface texture, cracks, density (for Mix Nos. 7 to 11 only) plus other assorted features. After the sanding was completed, the specimens were measured by calipers to obtain the necessary dimensions for the end stress and strain calculations. At the time of the compression tests, the time required to perform the test on each specimen and the age of the mix was recorded. After the compression tests were completed for a mix, the mode of failure, the angle of rupture and general post-testing notes were taken. Details of the above pre-sanding data, post-testing data and the compression testing information for the clay mortar mixes are in Appendix H.

From the pre-sanding data in Appendix H, each mix had specimens that were greyish in colour and had surface cracks. The grey colour comes naturally from the clay which is the major component of the clay mortar mixture. Cracks came in various widths and lengths. Widths of the cracks were from hairline thickness up to a maximum of 0.082 inch while the lengths went from the very small up to an inch; some hairline cracks may of been longer but due to their erratic shape, the lengths were not measured.

Data taken on the shape, surface texture, density (Mix Nos. 7 to 11) and other assorted features changed from mix to mix but did have some similarities (see Appendix H for details). Table VIII lists the measured density of selected clay mortar mixes. Mix Nos. 11 and 9 had the lowest and highest densities at 77 and 93 pounds per cubic foot (pcf.) respectively. From the mixes that were measured, the average density was 85 pcf.

Table VIII

Measured Density[1] of Clay Mortar Mixes

Mix No.	Average Density[1] (pcf.)
1-6	Not Measured
7	84
8	88
9	93
10	85
11	77
Average	85

[1]Average values based on three specimens per mix using the water displacement volumes.

The dimensions of the specimens prior to the compression test, the time required to perform each test and the age of each mix at the time of testing is recorded in Table H-V of Appendix H, pages 454 to 455.

During the compression test, all of the clay mortar mixes failed with a peak load except for Mix Nos. 7, 8, 10 and 11. The failure cracks on all of the specimens of all the mixes indicated a splitting mode of failure with a corresponding angle of rupture of 90 degrees. In addition to the splitting failure, Mix Nos. 1 and 5 had cracks indicating a pyramidal fracture with respective angles of rupture of 80 and 60 degrees.

With Mix Nos. 7, 8, 10 and 11 having no peak failure load and with the loading continuing up to high deformations, the specimens resulted in having a crushed, barrel shaped appearance. This indicates a ductile, plastic material. As with the rest of the clay mortar mixes, the specimens in general showed evidence of being restrained on the loading surface(s) and were slightly bowed out at the mid-height of the specimens; this gave the specimens a slightly crushed appearance.

In the calculation of the compressive strength of a specimen, the procedure outlined in Subsection 7.11.10, Part a) of CSA A8-1970 [15] was followed. From the same Standard, Subsection 7.11.10, Part b) partially states that cubes that give strengths differing more than 10 percent from the average value of all test specimens made from the same sample and tested at the same period, shall not be considered in determining the compressive strength; this specification was not followed.

4.1.3 Plots

All of the calculated compressive stress-strain data points of the clay mortar mixes were plotted to scale on computer plots. For each mix, three different symbols were used to represent the three specimens per mix. A single curve was then drawn to represent the compressive strength and failure characteristics of the mix during the compression test.

Specific combinations of these single curves were then matched so as to give four different study plots.

On all of the plots, when an index such as "x 10^1" is applied to an axis of numbers, it means that one should take the numbers labelled and apply that index to those numbers. It does not mean that the index was previously applied to the numbers.

4.1.3.1 Compression Testing Data Plots

From the general shape of the plotted data points, it was decided to use polynomial curves to describe the compressive strength and failure characteristics of the mixes when curve fitting. The general equation of the polynomial curves that was used is:

$$y = c_1 + c_2x + c_3x^2 + \ . \ . \ . + c_nx^{n-1}$$

where

$$f_1(x) = 1.0$$
$$f_2(x) = x$$
$$f_3(x) = x^2$$
$$\vdots \qquad \vdots$$
$$f_n(x) = x^{n-1}.$$

The constants of these polynomial equations were determined using a least-square fit computer program from Reference No. 39 [pages 309 to 312]. As printed in this reference, this program has errors in it. These errors were corrected. Additional changes were done to this program to suit the requirements of this study. The least-square fit of a polynomial computer program as used in this study is listed in Appendix G as Computer Program No. 2.

In choosing a best-fit curve, the lowest degree polynomial that followed the data points was sought. Since all of the data points indicated some curvature, the polynomial initially tested for each clay mortar mix was of second degree. To make the best-fit polynomials start at the origin, as directed by the data points, the best-fit curves defined by the variable "y" were made totally dependent upon the variable "x". This was achieved by having all of the coefficients determined by the least-square fit computer program attached to the variable "x". Hence, the initial polynomial trialed for each clay mortar mix had the form:

$$y = c_2x + c_3x^2.$$

After obtaining the second degree coefficients, the data points and the best-fit curve were plotted out using a computer program developed primarily through the aid of Reference Nos. 25 and 29. A copy of this best-fit curve plotting program is in Appendix G, listed as Computer Program No. 3.

To correct any initial seating problems between the specimen and the testing machine during the compression test, a correction value called **xstart** was incorporated in the above program to adjust the x-/strain values. An initial seating problem was considered to exist if a bilinear testing curve was anticipated for the initial data points. From the plot of the data points, an initial seating problem was not evident and therefore the correction value **xstart** was given the value of zero for all of the clay mortar mixes.

The best-fit curve plotting program was written in a way that the best-fit curve ended just before a negative slope began or at the maximum y-/stress value obtained in the test data. If the mix did not have peak loads for all of the specimens, a straight dashed line was drawn horizontally from the end of the best-fit curve to the far right of the plot. This dashed line represents that loading was continued after this cut-off point, but no peak load occurred. It should be noted though that the path of this dashed line does not necessarily represent the actual path taken during the test or of the best-fit curve.

In addition to plotting the best-fit curve, the above program also calculated the adjusted coefficient of multiple determination (R_A^2). R_A^2 was calculated for the best-fit curve up to and including the maximum x-value data point although the best-fit curve may or may not of extended to this point. A R_A^2 value of 1.0 represents an excellent fit while a value closer towards zero indicates a poor relationship between the best-fit curve and the data points.

If the best-fit curve visually described the data points behaviour satisfactorily and the value of R_A^2 was above the value of 0.5, the coefficients/polynomial was used for the mix. In the case where this was not true, the next higher degree polynomial was tried until these conditions were met. A third degree polynomial would have the form:

$$y = c_2x + c_3x^2 + c_4x^3.$$

As one uses a higher degree polynomial for a best-fit curve, the value of the coefficient of multiple determination (R^2) will also rise. To balance the cost of using more parameters (a higher degree polynomial) against the gain in the value of the R^2, an adjustment factor was calculated and applied to all of the R^2 calculations. The R^2 adjustment factor was used irrespective of the degree of polynomial used.

The best-fit polynomial curve coefficients used for each of the clay mortar mixes and their respective value of R_A^2 is shown in Table IX. Resultant curves from these coefficients are shown in Figures 4 to 15. Included in these figures, for each mix, are the stress-strain data points for each specimen; these data points are plotted to scale. Figures 4 to 15 are to be taken as the representative stress-

Table IX

Computer Plotting Information for Clay Mortar Mixes[1]

General Equation: $y = c_1 + c_2x + c_3x^2 + c_4x^3$

Mix No.	Coefficients c_1	c_2	c_3	c_4	R_A^2
1	0.0	609.3	-101.5	0.0	0.89
2	0.0	288.5	-23.90	0.0	0.87
3	0.0	161.6	-11.22	0.0	0.91
4	0.0	225.1	-17.34	0.0	0.67
5A	0.0	208.9	-18.62	0.0	0.86
5B	0.0	561.4	-146.1	10.02	0.67
6	0.0	56.09	-2.286	0.0	0.95
7	0.0	24.49	-0.8360	0.0	0.94
8	0.0	27.15	-1.016	0.0	0.94
9	0.0	90.52	-6.747	0.0	0.84
10	0.0	36.10	-1.174	0.0	0.90
11	0.0	28.88	-0.8318	0.0	0.93

[1]Determined by the least-square fit of a polynomial computer program -- Program No. 2 of Appendix G.

strain plots for the clay mortar mixes.

The representative plots for Mix Nos. 7, 10 and 11 (Figures 11, 14 and 15, pages 112, 115 and 116) were noted to have satisfactory R_A^2 values but visually did not describe the data points behaviour accurately. Higher degree polynomial curves other than the second degree were tested with but also proved to be unsatisfactory. In order to have curves that visually described Mix Nos. 7, 10 and 11 better, hand-drawn curves were drawn in addition to the computer plots for material property analysis. Hand-drawn curves for Mix Nos. 7, 10 and 11 are shown in Figures 16 to 18.

Figures 16 to 18 were drawn up using two parts to a curve. The first part was a linear curve used from the origin to the point where the linear behaviour stopped. From this point, a smooth non-linear second curve was drawn to the same position where the representative computer plots stopped. The data point (strain, stress) where the linear portion stopped for Mix Nos. 7, 10 and 11 are (1.12%, 49.0 psi.), (0.90%, 74.0 psi.) and (0.80%, 55.0 psi.) respectively.

Mix Nos. 7, 8, 10 and 11 had increasing stress-strain testing values with no indicative peak failure load. Computer plots containing all of the stress-strain values that were obtained during the compression tests, for thes mixes, are shown in Figures 19 to 22.

The computer program used in plotting Figures 19 to 22 is listed in Appendix G as Computer Program No. 4. This program was developed primarily through the aid of Reference No. 25. The plotting in this program is classified as simple plotting; the curve for each tested specimen is obtained by simply joining a smooth curve from data point to data point.

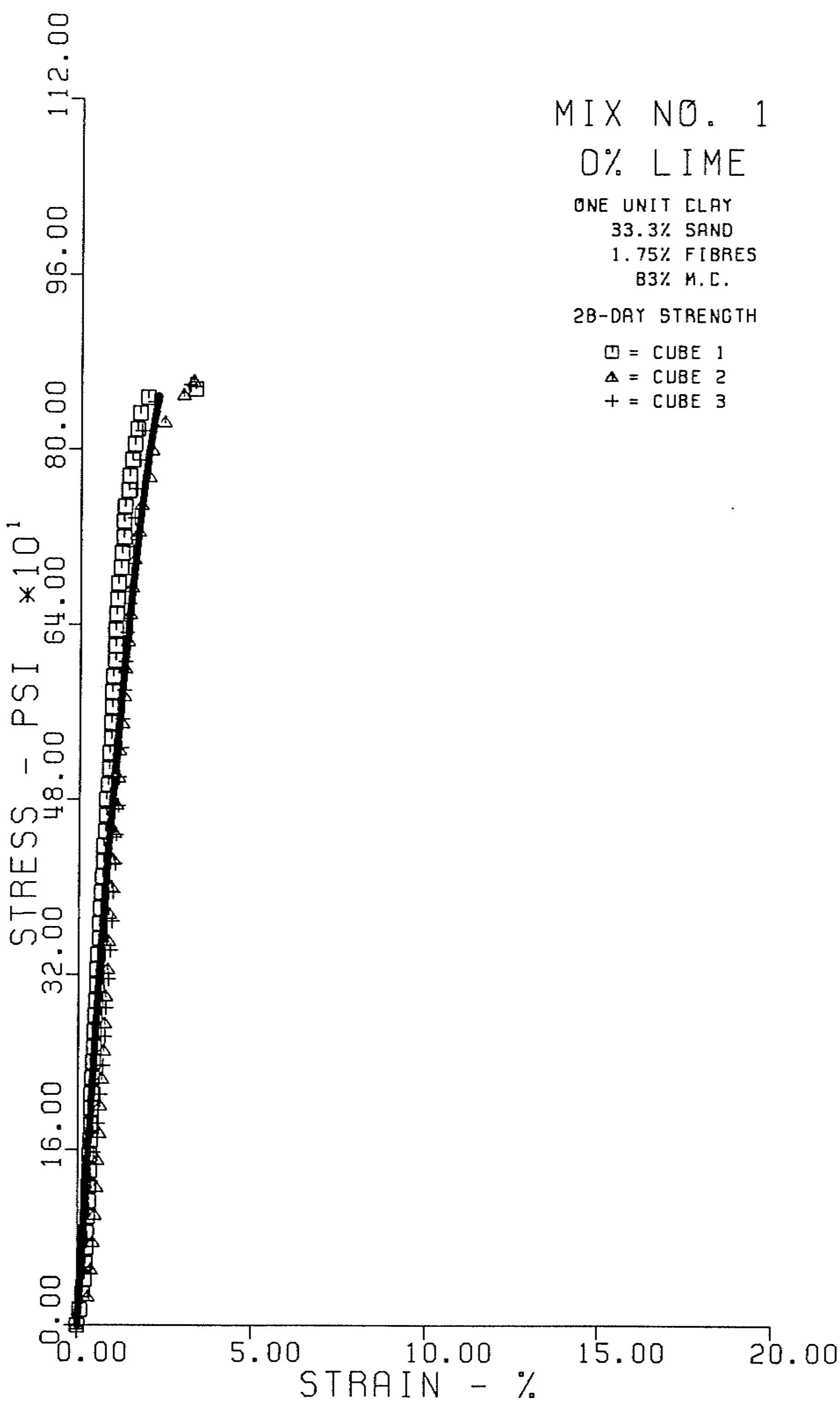


Figure 4: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 1

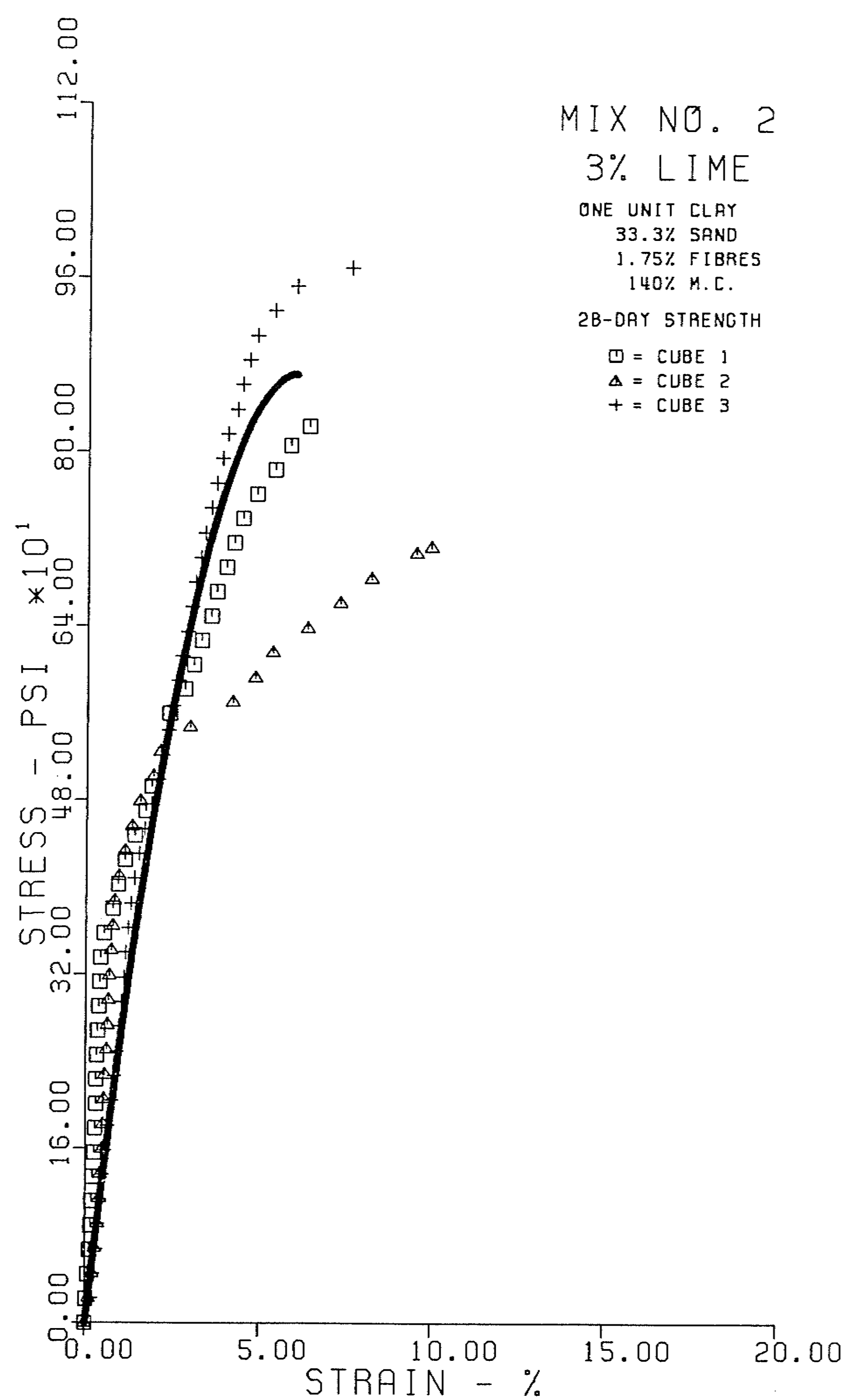


Figure 5: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 2

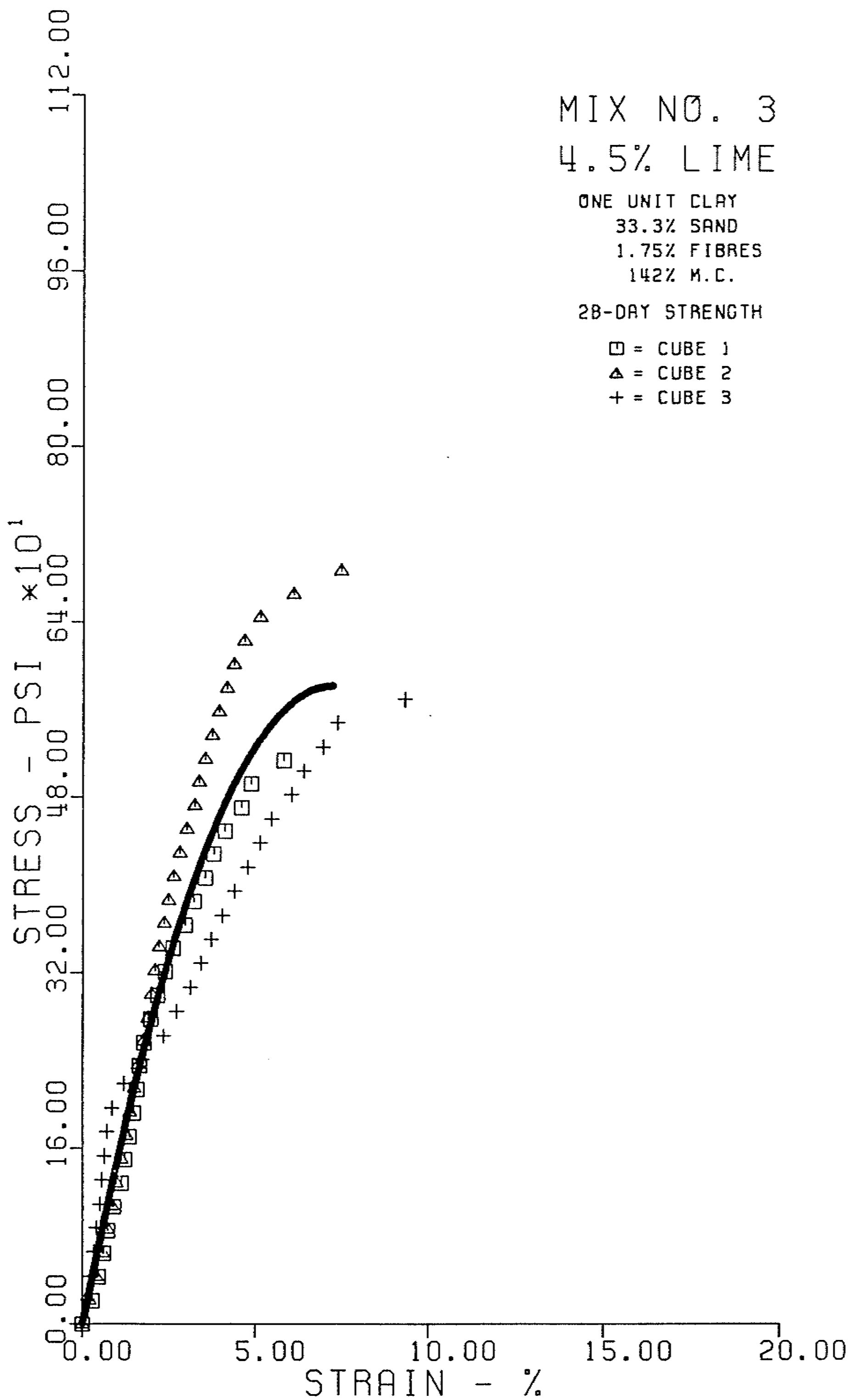


Figure 6: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 3

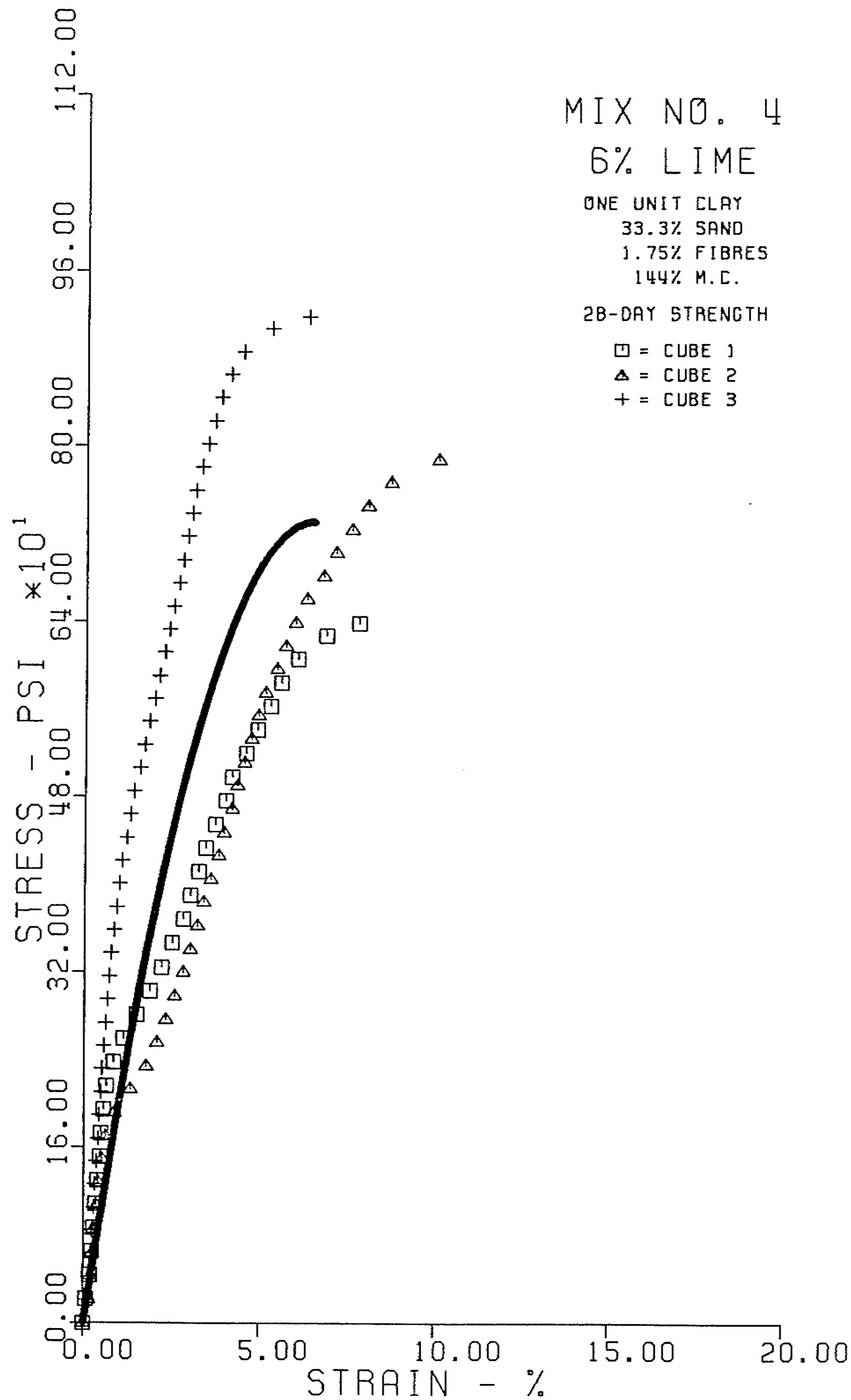


Figure 7: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 4

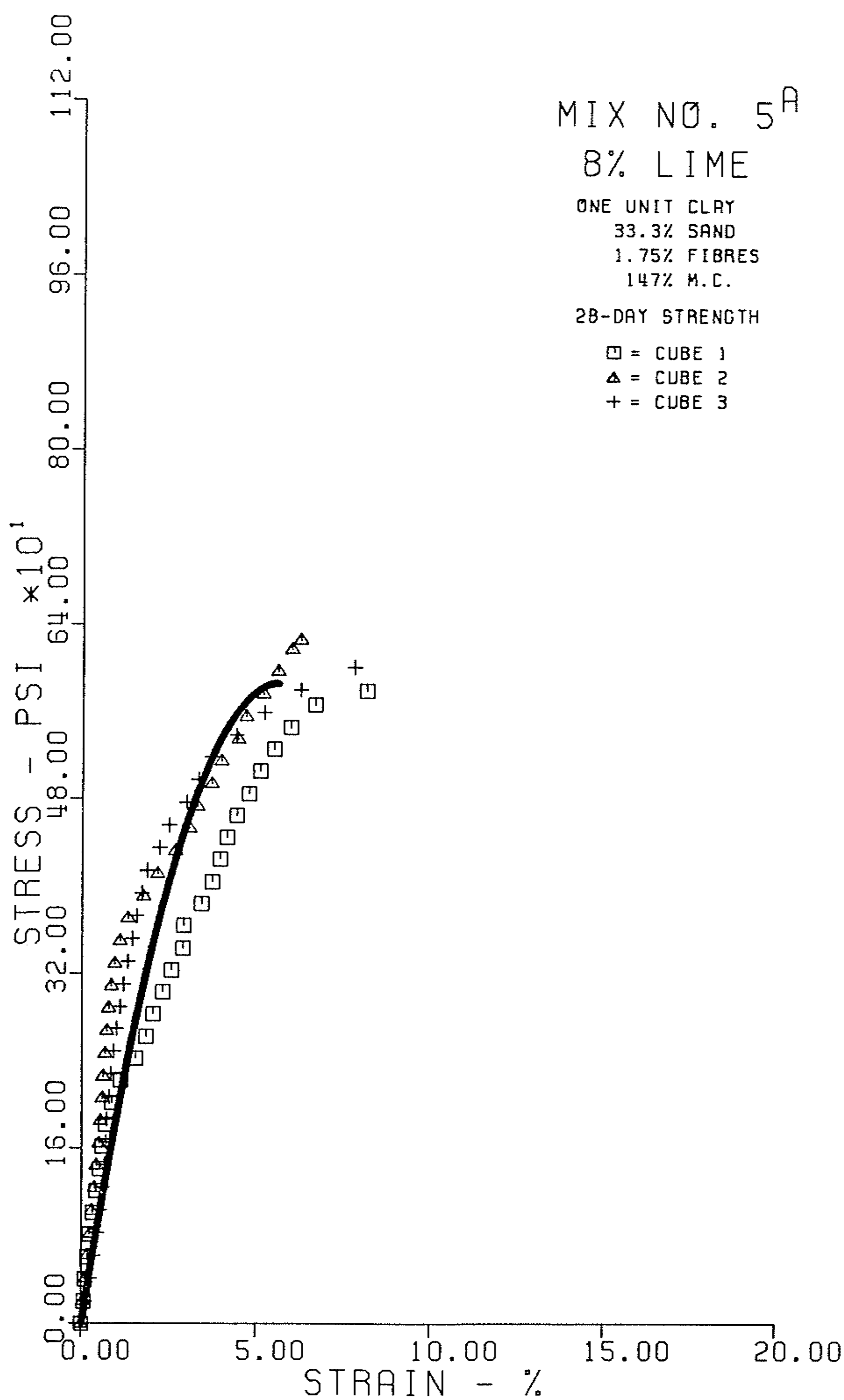


Figure 8: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 5A

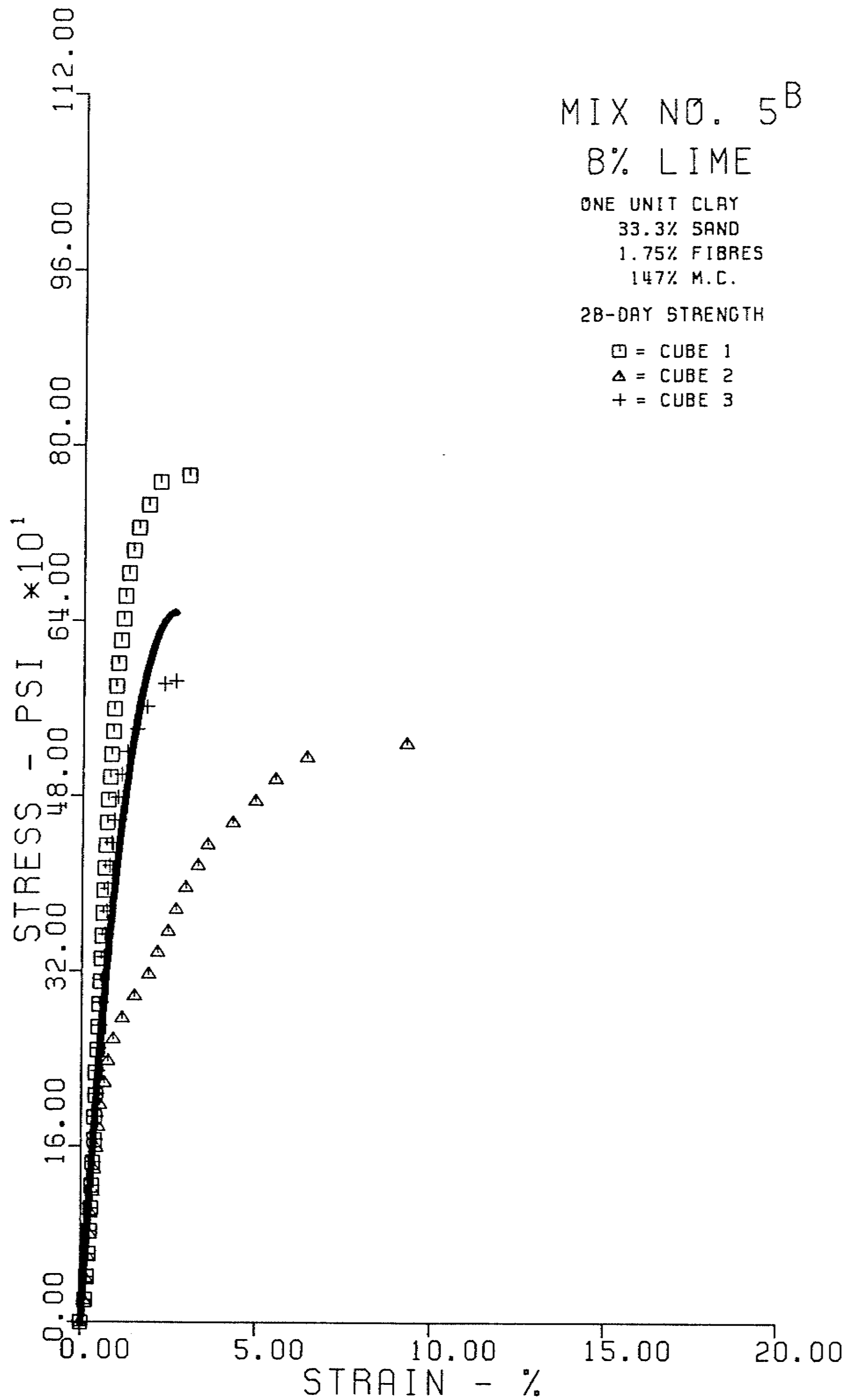


Figure 9: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 5^B

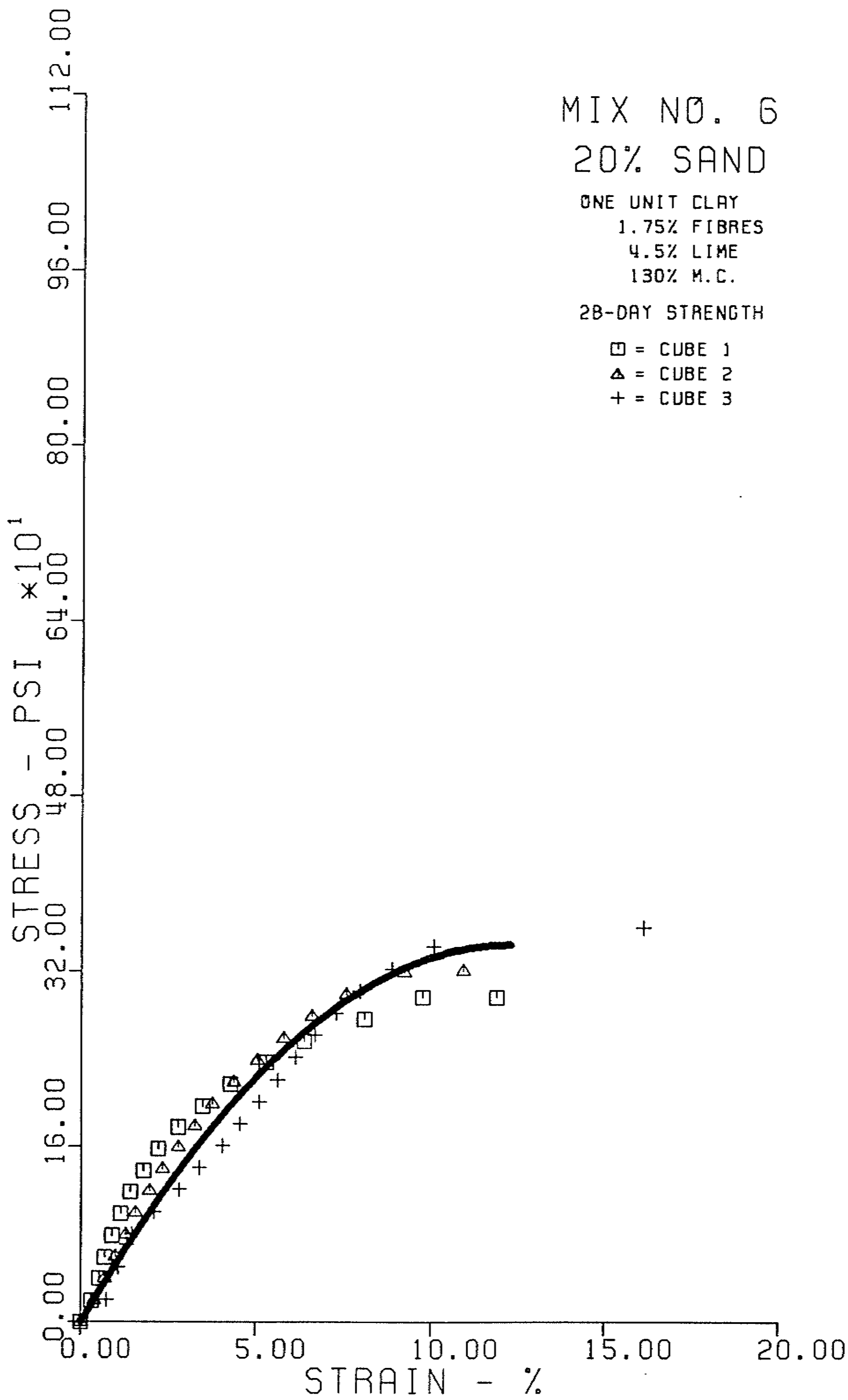


Figure 10: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 6

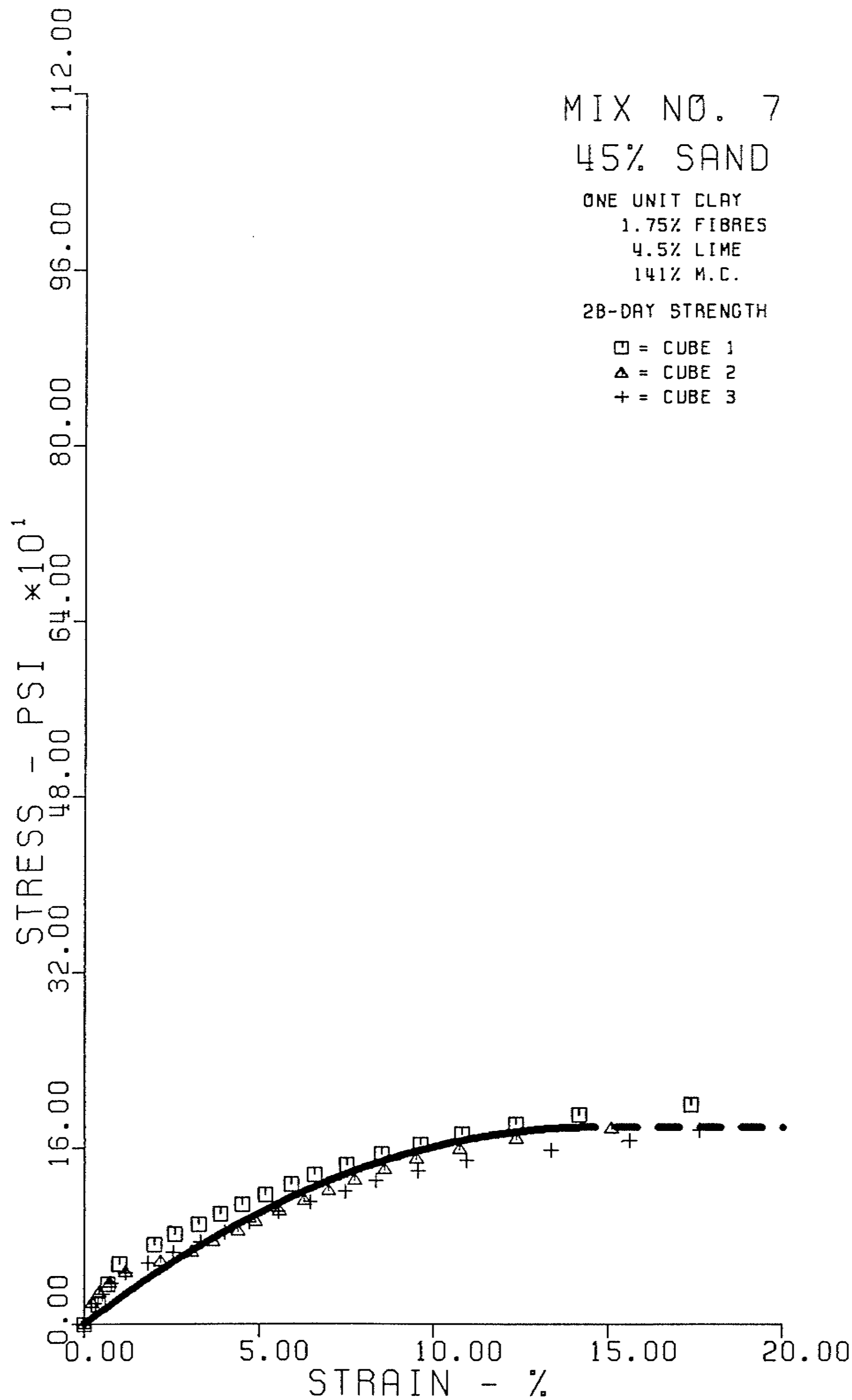


Figure 11: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 7

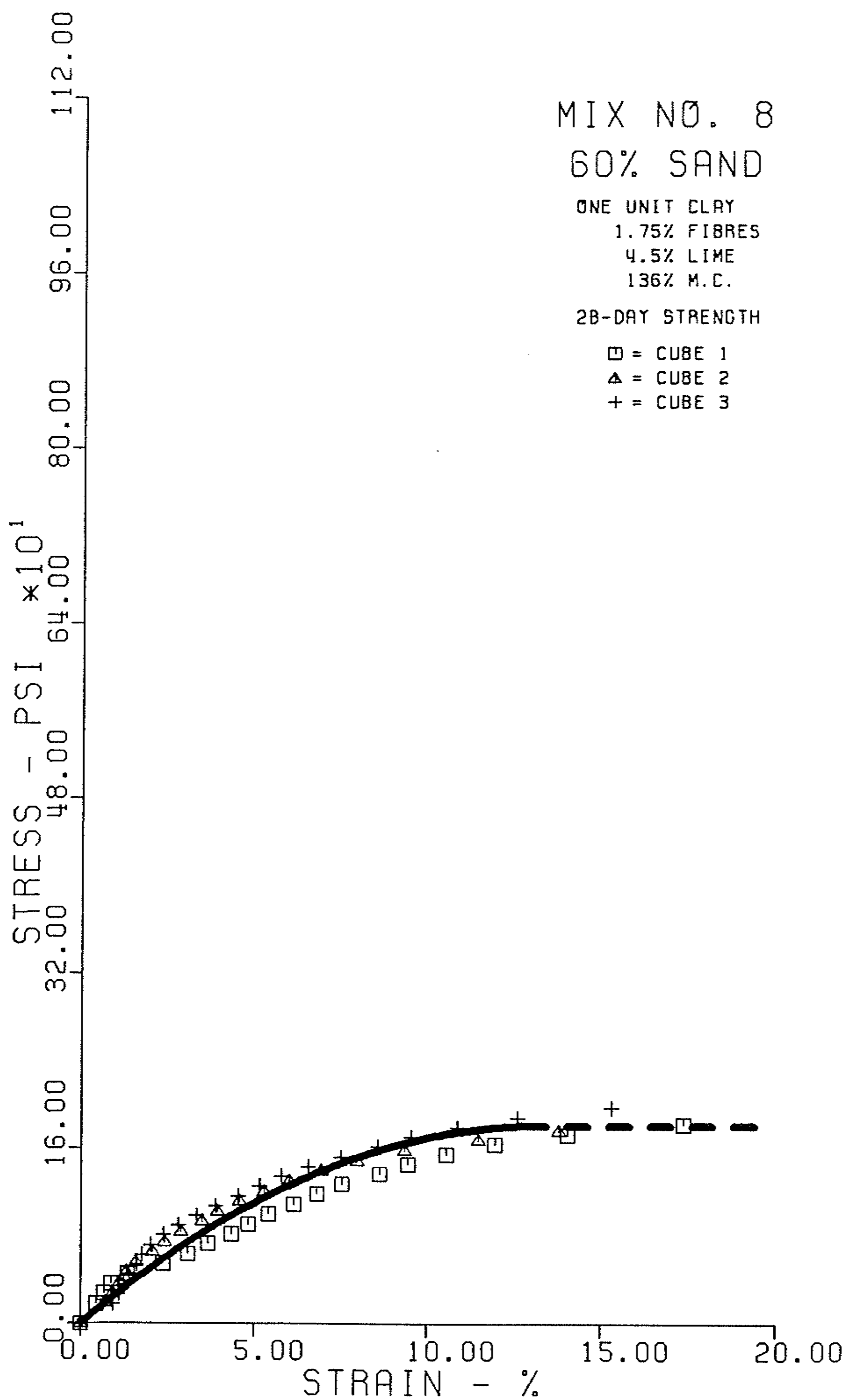


Figure 12: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 8

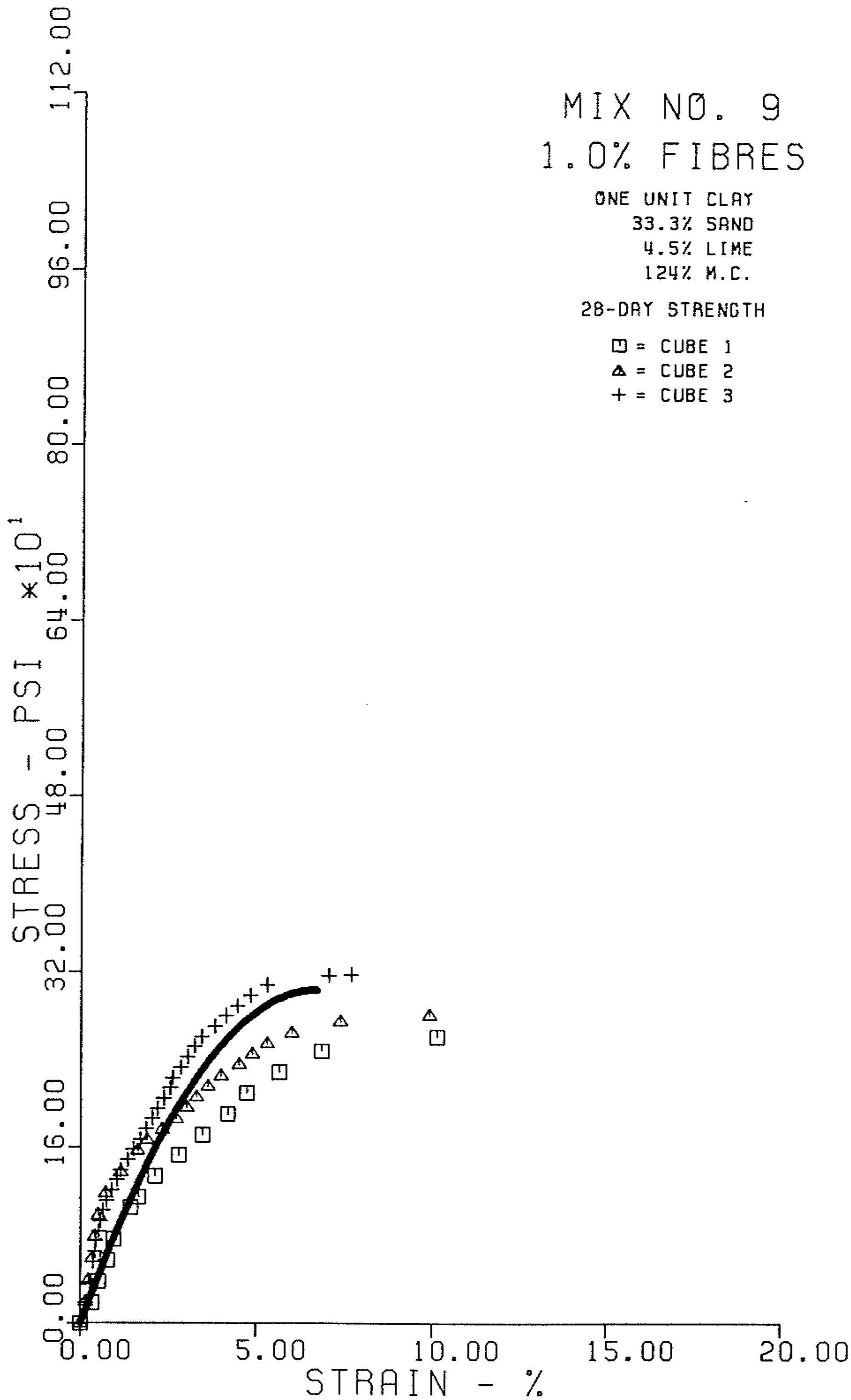


Figure 13: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 9

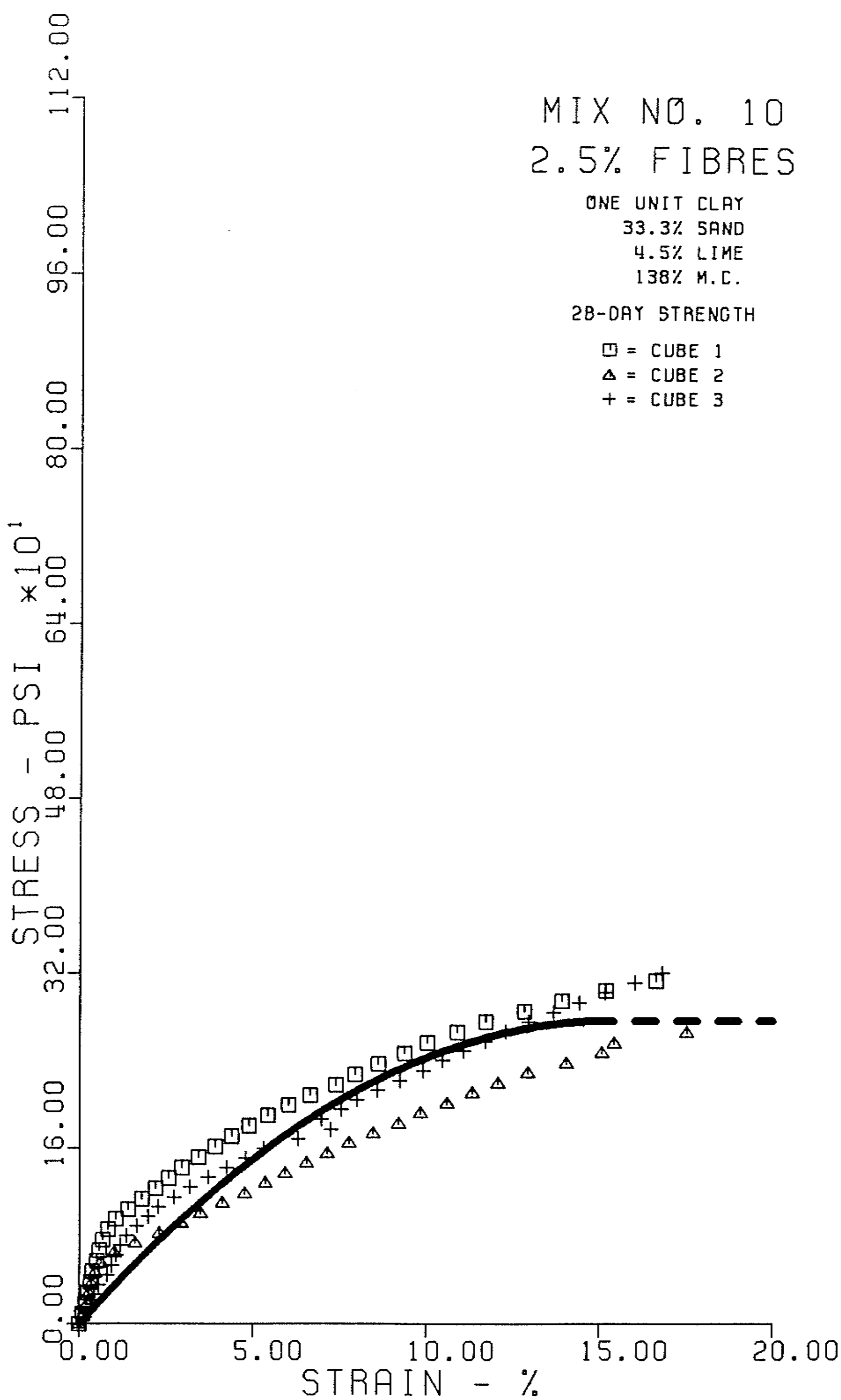


Figure 14: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 10

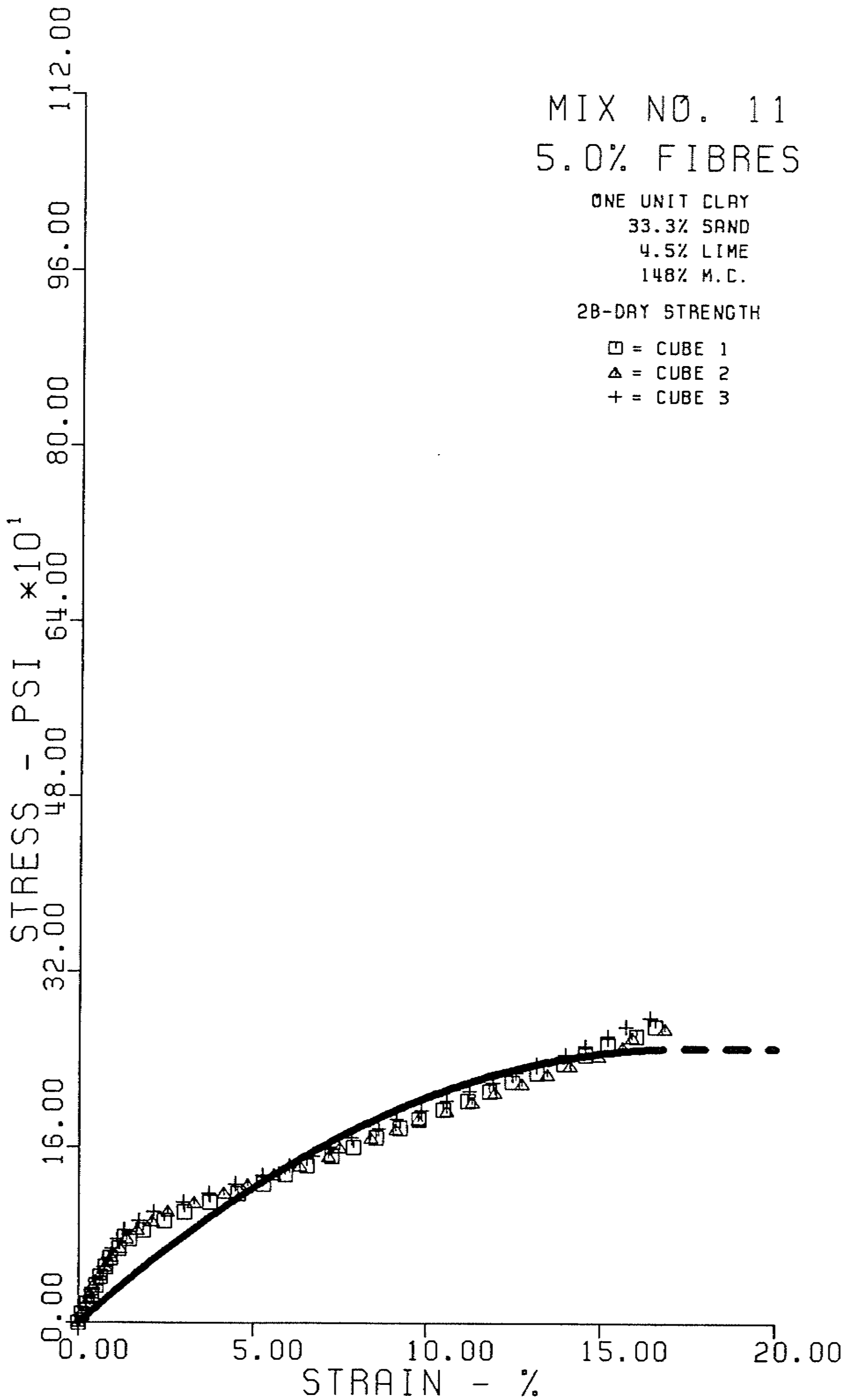


Figure 15: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 11

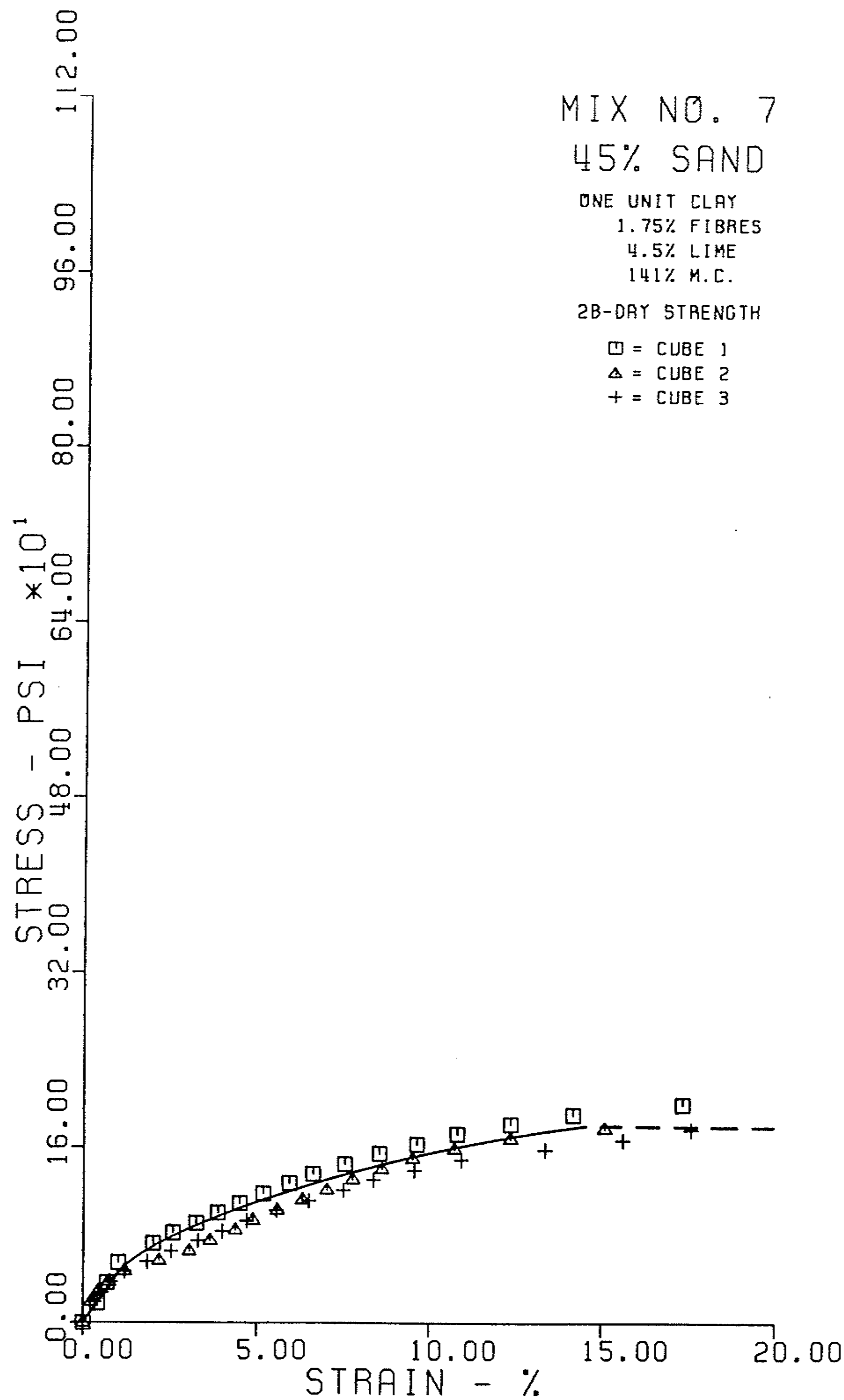


Figure 16: Hand-Drawn Curve Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 7

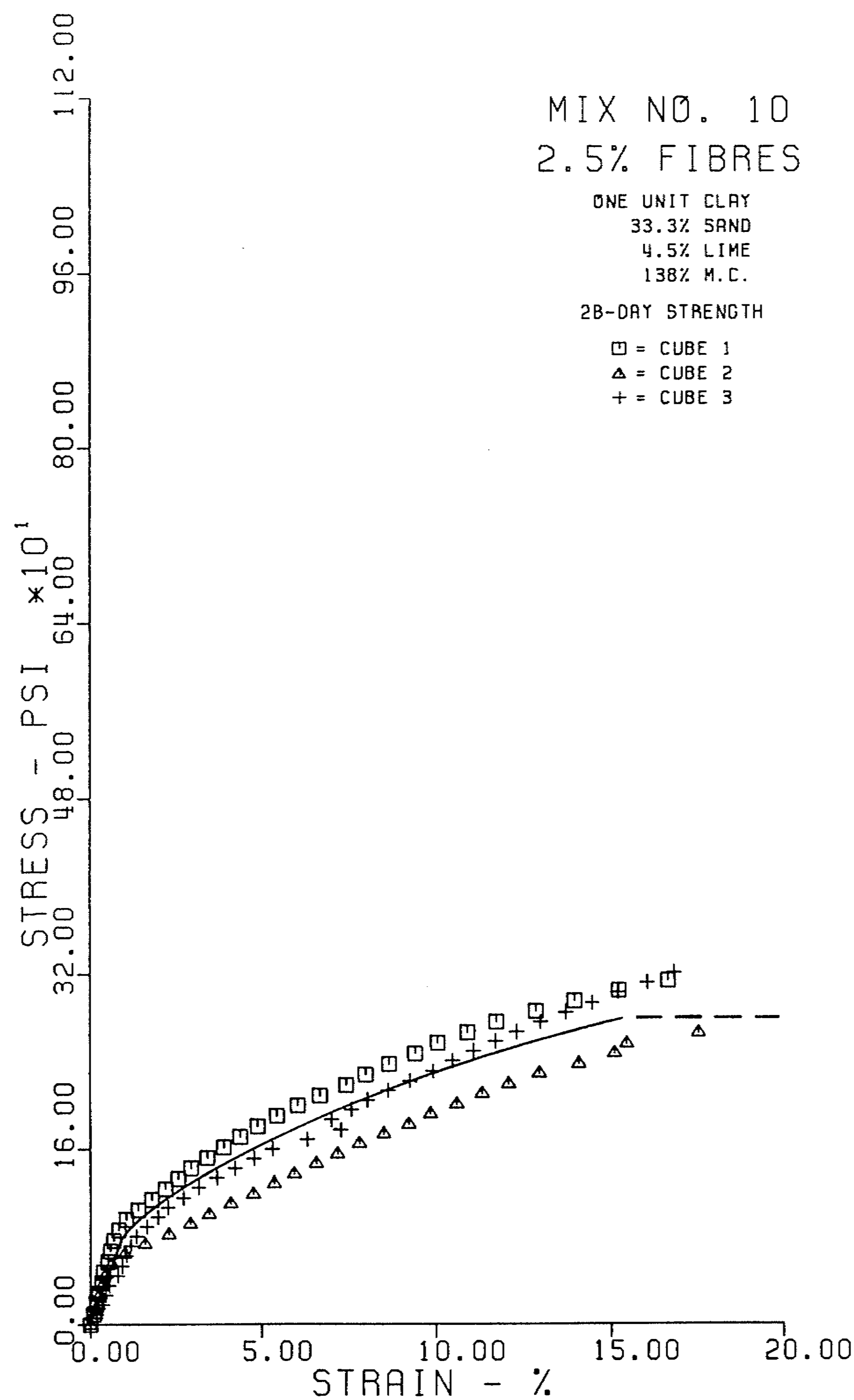


Figure 17: Hand-Drawn Curve Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 10

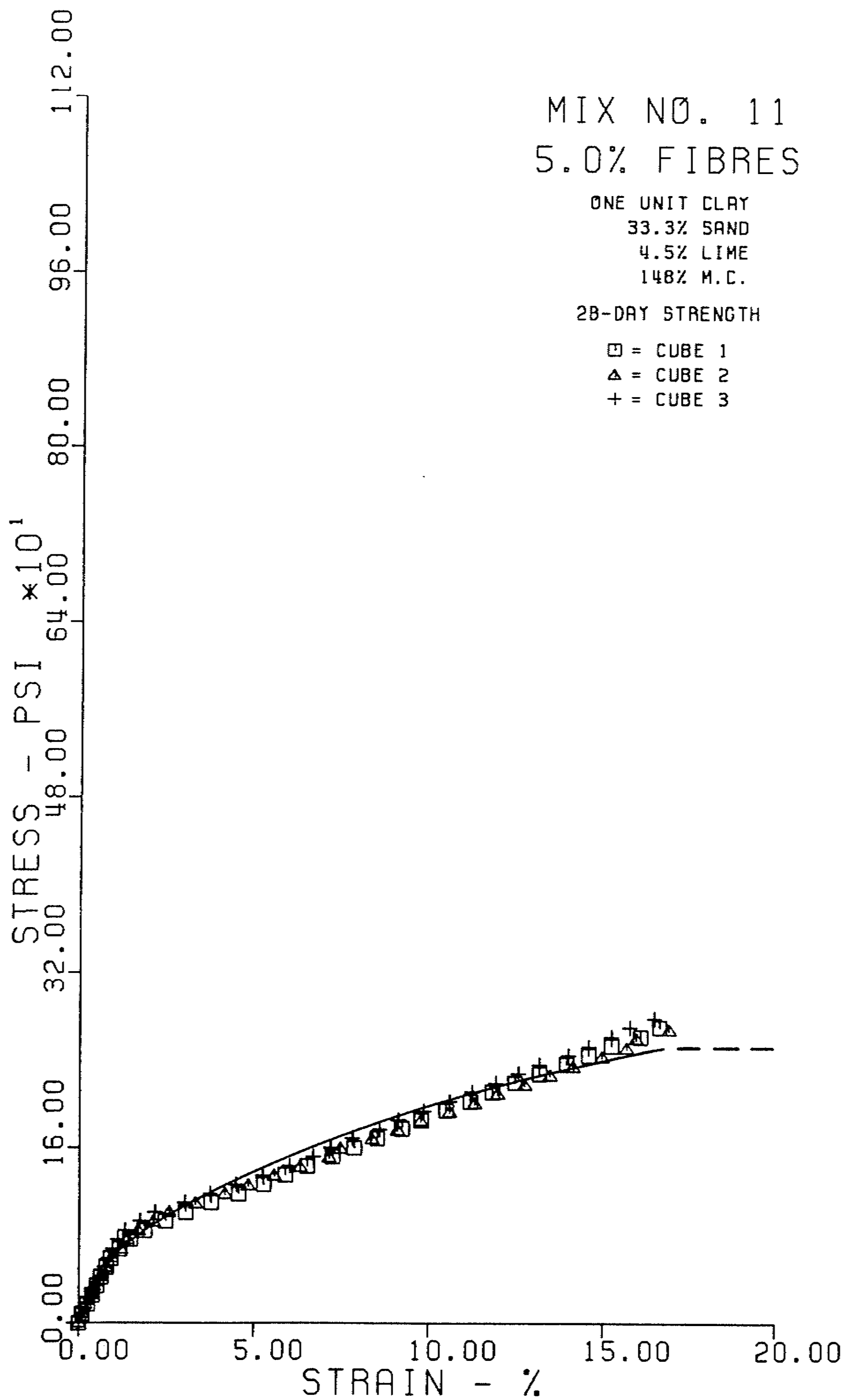


Figure 18: Hand-Drawn Curve Showing the 28-Day Compressive Strength and Failure Characteristics of Clay Mortar Mix No. 11

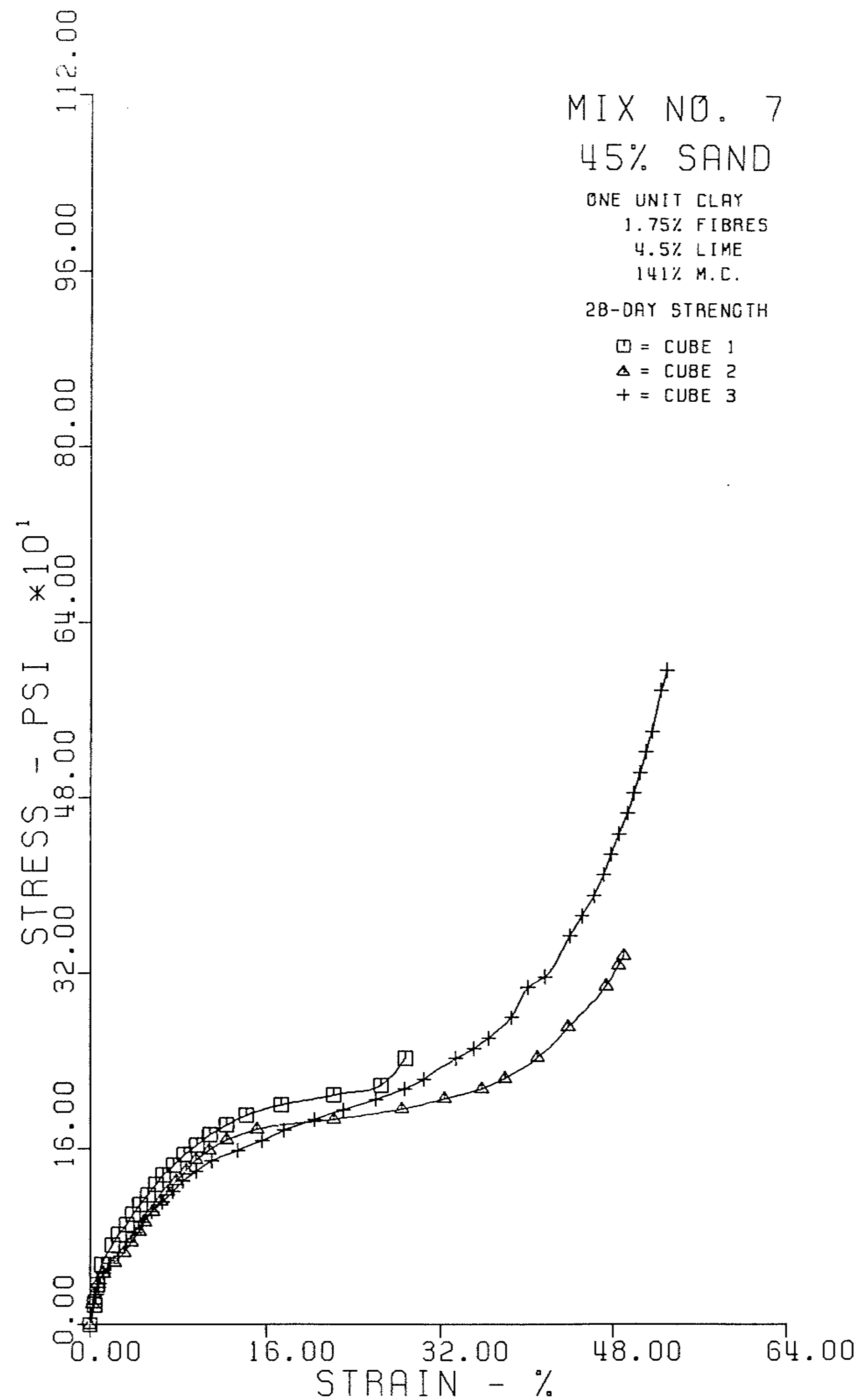


Figure 19: Computer Plot Showing All of the Recorded 28-Day Compressive Stress-Strain Data of Mix No. 7 with No Peak Failure Load

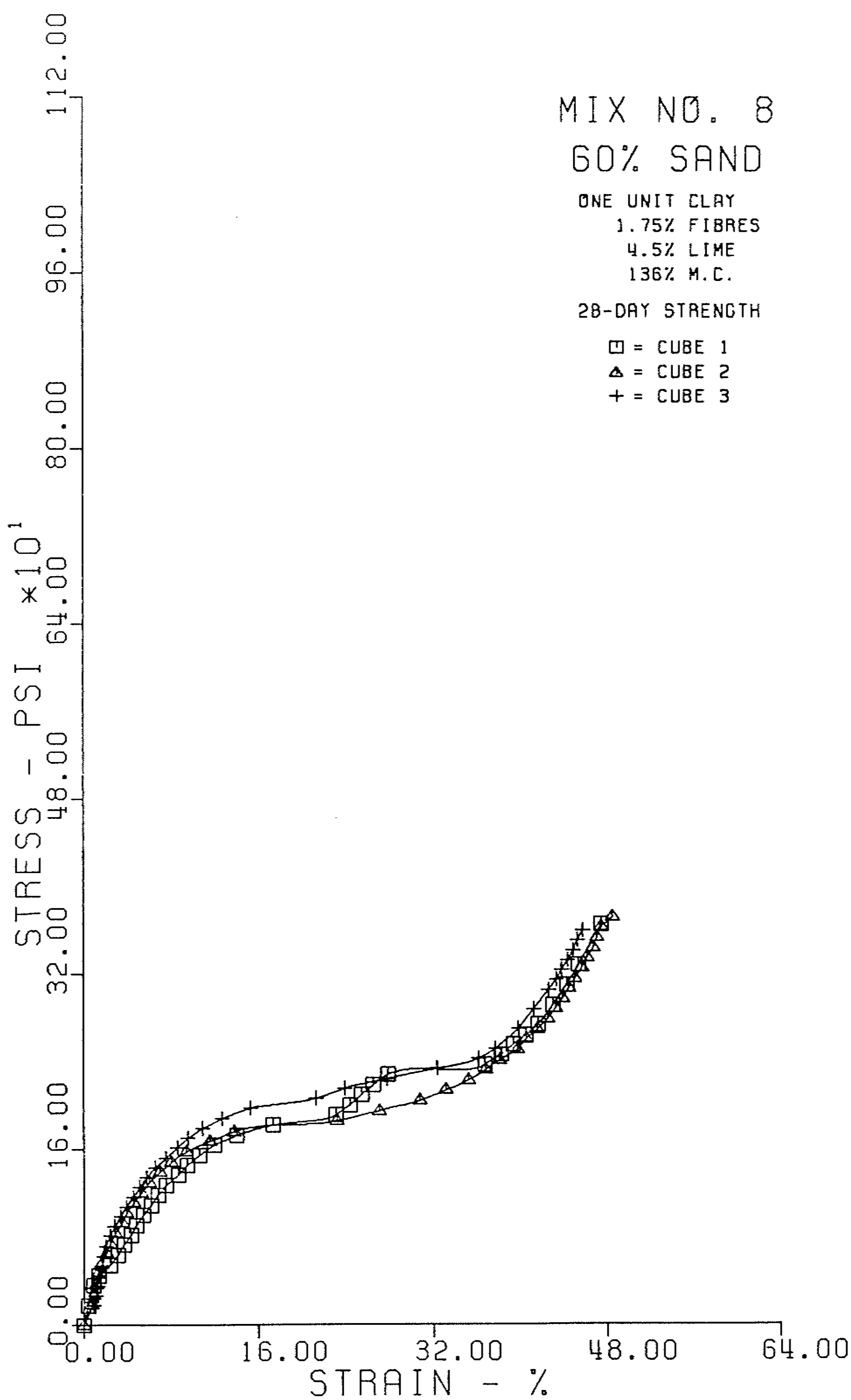


Figure 20: Computer Plot Showing All of the Recorded 28-Day Compressive Stress-Strain Data of Mix No. 8 with No Peak Failure Load

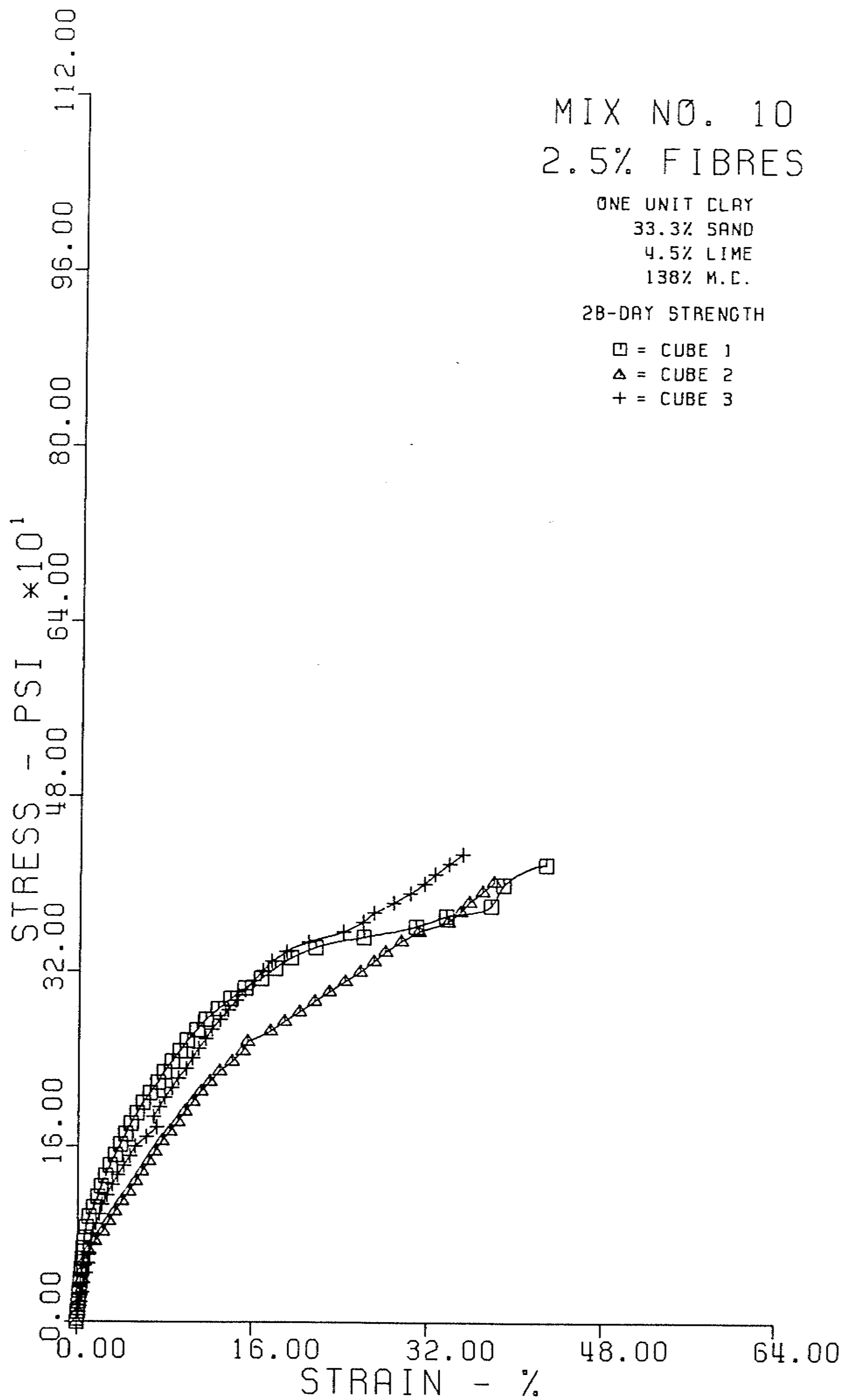


Figure 21: Computer Plot Showing All of the Recorded 28-Day Compressive Stress-Strain Data of Mix No. 10 with No Peak Failure Load

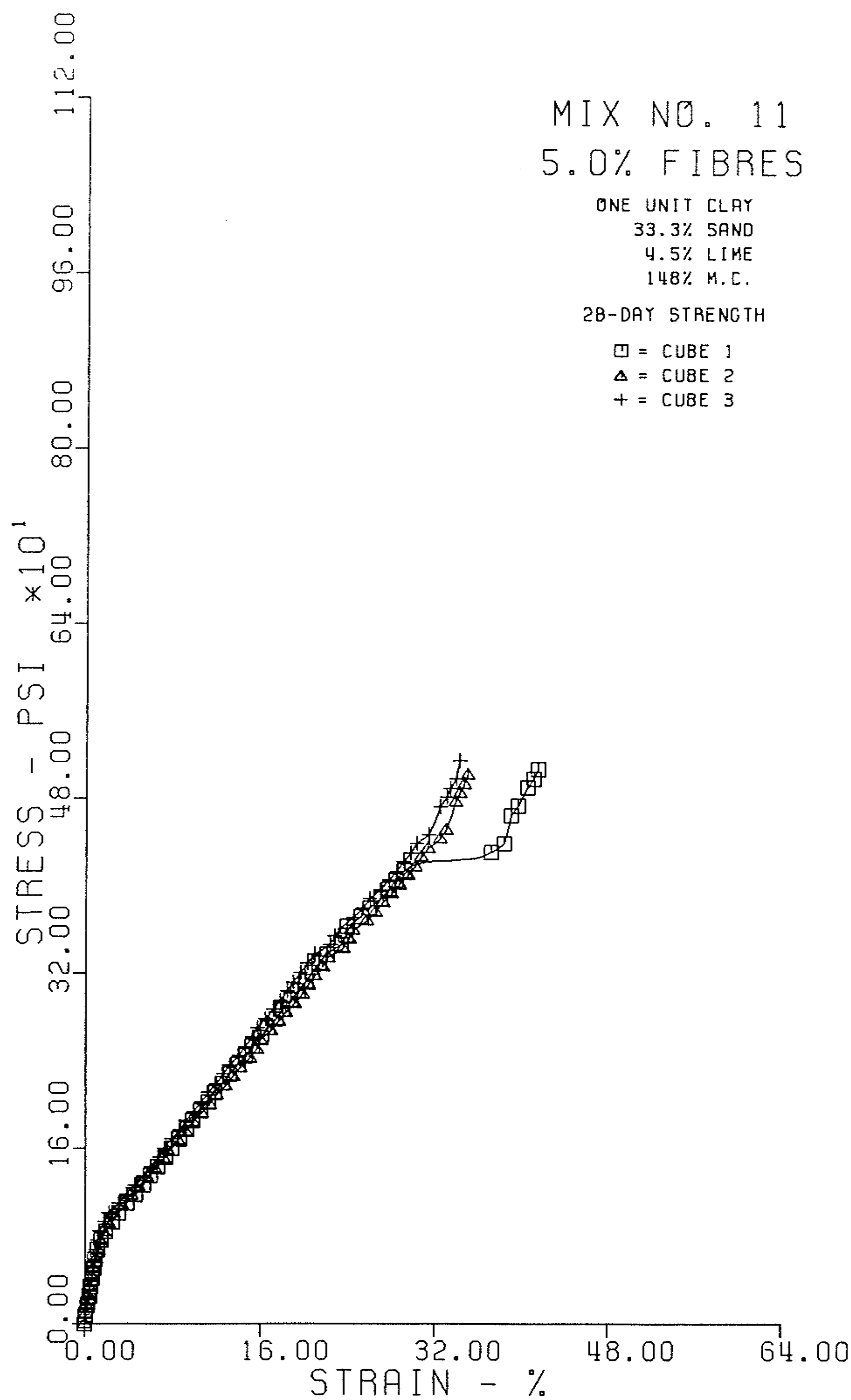


Figure 22: Computer Plot Showing All of the Recorded 28-Day Compressive Stress-Strain Data of Mix No. 11 with No Peak Failure Load

In Figures 19 to 22, there exists a general trend that as the strain values of the tested specimen passed the approximate value of 20 percent, the curves start to climb vertically. Together with the high strain values, this would indicate that the testing of the specimen had stopped. It was for this reason that the maximum strain value was put at 20 percent for the representative and hand-drawn clay mortar plots (Figures 4 to 18, pages 105 to 119). Figures 19 to 22 are to be taken for informative purposes only.

4.1.3.2 Study Plots

The compressive strength and failure characteristics of each clay mortar mix is described by the curves given in Figures 4 to 15, pages 105 to 116. From these figures, different combinations of the curves were put together to obtain four different studies: 1) lime study, 2) sand study, 3) fibre study, and 4) moisture curing study. The first three studies were designed to help determine the best proportion of lime, sand and fibres to go with the clay for a clay mortar mix. The purpose of the moisture curing study was to determine if any benefits would exist when moisture curing was applied to clay mortar.

The above studies were plotted out through the use of a computer plotting program. This program was developed primarily through the aid of Reference No. 25. A copy of this computer plotting program is listed in Appendix G as Computer Program No. 5. The computer plots giving the above clay mortar studies are shown in Figures 23 to 26.

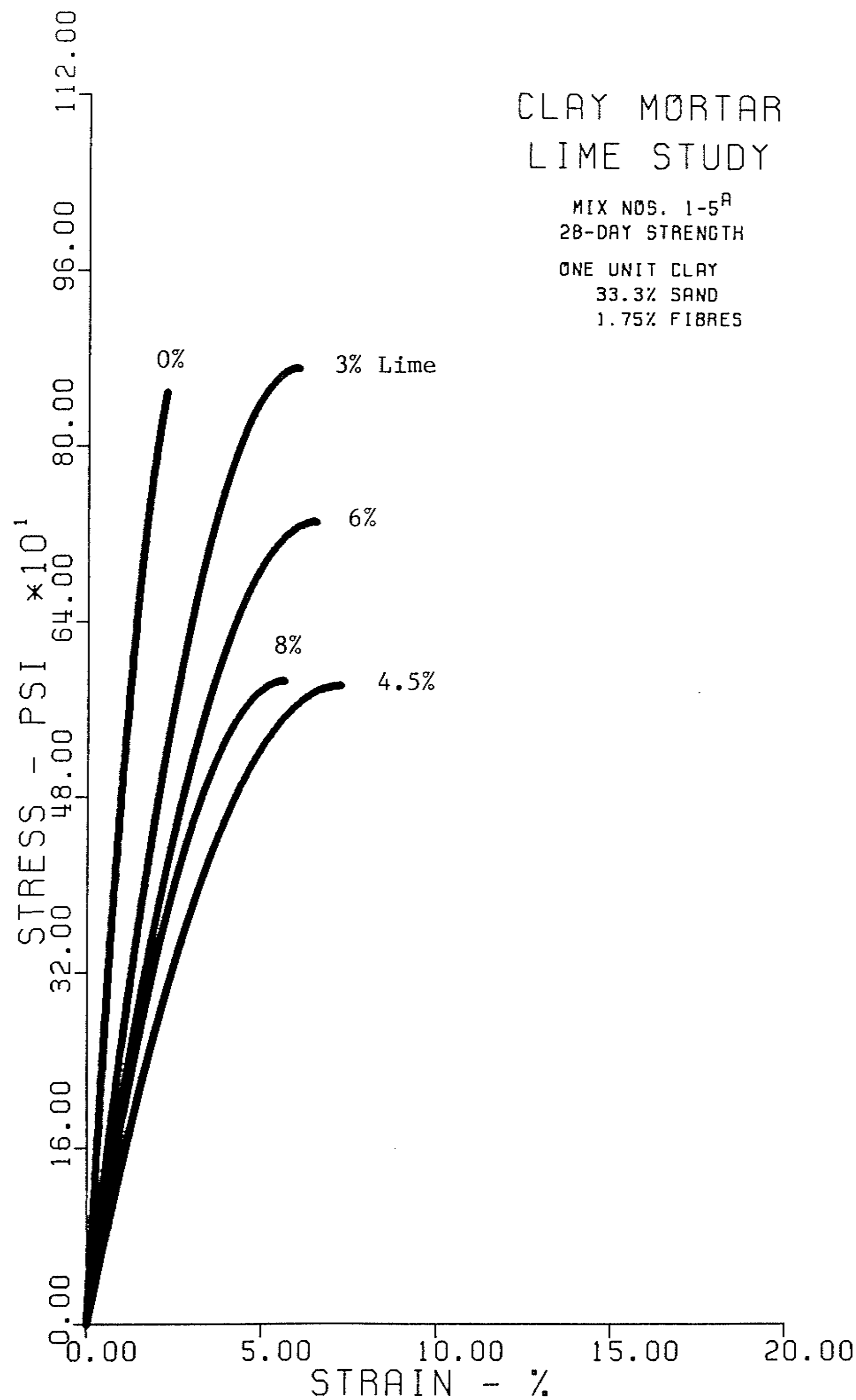


Figure 23: Lime Study Plot for Clay Mortar Mixes

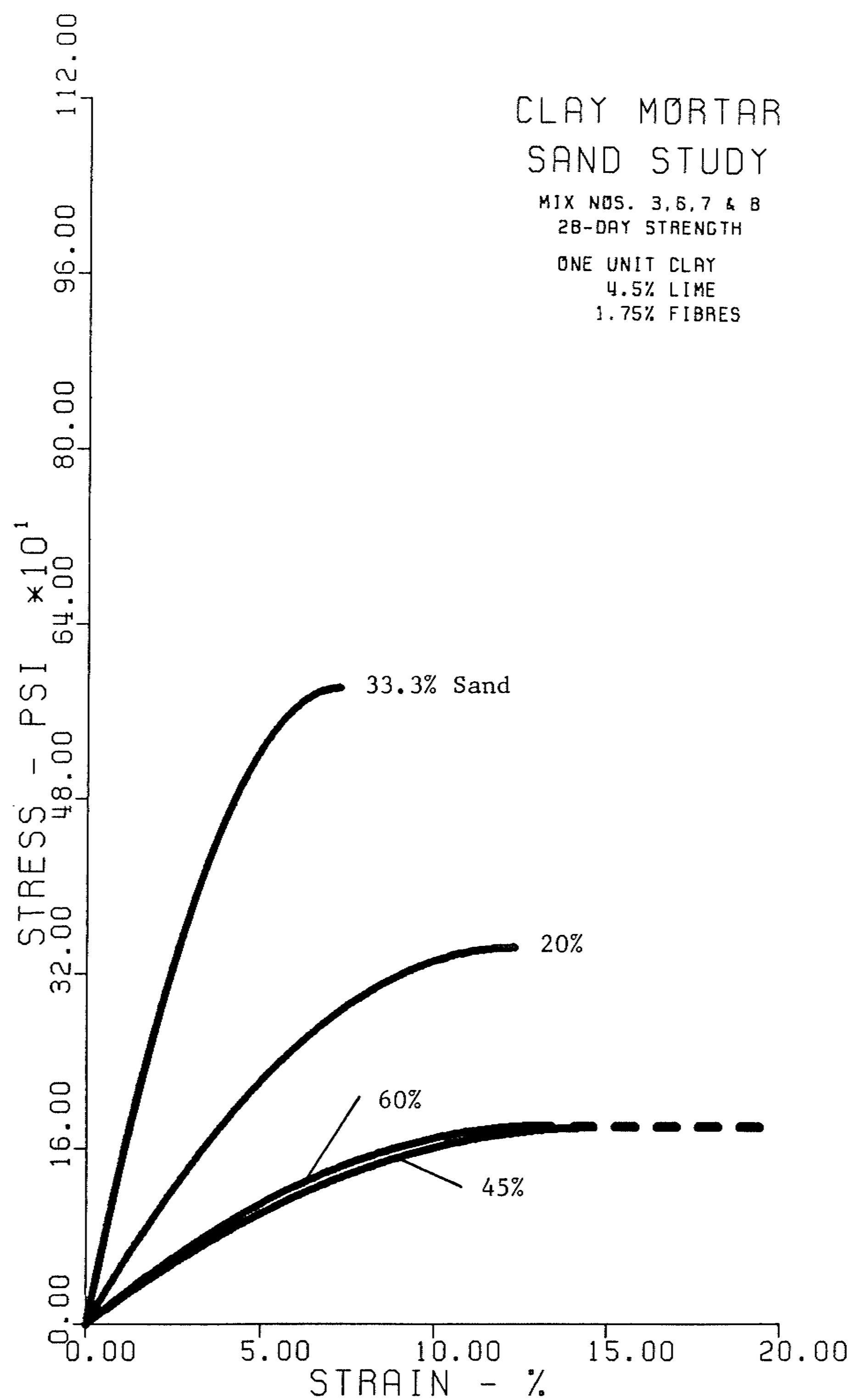


Figure 24: Sand Study Plot for Clay Mortar Mixes

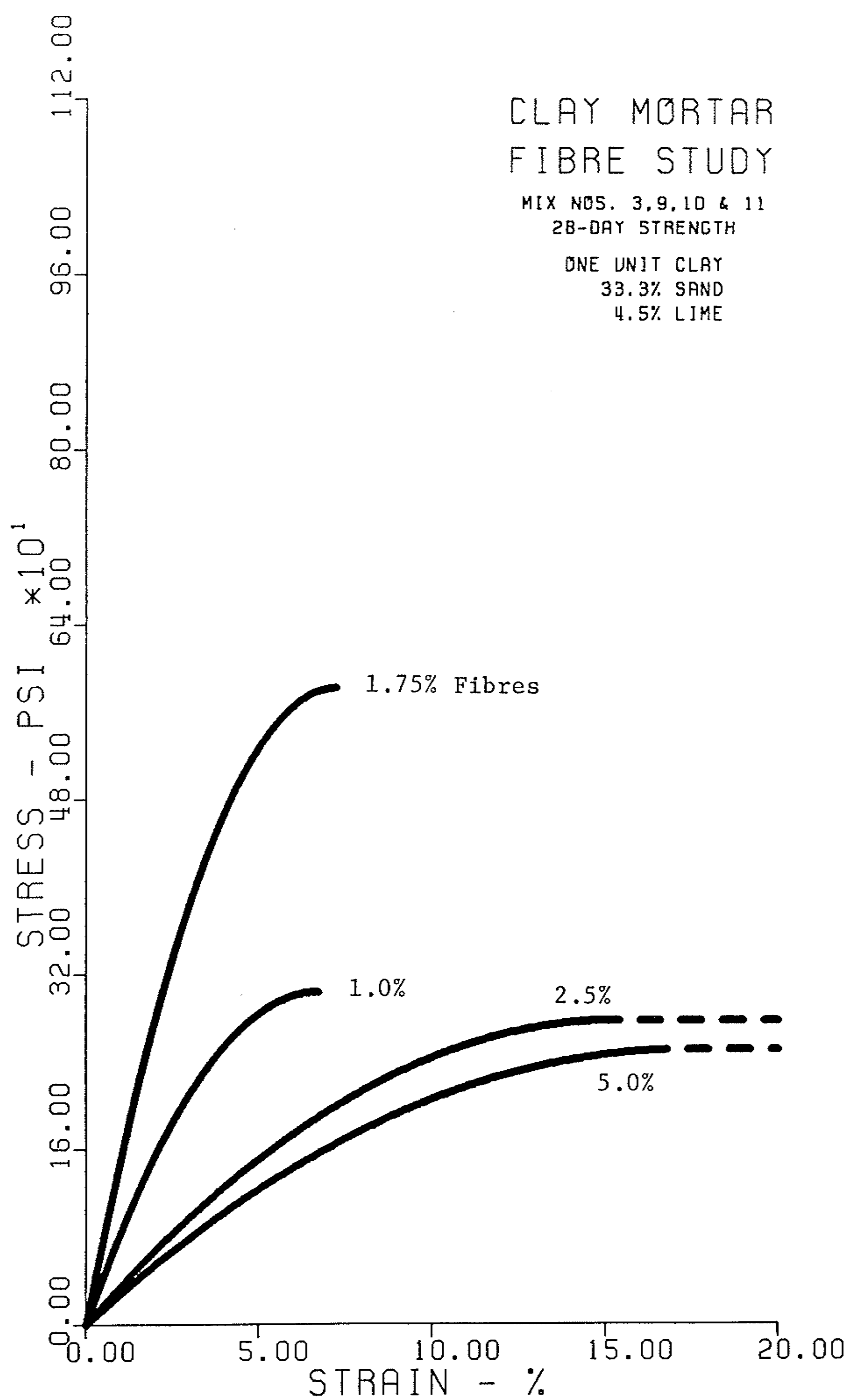


Figure 25: Fibre Study Plot for Clay Mortar Mixes

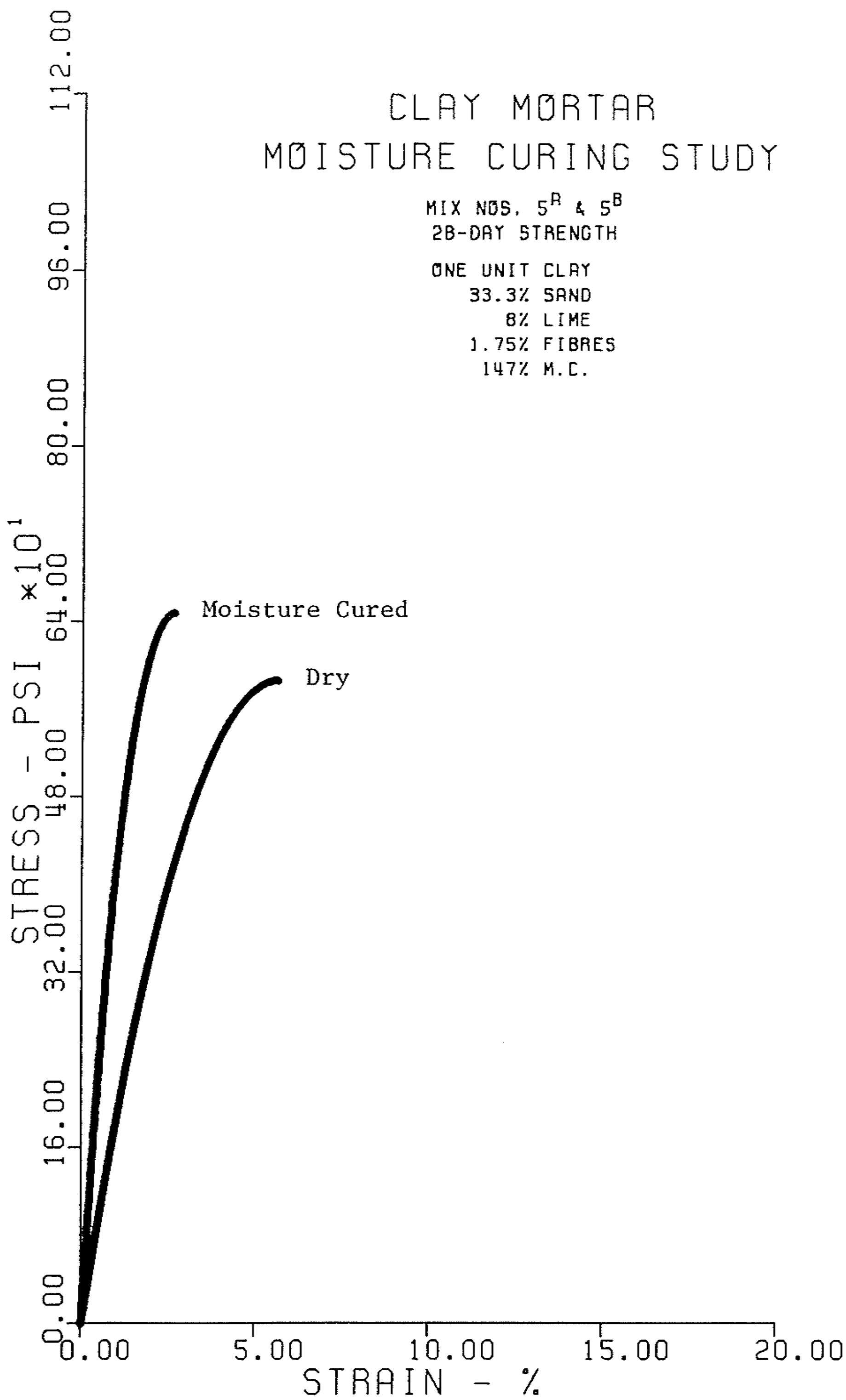


Figure 26: Moisture Curing Study Plot for Clay Mortar Mixes

4.1.4 Material Compressive Properties

From the representative computer plots of Figures 4 to 15, pages 105 to 116, material compressive properties of the clay mortar mixes were obtained. Properties tabulated were the maximum strain and stress, the moduli of elasticity, modulus of elastic resilience and the moduli of toughness.

4.1.4.1 Maximum Strain and Stress

Table X lists the maximum compressive strain and stress values of each clay mortar mix, as defined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

4.1.4.2 Moduli of Elasticity

For each clay mortar mix, the initial tangent modulus of elasticity (E_o) and the secant modulus of elasticity (E_m) were calculated. These calculations were performed using the computer printout of the best-fit curve plotting data points representing the curves of Figures 4 to 15, pages 105 to 116. E_o was defined as the slope of a line drawn tangent to the curve at the origin. E_m was defined as the slope of a straight line drawn from the origin to a point on the stress-strain curve which represented one-half the maximum stress indicated by the best-fit curve; this definition of E_m is similar to what is customarily done in design calculations for concrete [64, p. 6]. The resultant values of E_o and E_m for the clay mortar mixes are in Table XI.

Table X

Maximum Compressive Strain and Stress of Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	Maximum Compressive	
		Strain (%)	Stress (psi.)
1	Yes	2.2	849
2	Yes	6.0	871
3	Yes	7.2	582
4	Yes	6.5	731
5A	Yes	5.6	586
5B	Yes	2.6	648
6	Yes	12.3	344
7	No	14.6	179
8	No	13.4	181
9	Yes	6.7	304
10	No	15.4	278
11	No	16.8	250

Note: For mixes with no peak failure load, the strain and stress shown is where the best-fit curve plotting was stopped.

[1]In the compression tests as defined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

A supplementary set of E_o calculations were done for Mix Nos. 7, 10 and 11. These additional calculations were based on the hand-drawn curves of Figures 16 to 18, pages 117 to 119. Since these figures were drawn with the initial part of the curve having a straight-line proportion, the calculation of E_m was not applicable. Table XII lists the resultant supplemental values of E_o.

Table XI

Moduli of Elasticity for Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	Modulus of Elasticity -- (psi.) Initial Tangent E_o	Secant[2] E_m
1	Yes	59,900	52,745
2	Yes	28,600	24,632
3	Yes	16,000	13,787
4	Yes	22,300	19,216
5A	Yes	20,700	17,828
5B	Yes	54,700	46,418
6	Yes	5,600	4,787
7	No	2,400	2,130
8	No	2,700	2,317
9	Yes	9,000	7,725
10	No	3,600	3,082
11	No	2,900	2,419

[1] In the compression tests as defined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

[2] Based at one-half the maximum stress indicated by the best-fit curves of Figures 4 to 15, pages 105 to 116.

4.1.4.3 Modulus of Elastic Resilience

A mortar that posesses good resilience is desirable. The amount of resilience of each clay mortar mix is determined by calculating the modulus of elastic resilience (R_e). The area under the stress-strain curve up to the elastic limit will represent this resilience.

In the calculations, the elastic limit was taken at one of two possible stress points. For a stress-strain curve

Table XII

Supplementary Initial Tangent Modulus of Elasticity for Specific Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	Initial Tangent Modulus of Elasticity -- E_o (psi.)
7	No	4,375
10	No	8,222
11	No	6,875

[1]In the compression tests as defined by the hand-drawn curves of Figures 16 to 18, pages 117 to 119.

that is continuously curved, for comparison purposes, the elastic limit was taken at the same stress point that the secant modulus of elasticity was calculated; this was at one-half the maximum compressive stress reached by the best-fit curve. In the case where the stress-strain curve was initially or totally linear, the elastic limit was taken at the point where the straight-line proportionality stopped.

The modulus of elastic resilience for a continuously sloped curve was approximated by a triangular area. This area was defined with the secant modulus of elasticity slope approximating the stress-strain curve from the origin to the assumed elastic limit stated above. See Figure 27 for an illustration of this area. For the stress-strain curve that was initially or totally linear, the area below the curve for elastic resilience was naturally defined by a triangle. From this, the resilience was one-half the product of the elastic limit stress times the elastic limit strain. This can be written as:

$$R_e = 1/2(\sigma_e)(\varepsilon_e)$$

where R_e = modulus of elastic resilience

σ_e = elastic limit stress

ε_e = elastic limit strain.

Alternatively, this can be written as:

$$R_e = 1/2(\sigma_e)(\sigma_e/E_m)$$
$$= \sigma_e^2/2E_m$$

where E_m = secant modulus of elasticity.

All of the representative stress-strain curves (Figures 4 to 15, pages 105 to 116) for the clay mortar mixes were continuously sloped. For Mix No. 1,

$\sigma_e = 1/2(849) = 425$ psi. (see Table X, page 131)

$E_m = 52,745$ psi. (see Table XI, page 132)

$R_e = \sigma_e^2/2E_m = (425)^2/2(52,745) = 1.71$ in.-lbs./in.^{3}.

The modulus of elastic resilience for all the clay mortar mixes are listed in Table XIII.

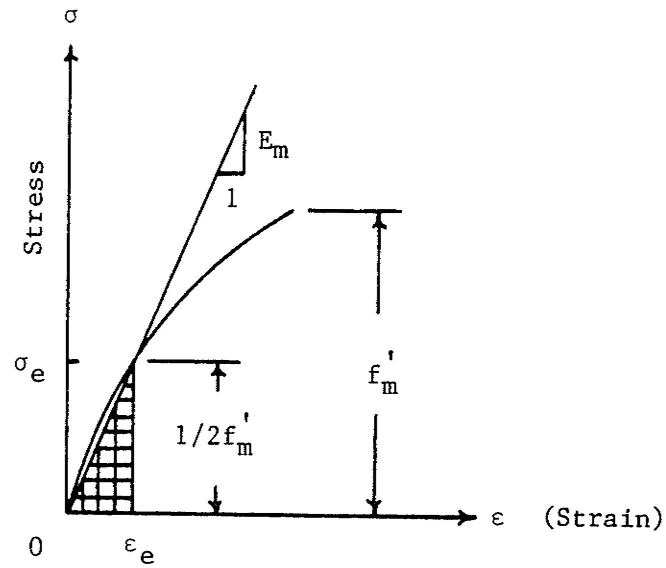


Figure 27: Area (Crosshatched) Under A Continuously Curved Stress-Strain Curve Representing the Modulus of Elastic Resilience

A supplementary set of moduli of elastic resilience calculations were performed for Mix Nos. 7, 10 and 11. These calculations were based on the hand-drawn curves of Figures 16 to 18, pages 117 to 119. In these figures, the stress-strain curve was initially linear. Table XIV lists the resultant supplemental values of R_e.

4.1.4.4 Moduli of Toughness

Toughness is a measure of a material's ability to resist energy load [52, p. 393]. Two measures of toughness were calculated for each clay mortar mix, the modulus of toughness (T) and the modified modulus of toughness (T'). T was defined as the total area under the stress-strain curve up to fracture as shown by the area ACD in Figure 28.

Table XIII

Modulus of Elastic Resilience (R_e) for Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	R_e $\frac{\text{in.-lbs.}}{\text{in.}^3}$
1	Yes	1.71
2	Yes	3.85
3	Yes	3.07
4	Yes	3.48
5A	Yes	2.41
5B	Yes	1.13
6	Yes	3.09
7	No	1.88
8	No	1.77
9	Yes	1.50
10	No	3.13
11	No	3.23

[1] In the compression tests as defined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

Upon the release of the load (stress), beyond the elastic limit and up to the failure point, a certain amount of energy absorbed by a material is released from the material [28, pp. 41 to 43; 52, p. 393]. At failure, Point C in Figure 28, the amount of energy released is represented by the area of the triangle CDE. Line CE in this figure is parallel to line AB which is defined by the initial tangent modulus of elasticity (E_o). Point D is the corresponding failure strain to the failure stress at Point C. Referring to Figure 28, the total area under the stress-strain curve up

Table XIV

Supplementary Modulus of Elastic Resilience (R_e) for Specific Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	R_e $\frac{\text{in.-lbs.}}{\text{in.}^3}$
7	No	0.274
10	No	0.333
11	No	0.220

[1] In the compression tests as defined by the hand-drawn curves of Figures 16 to 18, pages 117 to 119.

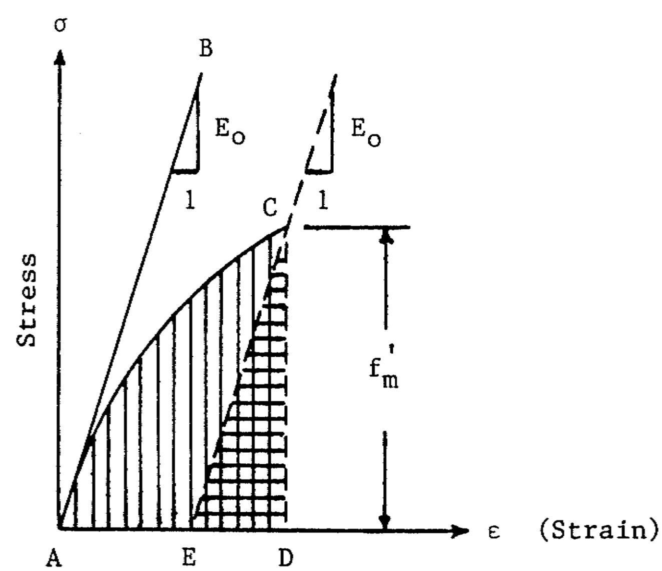


Figure 28: Measurement for Moduli of Toughness

to fracture (area ACD) minus the triangular area CDE is defined as T'.

The amount of energy represented by T' is more useful than T since it is the amount of energy that a material can absorb in deformation. This is important for example in earthquake analysis. Table XV lists the calculated values of T and T' for the clay mortar mixes; these values are with respect to the representative curves of Figures 4 to 15, pages 105 to 116.

A supplementary set of moduli of toughness calculations were performed for Mix Nos. 7, 10 and 11. These additional calculations were based on the hand-drawn curves of Figures 16 to 18, pages 117 to 119. Table XVI lists the resultant supplemental values of T and T'. These values were approximated for the reason noted within the table.

Table XV

Moduli of Toughness for Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	Modulus of Toughness -- $\frac{\text{in.-lbs.}}{\text{in.}^3}$ T	Modified T'
1	Yes	11.1	5.1
2	Yes	34.7	21.5
3	Yes	27.9	17.4
4	Yes	31.7	19.7
5A	Yes	21.9	13.6
5B	Yes	11.6	7.7
6	Yes	28.3	17.7
7	No	17.4	10.7
8	No	16.2	10.1
9	Yes	13.6	8.4
10	No	28.5	17.8
11	No	27.6	16.8

Note: For mixes with no peak failure load, the moduli of toughness was calculated with the best-fit curve ending at the strain and stress values listed in Table X, page 131.

[1]In the compression tests as defined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

Table XVI

Supplementary Moduli of Toughness for Clay Mortar Mixes[1]

Mix No.	Was Peak Failure Load Reached? Yes/No	Modulus of Toughness -- $\frac{in.-lbs.}{in.^3}$ T	Modified T'
7	No	15.7	12.1
10	No	25.8	21.1
11	No	24.7	20.1

Note: These values are approximate due to the curved portion of the hand-drawn curves (Figures 16-18, pages 117 to 119) being undefined by an equation. This area was approximated by a rectangle. The rectangle had a width equivalent to the width of the curved portion and a height midway between the final stress and the stress where the curve portion started.

[1]In the compression tests as defined by the hand-drawn curves of Figures 16 to 18, pages 117 to 119.

4.2 LIME-SAND MORTAR

4.2.1 Constituent Data Results

The mechanical procedure used for mixing the lime-sand mortar mixes proved to be satisfactory; this held true for both the original and remix mixes. Comparing each remix mix to its original mix, no differences was seen in terms of the mixing and handling aspect of the mortar.

Between the two lime brands there was no difference in terms of mixing, but there was some difference in the handling of the mortars. During the moulding for the flow test and the test specimens, lime Brand B was found to be more plastic than lime Brand A. At lower lime concentrations, lime Brand B was not as cohesive as Brand A. However, as the lime concentration increased up to the lime:sand ratio of 1:3 for lime Brand B, the cohesiveness of the mass became similar to that of lime Brand A.

The remix age at which the remains of the original mixes were broken up and remixed for the remix mixes is tabulated in Table XVII. Upon the breaking up of the dried lime-sand mortar, it was noted that in the cross-section, the material was porous. The method used to break up the mortar (see Article 3.2.3.1, Preparation of the Materials) proved to be satisfactory with only moderate effort required.

The end resultant flow and moisture content of each lime-sand mortar mix is respectively listed in Tables XVIII and XIX.

The lime-sand mortars tested in the flow test, with exception to Mix Nos. 20 and 21 of lime Brand B, had two distinct concentric circular areas. These areas are illustrated in Figure 29. The inner and outer circular areas were labelled as Areas I and II respectively. Area I

Table XVII

Remix Age of Lime-Sand
Mortar Remix Mixes

Lime Brand	Remix No.	Remix Age (days)
A	17	5
B	20	19
	21	19
	22	16
	23	17

appeared wetter and with more lime than Area II. For the mixes of lime Brand A, these two areas were well defined and remained clear for a unmeasured period of time. With the mixes of lime Brand B, the distinction of the two areas was not as clear and they blended together shortly after the completion of the flow test; for Mix Nos. 20 and 21, the detection of these two areas was not possible. The width of Area II was measured at eight locations per flow test. These locations are shown in Figure 29. Measurements varied from just below to just above an inch; the average measurement was one inch.

Table XVIII

Flow Test Results of
Lime-Sand Mortar Mixes

Lime Brand	Mix No.	Flow (%)
A	12	123
	13	111
	14	104
	15	105
	16	107
	17	112
	17-R	110
B	18	115
	19	114
	20	115
	20-R	114
	21	108
	21-R	116
	22	112
	22-R	116
	23	107
	23-R	111
Average		112

Note: R indicates remix.

For the modified Vicat tests performed on Mix Nos. 14 and 17, the time required for the rod settlement of 10 millimetres [see Reference 15, page 17] was approximately 29 hours for Mix No. 14 and approximately 37 hours for Mix No. 17. These times were interpolated as the rod penetrated too

Table XIX

Moisture Content of
Lime-Sand Mortar Mixes

Lime Brand	Mix No.	Moisture Content (%)
A	12	20.4
	13	20.8
	14	20.8
	15	21.3
	16	22.7
	17	29.6
	17-R	26.7
B	18	19.0
	19	18.4
	20	18.1
	20-R	18.0
	21	17.8
	21-R	17.5
	22	17.4
	22-R	17.3
	23	16.2
	23-R	15.8
Average		19.9

Note: R indicates remix.

much on the second last reading and then did not penetrate enough on the last reading.

The volumetric shrinkage measurements of each lime-sand mortar mix is given in Table XX. Both the seven- and 28-day results are the average of three specimens. At the 28-day

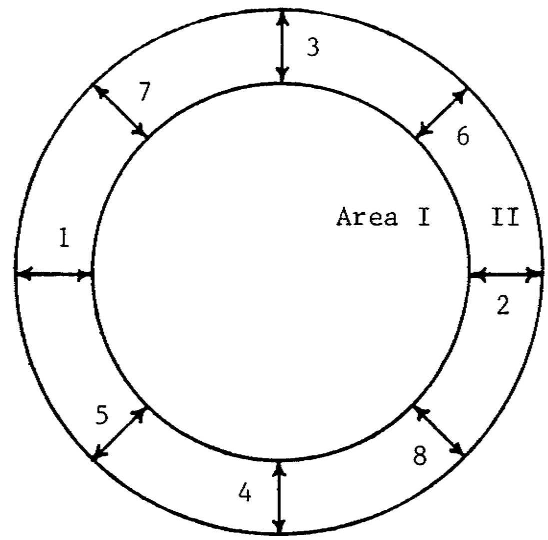


Figure 29: Two Concentric Circular Areas Existent in Flow Tested Lime-Sand Mortar

age, the lowest volumetric shrinkage occurred for Mix No. 13 at 1.1 percent while the highest at 12.1 percent took place for Mix No. 17. Overall, the average volumetric shrinkage at the seven- and 28-day age were approximately four and five percent respectively. From these measurements, it appears that the majority of the shrinkage took place within the first week of drying.

Table XX

Volumetric Shrinkage of Lime-Sand Mortar Mixes

Lime Brand	Mix No.	Volumetric Shrinkage -- (%) Age	
		7-Day	28-Day
A	12	1.9	4.1
	13	1.4	1.1
	14	1.1	2.0
	15	1.5	5.3
	16	3.9	7.0
	17	9.0	12.1
	17-R	5.4	11.0
B	18	3.3	3.9
	19	3.3	3.6
	20	3.7	4.4
	20-R	4.4	4.7
	21	4.2	3.9
	21-R	4.6	4.9
	22	4.0	4.5
	22-R	5.5	4.9
	23	5.0	4.6
	23-R	4.3	4.9
Average		3.9	5.1

Note: R indicates remix.

4.2.2 Testing Data

Prior to the compression test of each lime-sand mortar mix, notes were taken on the colour, shape and surface texture. Density measurements were also taken for the majority of the mixes. The specimens were measured with calipers to obtain the necessary dimensions for the density, stress and strain calculations. At the time of the compression tests, the time required to perform the test on each specimen and the age of the mix was recorded. After the compression tests were completed for a mix, the mode of fracture(s)/failure, the angle of rupture and general post-testing notes were taken. Details of the compression testing information and the post-testing data is tabulated in Appendix I.

Notes on the lime-sand mortar mixes (both original and remix) revealed that all of the specimens had a brownish-white (beige) colour and that the shape of the moulded sides and bottoms remained plane. With the top surface, all of the specimens developed a slight concave shape.

The surface texture on the sides, bottom and top of the specimens of lime Brand A was a smooth finish. For the lime Brand B specimens, the surface texture of the moulded sides and bottom was granular. Simply rubbing or scratching with a finger caused sand particles to come off. As the lime content increased in a mix, the sides and bottom of the specimens became less granular and more resistant to the loosening of sand particles with the rubbing or scratching of a finger.

The moulded top surface of the lime Brand B specimens had a smooth surface texture but also released some sand grains when rubbed or scratched; degree of sand grain loss was less than that on the sides and bottom. As the lime content increased in a mix, it became more difficult for the sand grains to be loosened. When the lime concentration increased to the lime:sand ratio of 1:3, i.e. that of Mix No. 22, no sand grains were released from the top when rubbed or scratched; this trend pertained to the remix mixes also.

No drying cracks were noted for any of the lime-sand mortar specimens.

Density of the mixes that were measured is recorded in Table XXI. The density ranged from 105 to 114 pounds per cubic foot (pcf.); average density for all of the mixes measured is approximately 110 pcf.

The dimensions of the specimens prior to the compression test, the time required to perform each test and the age at the time of testing is recorded in Table I-I of Appendix I, pages 459 to 464. Also in Appendix I is the post-compression testing data of the lime-sand mortar mixes, recorded in Table I-II, pages 465 to 467.

All of the lime-sand mortar mixes had specimens with peak failure loads during the compression test. The modes of fracture(s)/failure that took place, in order of higher occurrence, were pyramidal fracture, splitting failure and corner fracture. Combination of these modes took place with

Table XXI

Measured Density[1] of Lime-Sand Mortar Mixes

Lime Brand	Mix No.	Average Density -- (pcf.) Age 7-Day	28-Day
A	12	n.d.	108
	13	n.d.	n.d.
	14	n.d.	n.d.
	15	n.d.	n.d.
	16	n.d.	109
	17	n.d.	105
	17-R	n.d.	107
B	18	107	108
	19	107	106
	20	108	108
	20-R	107	107
	21	110	110
	21-R	109	109
	22	111	111
	22-R	110	111
	23	114	114
	23-R	114	114
Average		110	109

Notes: 1) n.d. indicates not done;
2) R indicates remix.

[1] Average values based on three specimens per mix using caliper measurements for volume.

mixes that had higher lime concentration; this pertained more so for the mixes of lime Brand B than lime Brand A. The average angle of rupture for the pyramidal fracture and splitting failure were 65 and 90 degrees respectively, measured from the horizontal. Most of the tested specimens had loaded surfaces which showed evidence of being restrained against lateral expansion. On the sides, most of the tested specimens showed crack characteristics of the mode of fracture(s)/failure (see Appendices H and I) and had material that was loosened or lost during testing. In the case where pyramidal and/or corner fracture(s) occurred, material loosened or lost was more pronounced.

Noted above, the average angle of rupture (θ) for the pyramidal fracture is 65 degrees. As detailed in Appendix H,

$$\theta = 45 + \phi/2$$

where 45 degrees represents the cohesion and ϕ equals the angle of internal friction of the material. Typical values of the drained shear strength parameter (ϕ') of sand can range from 27 to 45 degrees [26, p. 95]; the value depends upon the type of sand and how loose or dense it is. Since the observed θ angle was greater than half the largest shear strength parameter of sand, failure was due to cohesion and internal friction of the material. It is presumed that the cohesive action came from the cementitious action of the lime with sand. The average angle of internal friction of the lime-sand mortars thus works out to be:

$$\phi = 2(\theta - 45)$$
$$= 2(65 - 45)$$
$$= 40 \text{ degrees.}$$

Variance in the angle of rupture may in part be due to an unintentional slight difference in tamping pressure during the moulding.

On all of the tested lime-sand mortar mixes that had material fractured off, the inside portion of the specimen had weaker material than the outer surface. The material inside the specimens had little cohesiveness among the sand particles while the outside had a crust like formation of lime and sand. This indicates that the hardening process of carbonization had taken place on the outside of the specimens. Since a carbonized layer of lime-sand mortar is impervious to carbon-dioxide, the material inside the cubes was restricted from the process of carbonization (see Appendix E) and thus resulted in being a weaker material. This phenomenon was discussed in the preliminary literature search for the lime-sand mortars.

The procedure in calculating the compressive strength of a specimen and a mix for the lime-sand mortar mixes was identical to that used for the clay mortar mixes. This procedure relates to Subsection 7.11.10 of CSA A8-1970 [15].

4.2.3 Plots

All of the calculated compressive stress-strain data points of the lime-sand mortar mixes were plotted to scale on computer plots. For each mix, three different symbols were used to represent the three specimens per mix per age group. A single curve was drawn to represent the compressive strength and failure characteristics of the mix during the compression test for both the seven- and 28-day tests. Specific combinations of these single curves were then matched so as to give four different types of study plots.

On all of the plots, when an index such as "$x\ 10^{1}$" is applied to an axis of numbers, it means that one should take the numbers labelled and apply that index to those numbers. It does not mean that the index was previously applied to the numbers.

4.2.3.1 Compression Testing Data Plots

Initially, all of the calculated compressive stress-strain data were plotted on graphs with each of the specimens' data points joined by a simple smooth curve; this was done for each lime-sand mortar mix at both the seven- and 28-day testing age. The plots were done with the use of a computer plotting program listed in Appendix G as Computer Program No. 6. This program is similar to Computer Program No. 4 of Appendix G, which was used for the clay mortar mixes. In Program No. 6, the scales of the plots are set up differently so as to suit the data for the lime-sand mortar mixes.

From the above process, three types of plots were obtained. An example of each type is given in Figures 30 to 32. The first type, Figure 30, or Mix No. 16 at the 28-day strength, shows all of the specimens' data points plotted closely together with an approximately equal experimental error or seating problem at the initial stages of testing. This experimental error is indicated by the bilinear curve behaviour of the initial data points.

The second type of plot, Figure 31, or Mix No. 14 at the 28-day strength, shows the same characteristics as the first type except that one specimen had a larger experimental error than the other two.

Figure 32, or Mix No. 14 at the seven-day strength, shows the third type of plot. In this case, each of the specimens had a different degree of experimental error in the initial stages of testing.

To correct for differences in the initial part of the curves of the second and third type of plots, the data points were shifted so to to bring them into line with those of the first plot type. For the second plot type, an average initial strain value was first obtained for the two specimens with similar initial error. The difference between this value and the initial strain value of the third specimen was then obtained as a shift factor. This shift factor was then applied to all of the strain values of the

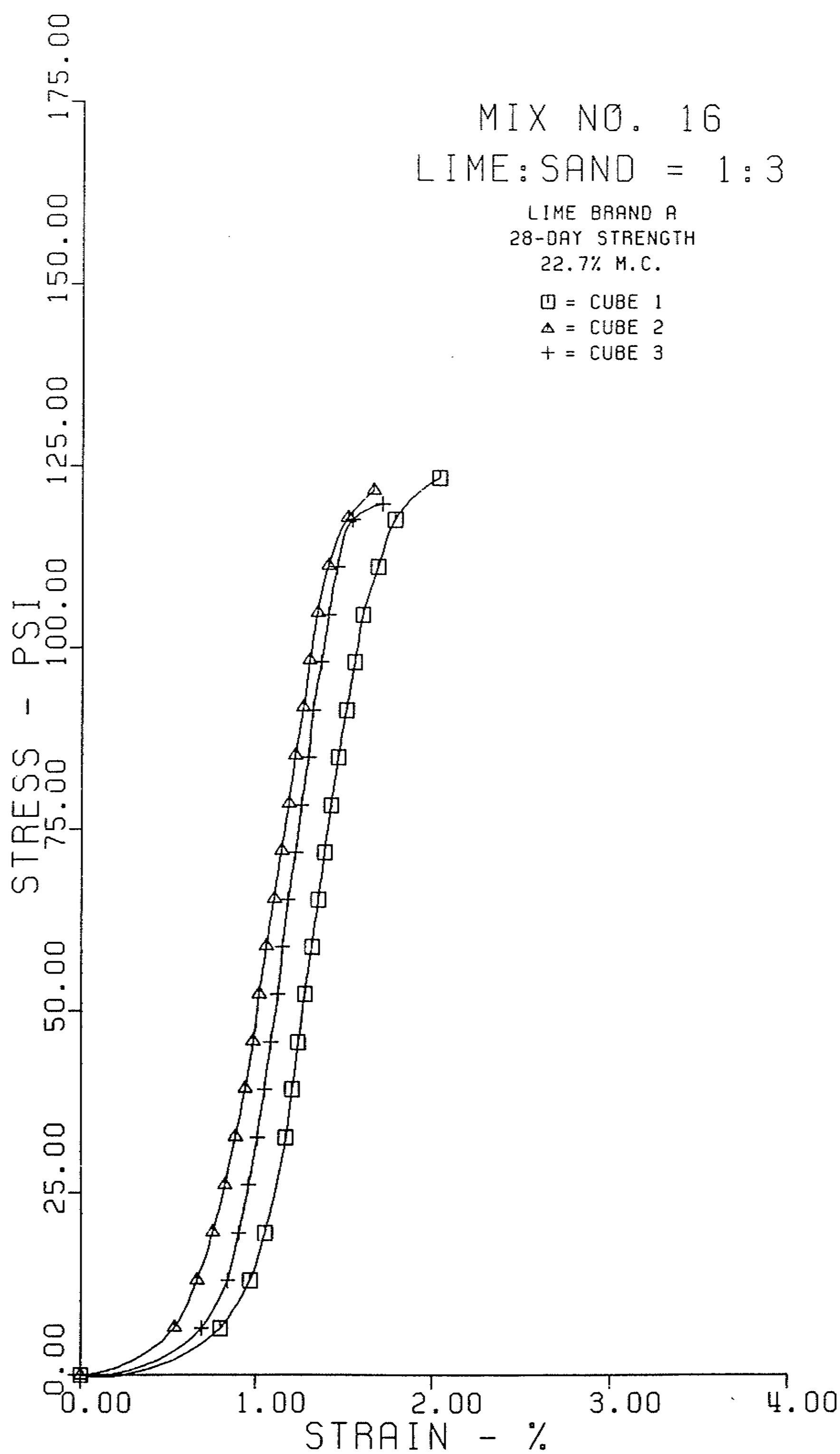


Figure 30: Equal Experimental Error/Seating Problem Among All Lime-Sand Mortar Specimens of a Test Set

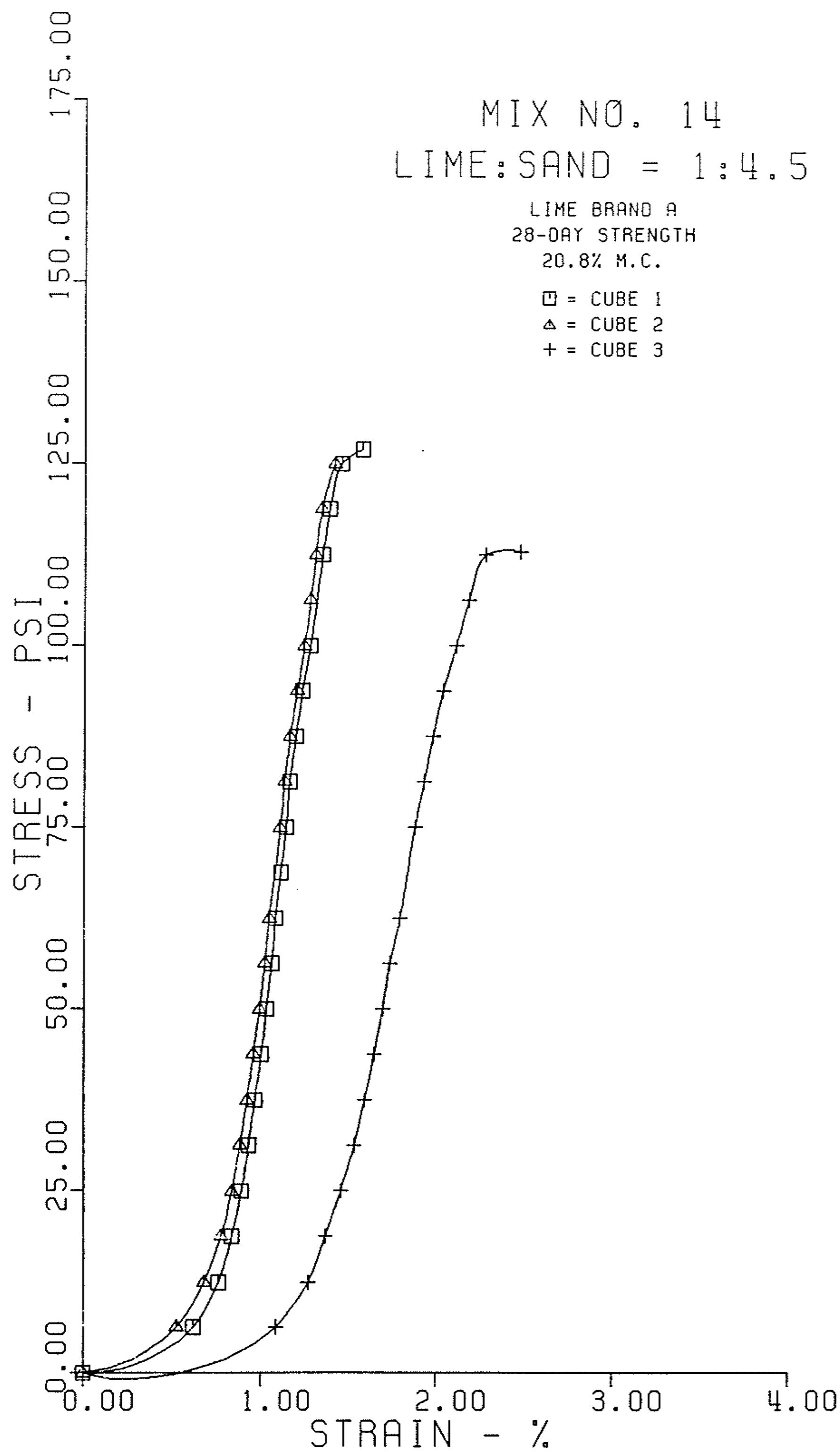


Figure 31: Two Equal, One Unequal Experimental Error/ Seating Problem Among the Lime-Sand Mortar Specimens of a Test Set

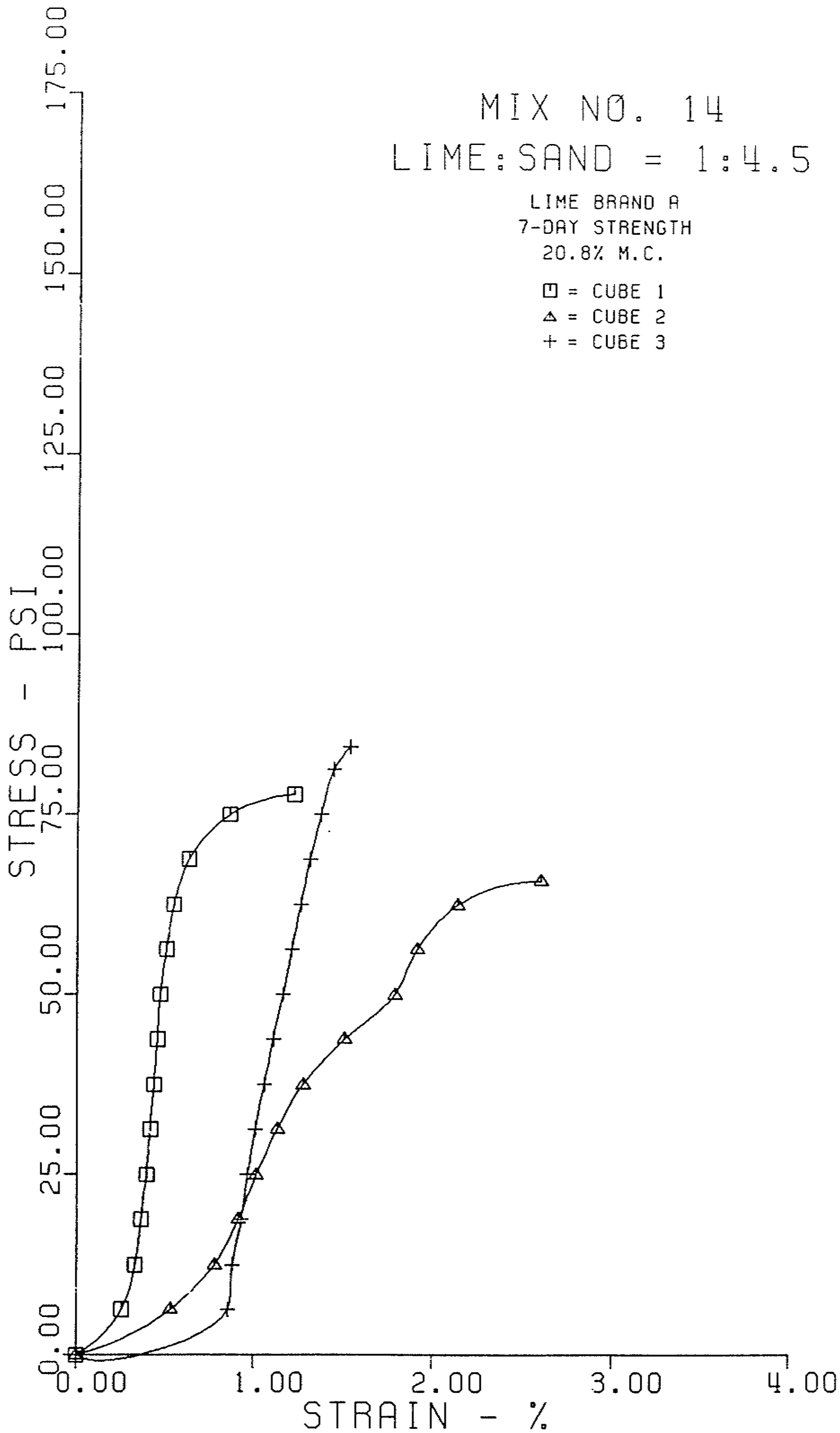


Figure 32: Unequal Experimental Error/Seating Problem Among All Lime-Sand Mortar Specimens of a Test Set

third specimen so as to produce plots similar in form to that of the other two specimens by decreasing the strain values.

Correction to the third type of plot was made by applying two different shift factors to the two specimens with the higher initial strain values. The respective shift factors were obtained from the difference between these strain values and the lower first strain value of the third specimen. Shifting was made in the same manner as the second type of plot except that two instead of only one set of data points were shifted to the left.

Table XXII lists the shift factors for the lime-sand mortar mixes with different experimental error among the specimens.

With the above shift factors applied, all of the simple curve plots had initial data points resembling that of the first type of plot, Figure 30, page 154. The experimental error or seating problem that remains with this type of plot was adjusted with a value called **xstart.**

The value of **xstart,** for the lime-sand mortar mixes, was defined as the strain value where the best-fit curve of a set of tests crossed the x-axis of a plot, otherwise known as the root of the best-fit curve. This value was applied to all of the strain values of a given set of tests so as to get a strain value of zero when the stress was also zero; in all cases this meant moving the data values to the left.

Table XXII

Shift Factors for Lime-Sand Mortar Mixes with Differential Initial Experimental Error

Lime Brand	Mix No.	Age (days)	First Strain Values -- (%)			Shift Strain Factor -- (%)		
			Specimen No.			Specimen No.		
			1	2	3	1	2	3
A	14	7	0.257	0.529	0.856	0.0	0.272	0.599
	14	28	0.620	0.525	1.083	0.0	0.0	0.510
	17-R	28	1.229	0.516	0.588	0.677	0.0	0.0
B	18	7	0.658	0.606	1.011	0.0	0.0	0.379
	19	28	1.115	0.615	0.617	0.499	0.0	0.0
	20-R	28	0.873	1.220	0.741	0.0	0.413	0.0
	21-R	7	0.775	1.174	0.781	0.0	0.396	0.0
	21-R	28	1.554	0.576	0.581	0.975	0.0	0.0

Note: R indicates remix.

The best-fit curves used to describe the compressive strength and failure characteristics of the lime-sand mortar mixes were polynomial curves. The general equation format of the polynomial curves used was the same as that used for the clay mortar mixes. The constant coefficients of these equations were determined using the same least-square fit computer program that was used for the clay mortar mixes; this program is listed in Appendix G as Computer Program No. 2.

The lowest degree polynomial that followed the data points was sought when choosing a best-fit curve. With the majority of the data points indicating some curvature, a second degree polynomial was initially tested for all of the lime-sand mortar mixes. The general format of the polynomial was:

$$y = c_1 + c_2x + c_3x^2.$$

After obtaining the required coefficients, the data points and the best-fit curve were plotted. This was accomplished by using a computer program similar to the one used for plotting the clay mortar plots (Computer Program No. 3) but modified for the lime-sand mortar mixes. Modification was necessary primarily due to the lower compressive stress and strain values resulting in changes to the specified scaling factors. Besides these changes, the use of the values of **xstart;** the way the best-fit curve was plotted; and the calculation of the adjusted coefficients of multiple determination (R_A^2) were all the same. The tests to determine whether a best-fit curve was satisfactory for a given set of data points was also the same. A copy of the computer plotting program used for the lime-sand mortar mixes is listed in Appendix G as Computer Program No. 7.

The best-fit polynomial curve coefficients used for each set of tests of the lime-sand mortar mixes, along with their respective values of **xstart** and R_A^2 are recorded in Table XXIII. Resultant curves from these coefficients and **xstart** values plus the previous shift factors of Table XXII, page 158 are shown in Figures 33 to 66. Included in these figures, for each mix, are the stress-strain data points for each cube specimen; these data points are plotted to scale. Most of these figures have initial data points with negative strain values; this phenomenon is due to the value of **xstart** in the plotting program. As explained previously, **xstart** in the computer plotting program was used to correct initial and/or seating error. Figures 33 to 66 are to be taken as the representative stress-strain plots for the lime-sand mortar mixes.

4.2.3.2 Study Plots

The compressive strength and failure characteristics of each lime-sand mortar mix, at the age of seven and 28 days, is

Table XXIII

Computer Plotting Information for Lime-Sand Mortar Mixes

General Equation: $y = c_1 + c_2x + c_3x^2$

Lime Brand	Mix No.	Age (days)	Coefficients c_1	c_2	c_3	xstart (%)	R^2_A
A	12	7	-73.18	145.6	-35.91	0.588	0.53
		28	-98.97	118.1	0.0	0.838	0.95
	13	9	-19.33	78.59	-17.20	0.261	0.73
		28	-76.58	131.9	-24.41	0.662	0.74
	14	8	-6.280	104.0	-34.72	0.062	0.43
		28	-129.3	234.6	-52.70	0.644	0.80
	15	9	-85.30	173.1	-43.92	0.577	0.81
		28	-97.57	189.3	-36.13	0.579	0.82
	16	8	-94.81	196.6	-53.44	0.571	0.93
		28	-94.08	156.5	-19.39	0.654	0.82
	17	8	-31.77	87.91	-19.84	0.397	0.83
		28	-78.01	174.6	-42.07	0.509	0.87
	17-R	7	-41.71	77.36	-9.223	0.579	0.83
		28	-82.67	167.3	-34.06	0.558	0.80
B	18	7	-86.89	126.7	0.0	0.686	0.93
		28	-114.6	169.2	-34.71	0.813	0.82
	19	7	-71.12	135.3	-27.74	0.599	0.58
		28	-50.44	82.32	0.0	0.613	0.95

Table XXIII

(Continued)

Lime Brand	Mix No.	Age (days)	Coefficients			**xstart** (%)	R^2_A
			c_1	c_2	c_3		
	20	7	-81.41	146.5	-22.29	0.613	0.86
		28	-85.46	148.4	-29.42	0.663	0.84
	20-R	8	-74.54	129.4	-26.73	0.668	0.89
		28	-67.31	99.01	-16.21	0.779	0.91
	21	7	-106.2	138.0	0.0	0.769	0.93
		28	-94.43	142.7	-9.215	0.693	0.91
	21-R	8	-76.18	115.7	-22.21	0.773	0.94
		28	-77.43	143.0	-24.04	0.603	0.95
B	22	7	-86.41	142.7	-1.562	0.609	0.86
		28	-141.1	207.5	-16.43	0.721	0.83
	22-R	7	-92.70	158.7	-34.06	0.685	0.79
		28	-113.2	173.7	-28.96	0.744	0.86
	23	7	-129.5	194.9	-35.11	0.772	0.70
		28	-114.5	190.8	-26.46	0.661	0.91
	23-R	7	-134.1	184.4	-28.65	0.836	0.89
		27	-128.1	166.8	0.0	0.768	0.91

Note: R indicates remix.

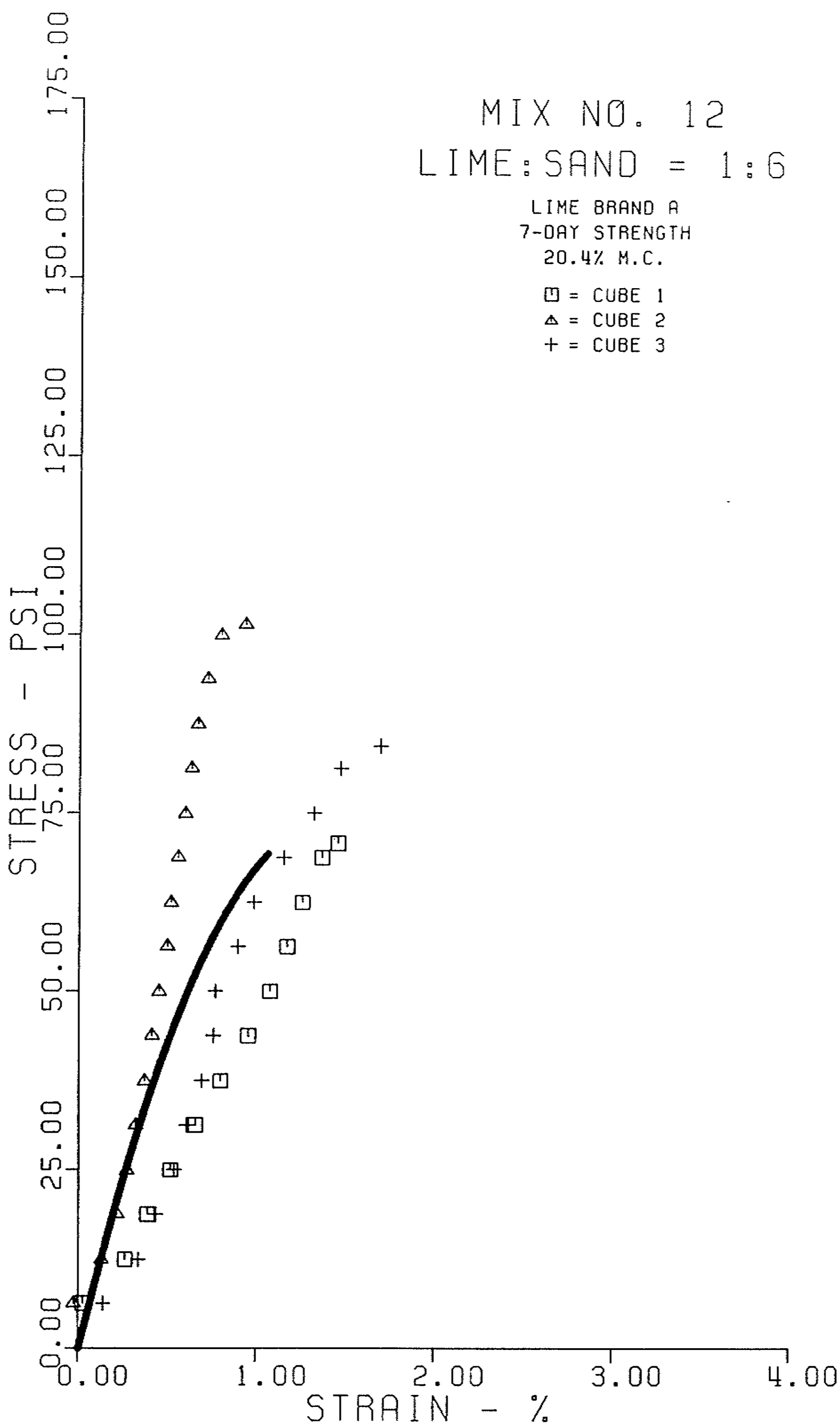


Figure 33: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 12

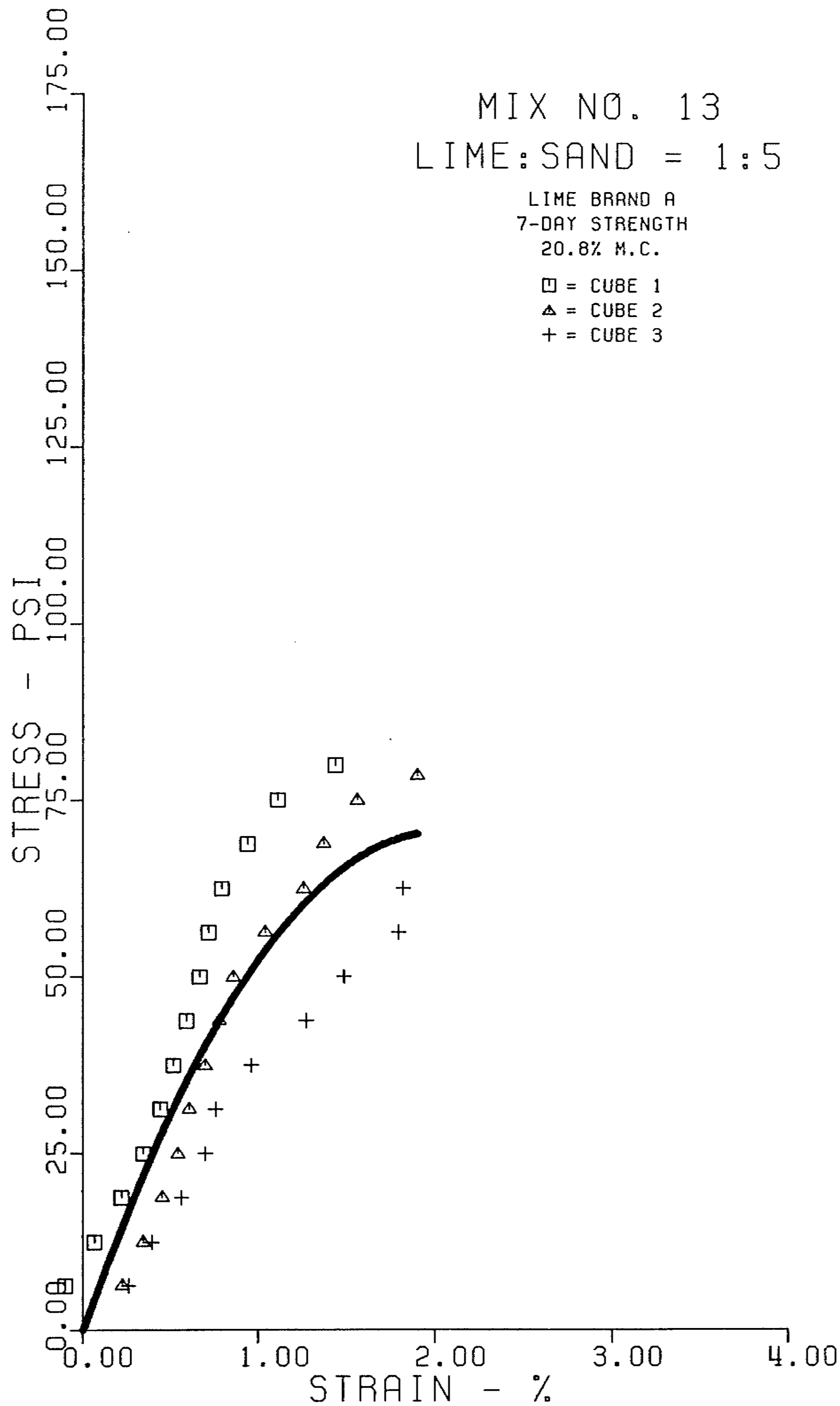


Figure 34: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 13

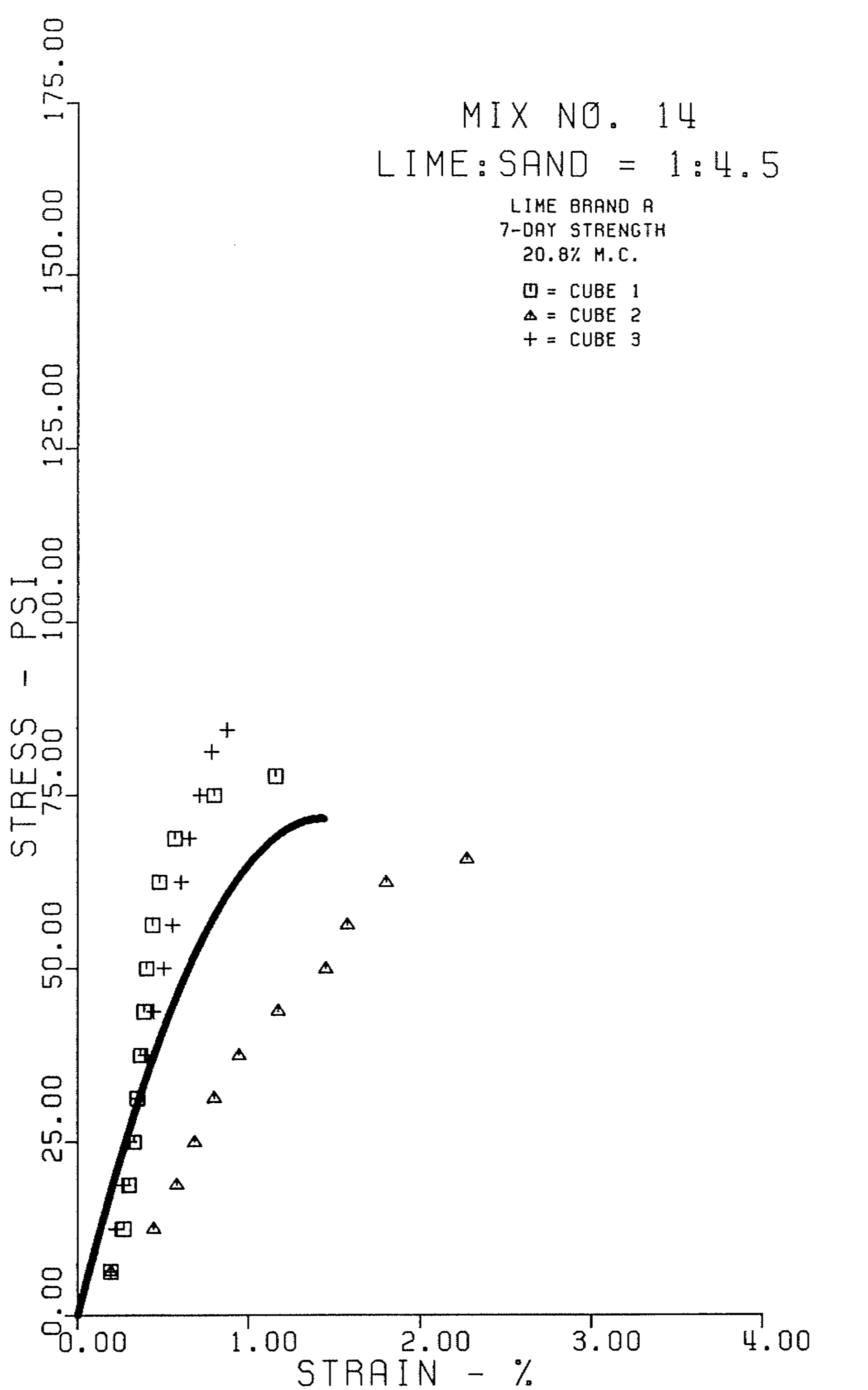


Figure 35: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 14

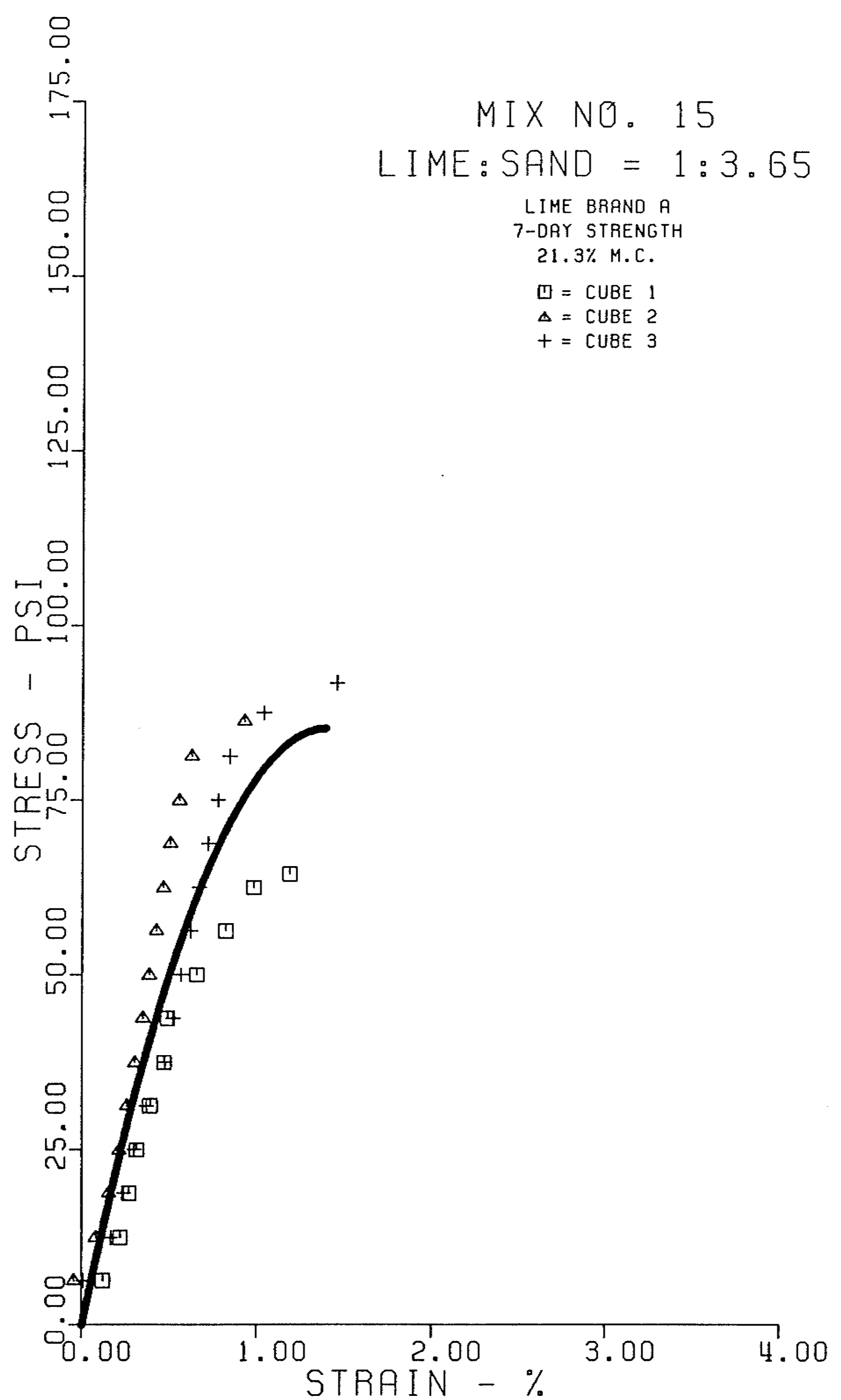


Figure 36: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 15

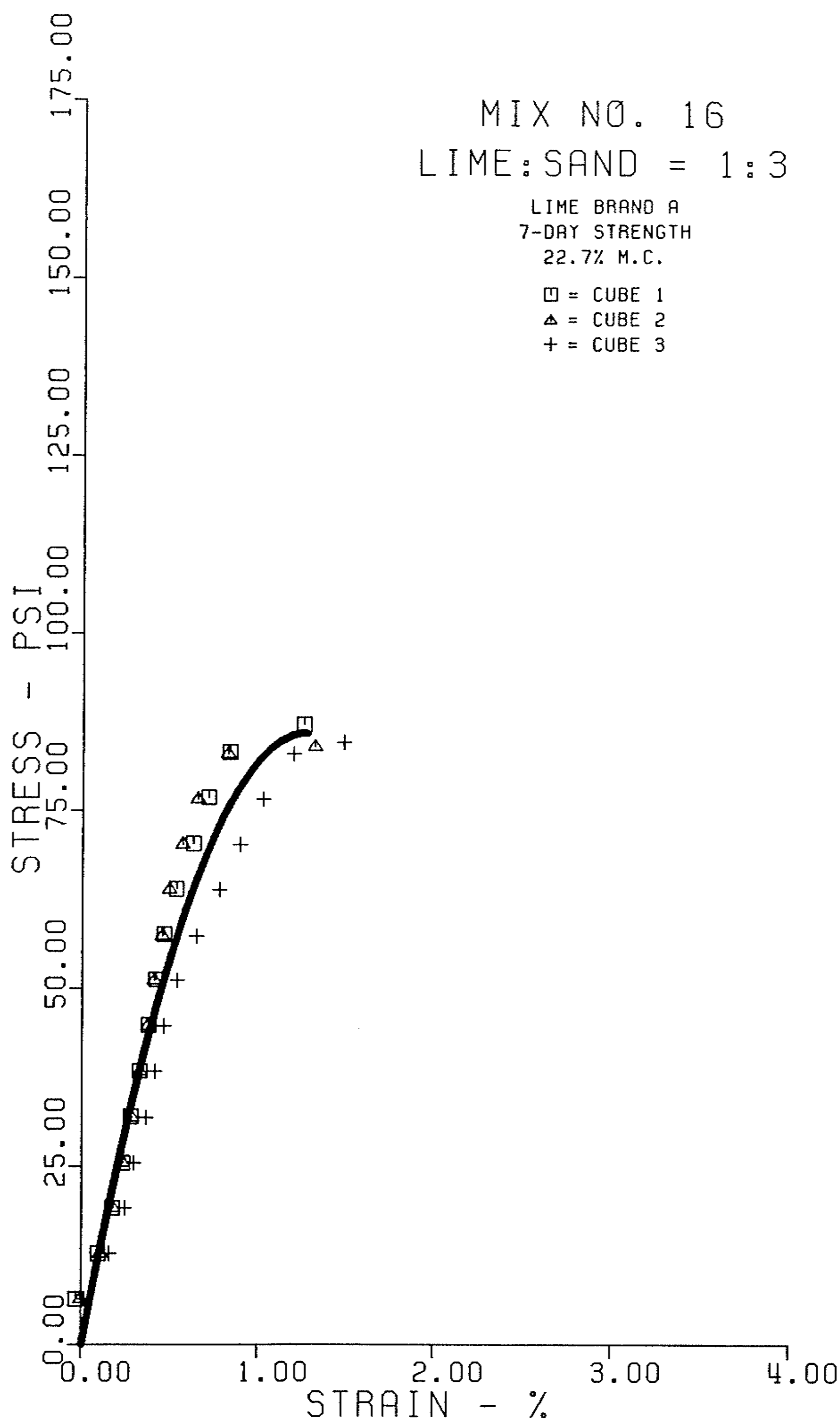


Figure 37: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 16

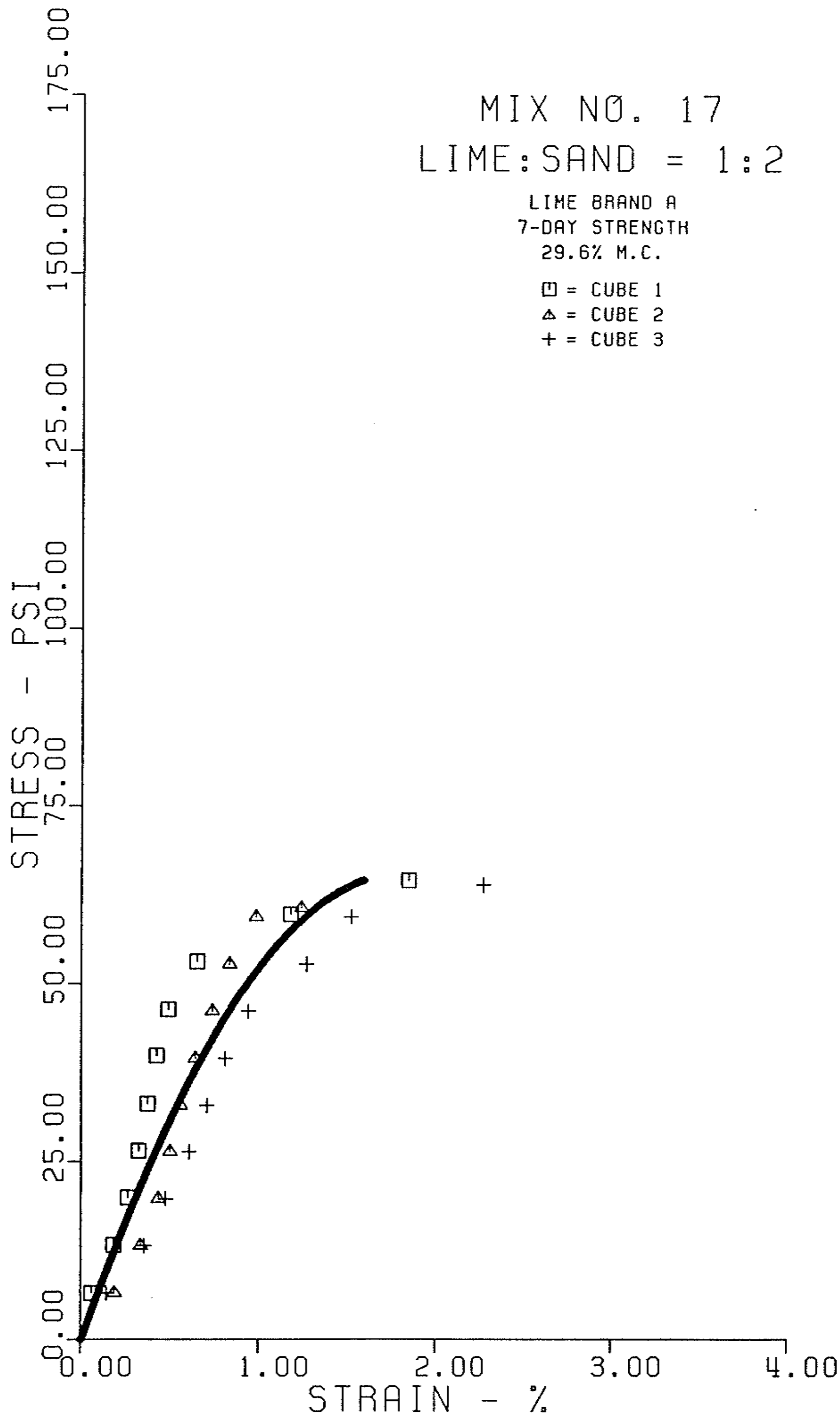


Figure 38: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 17

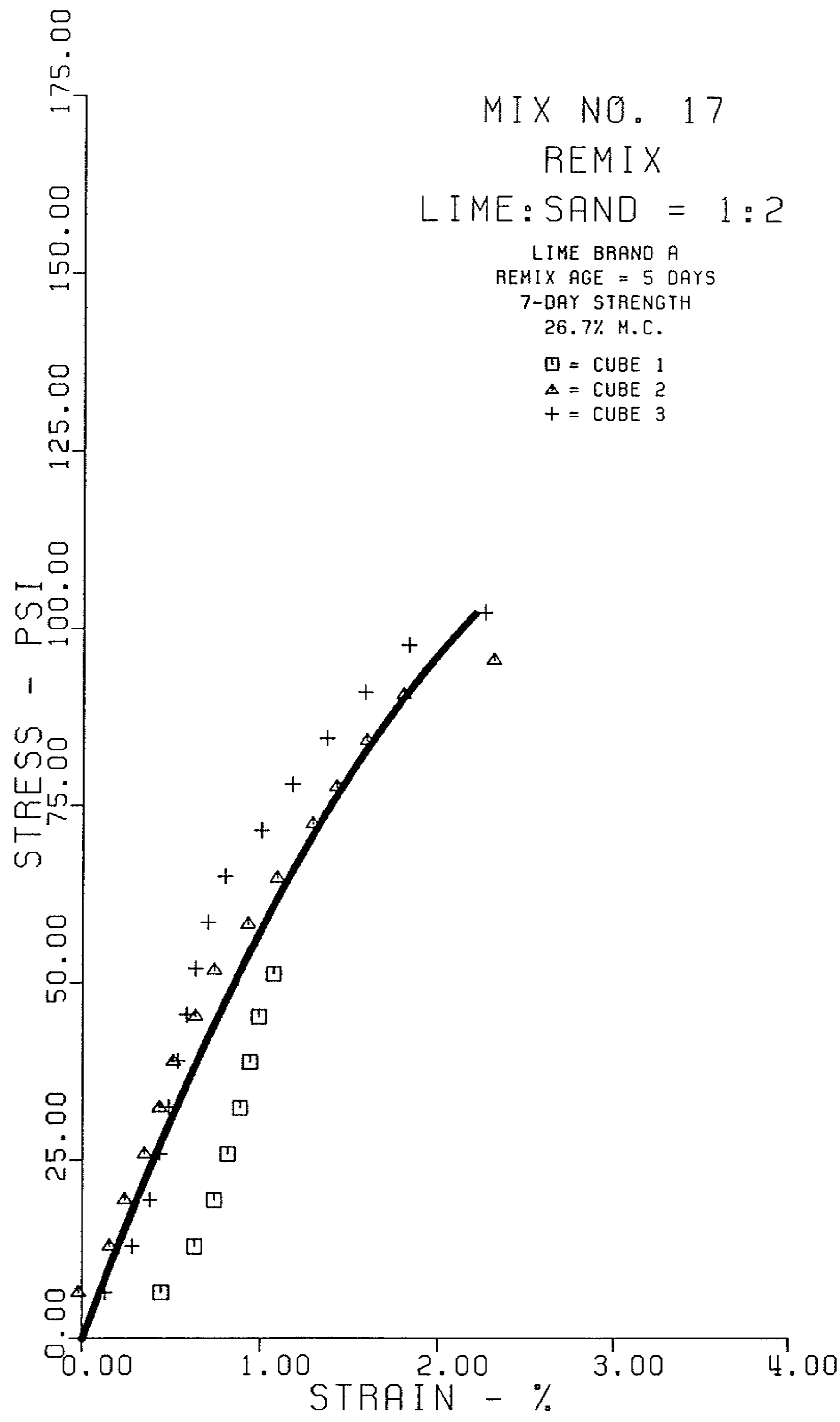


Figure 39: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 17

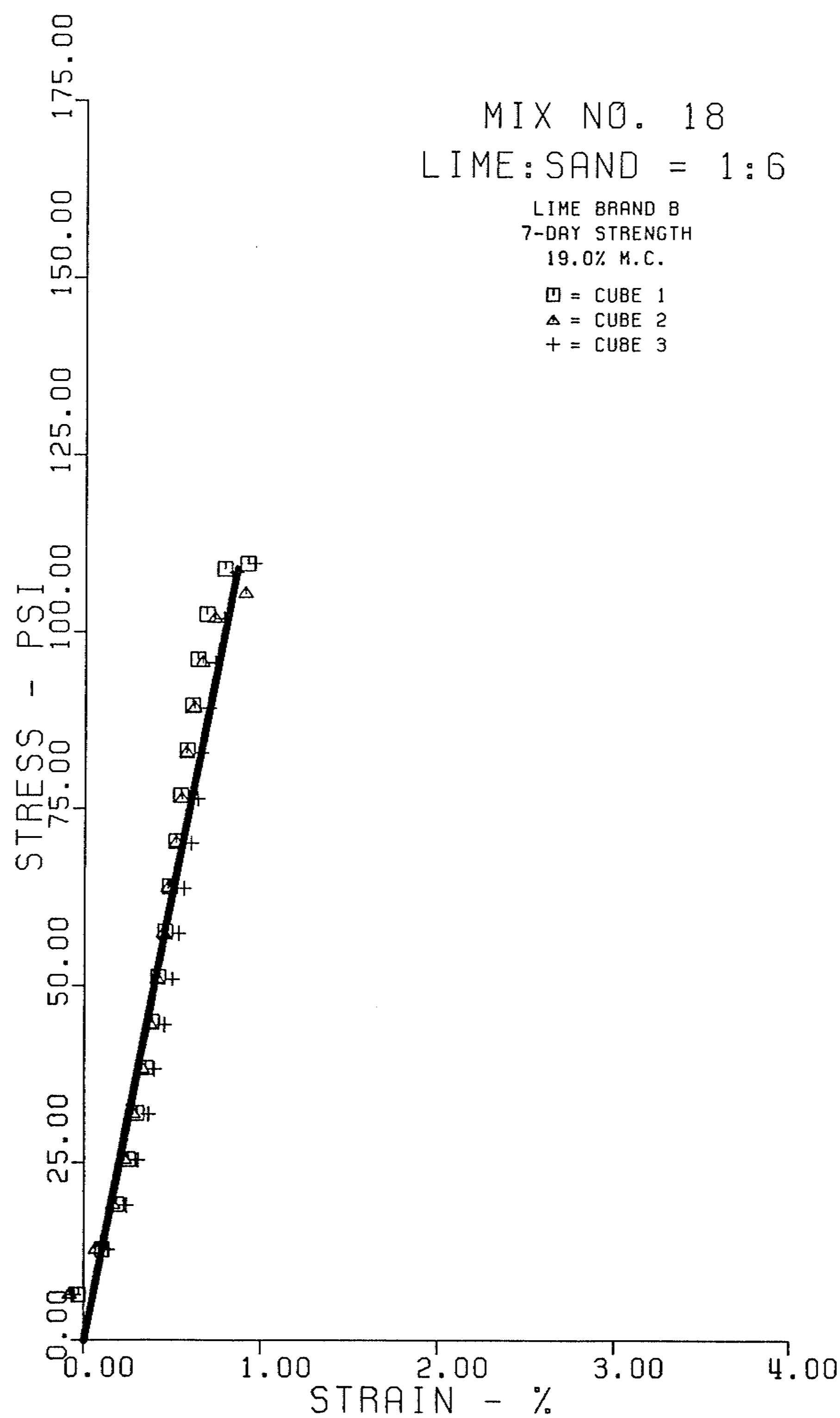


Figure 40: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 18

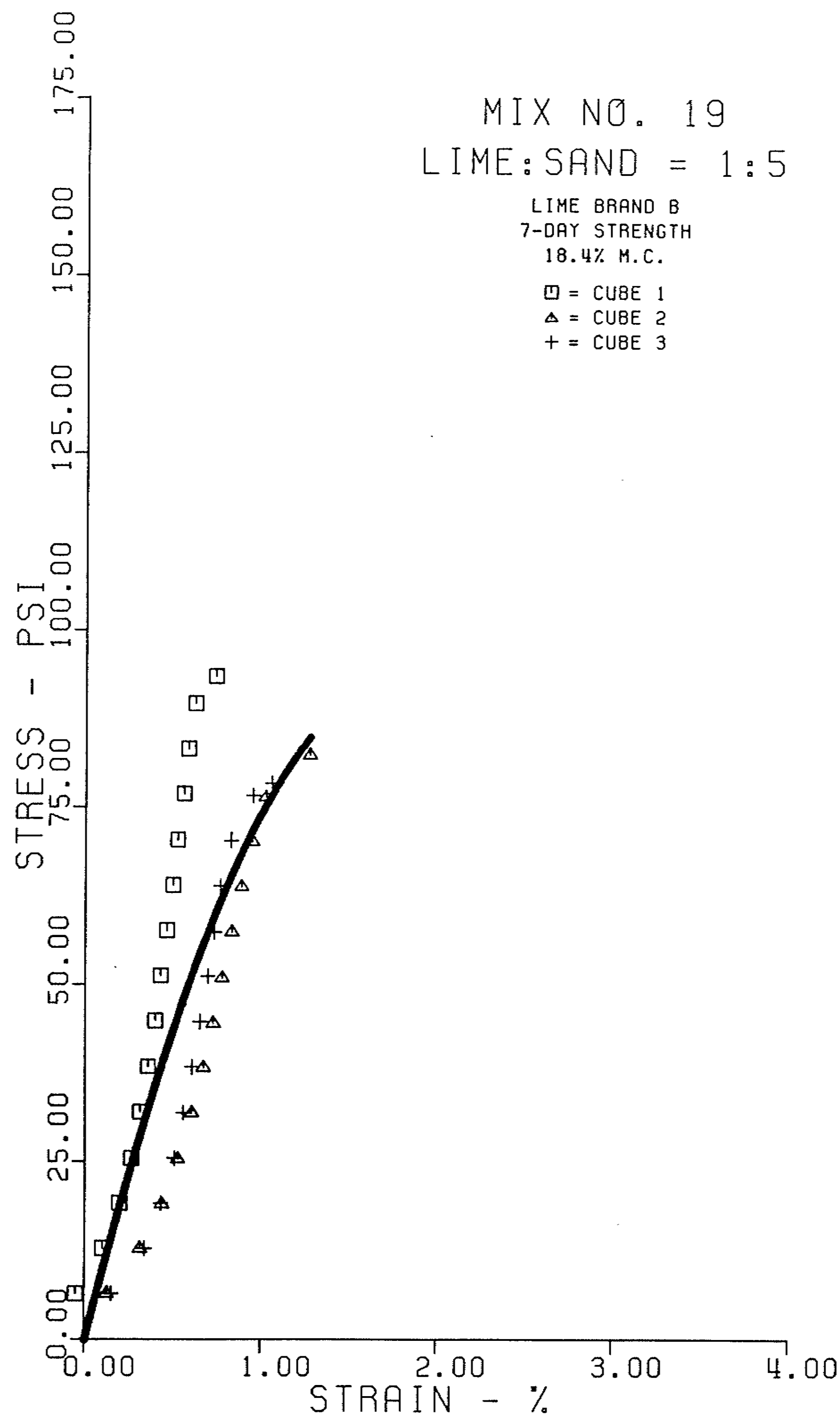


Figure 41: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 19

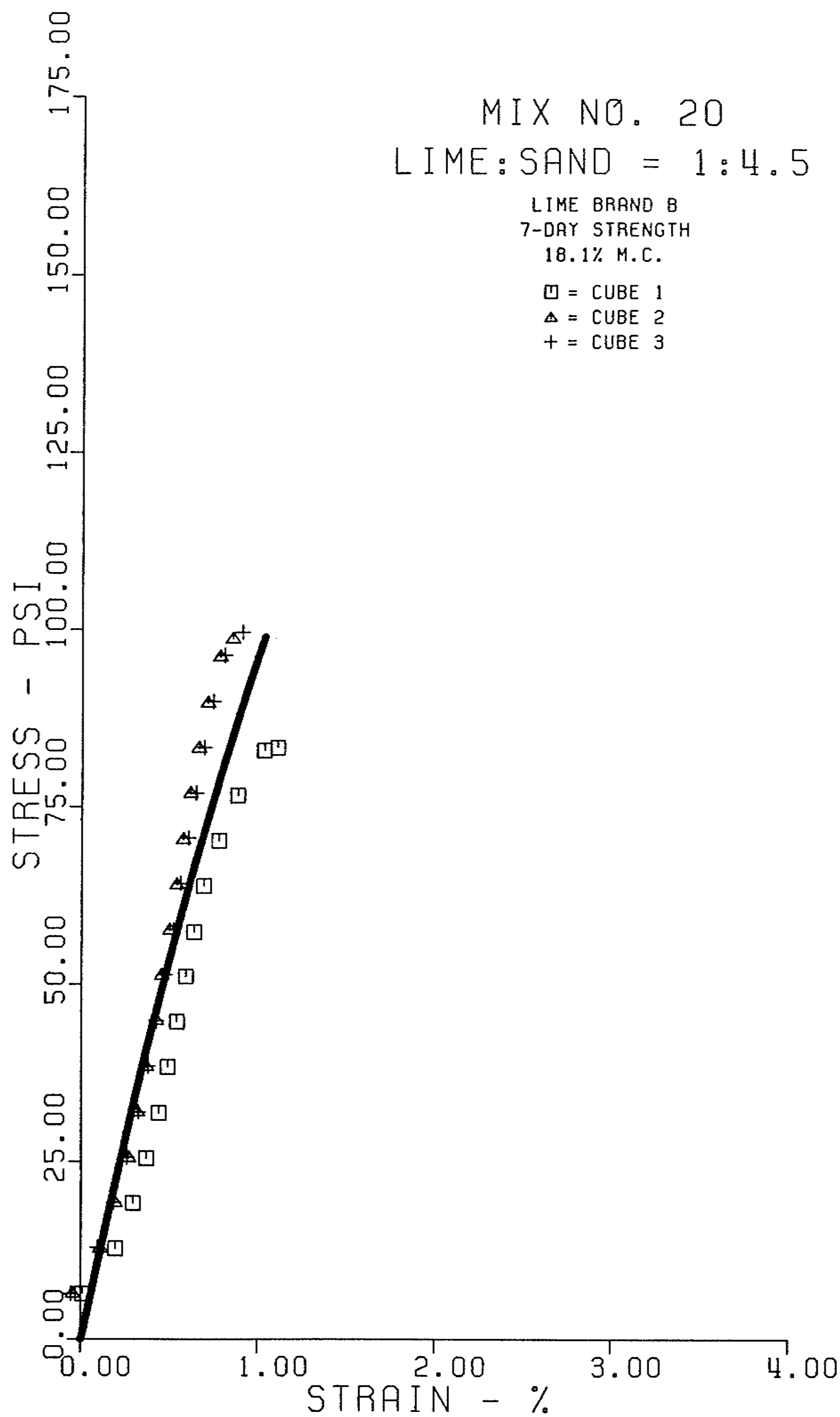


Figure 42: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 20

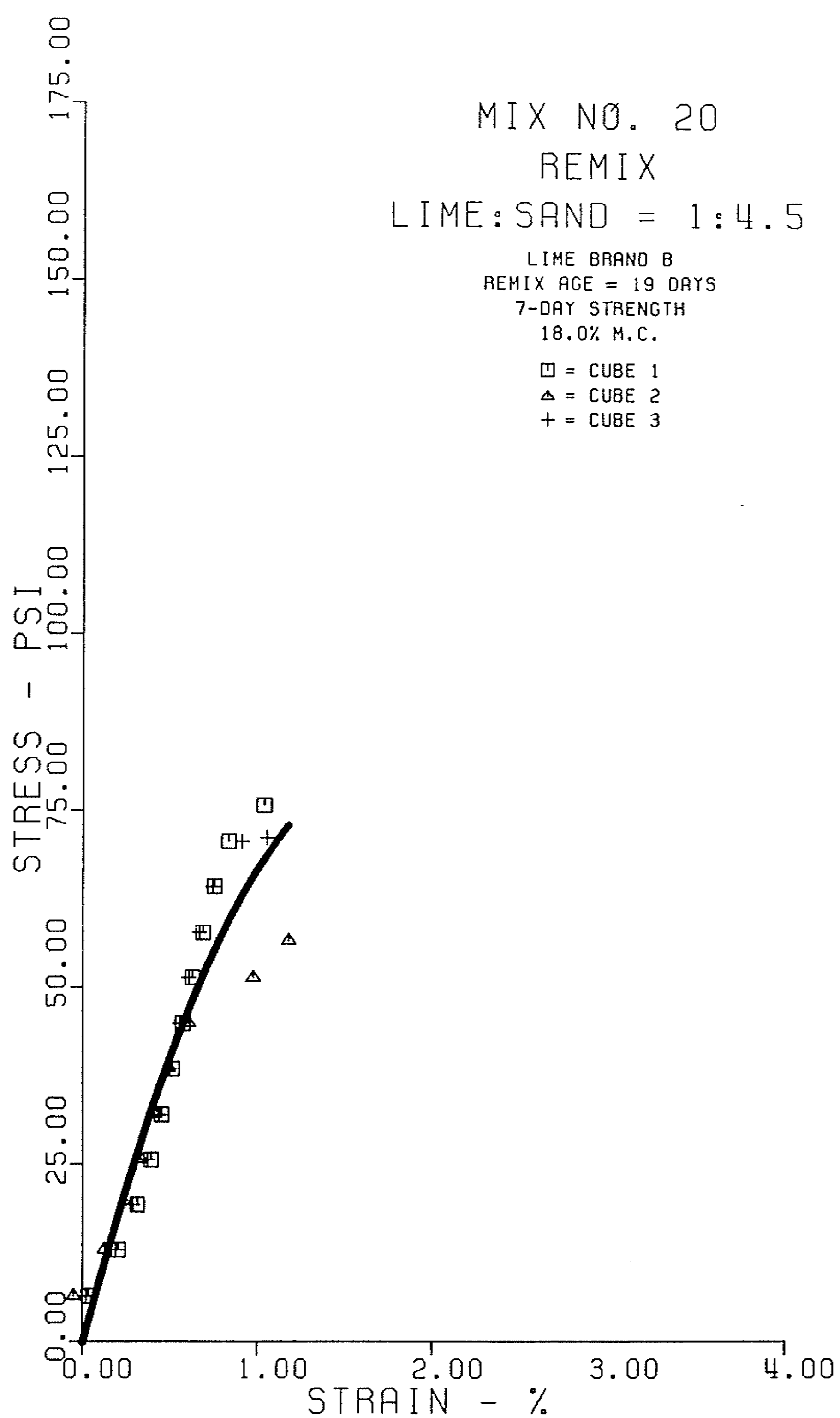


Figure 43: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 20

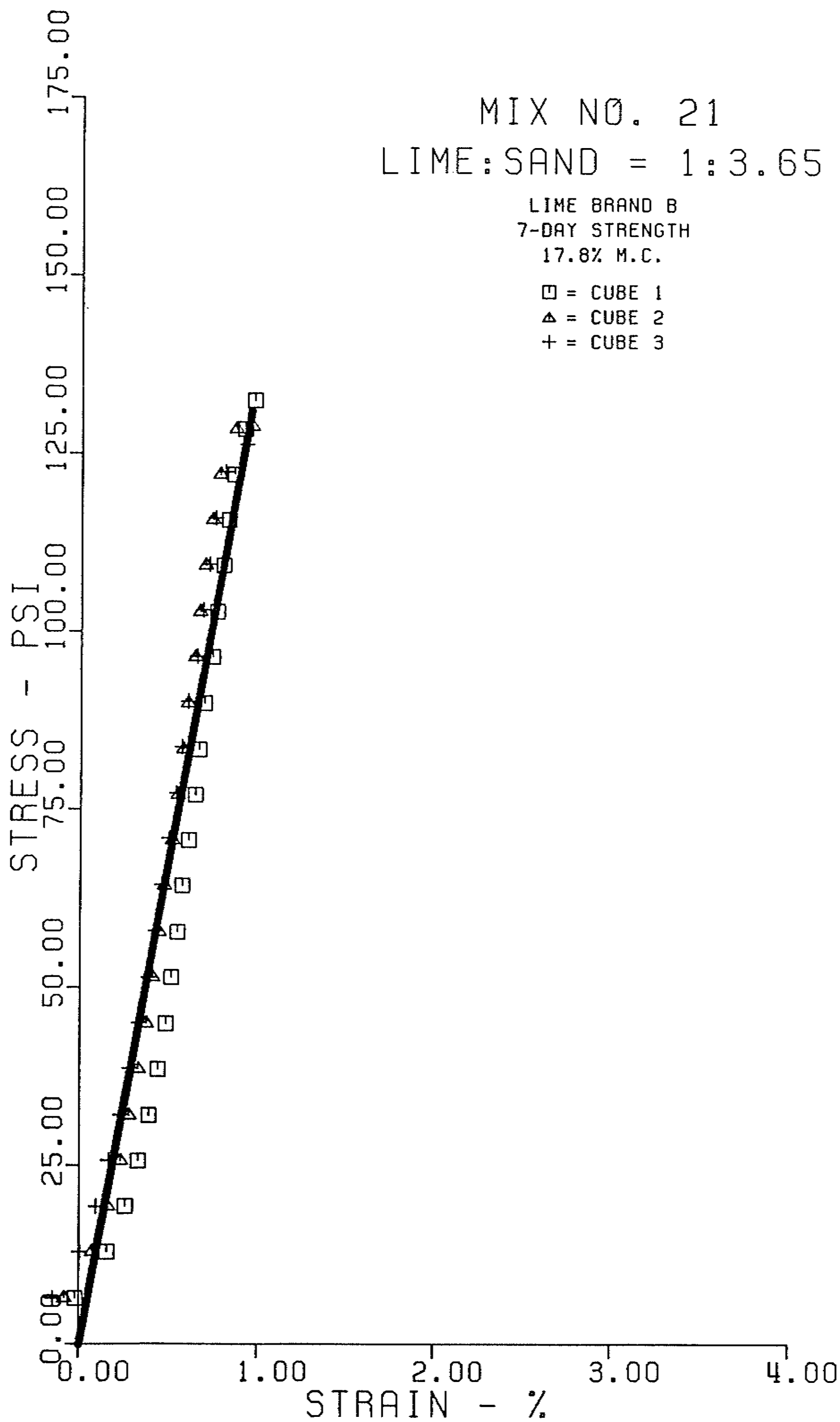


Figure 44: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 21

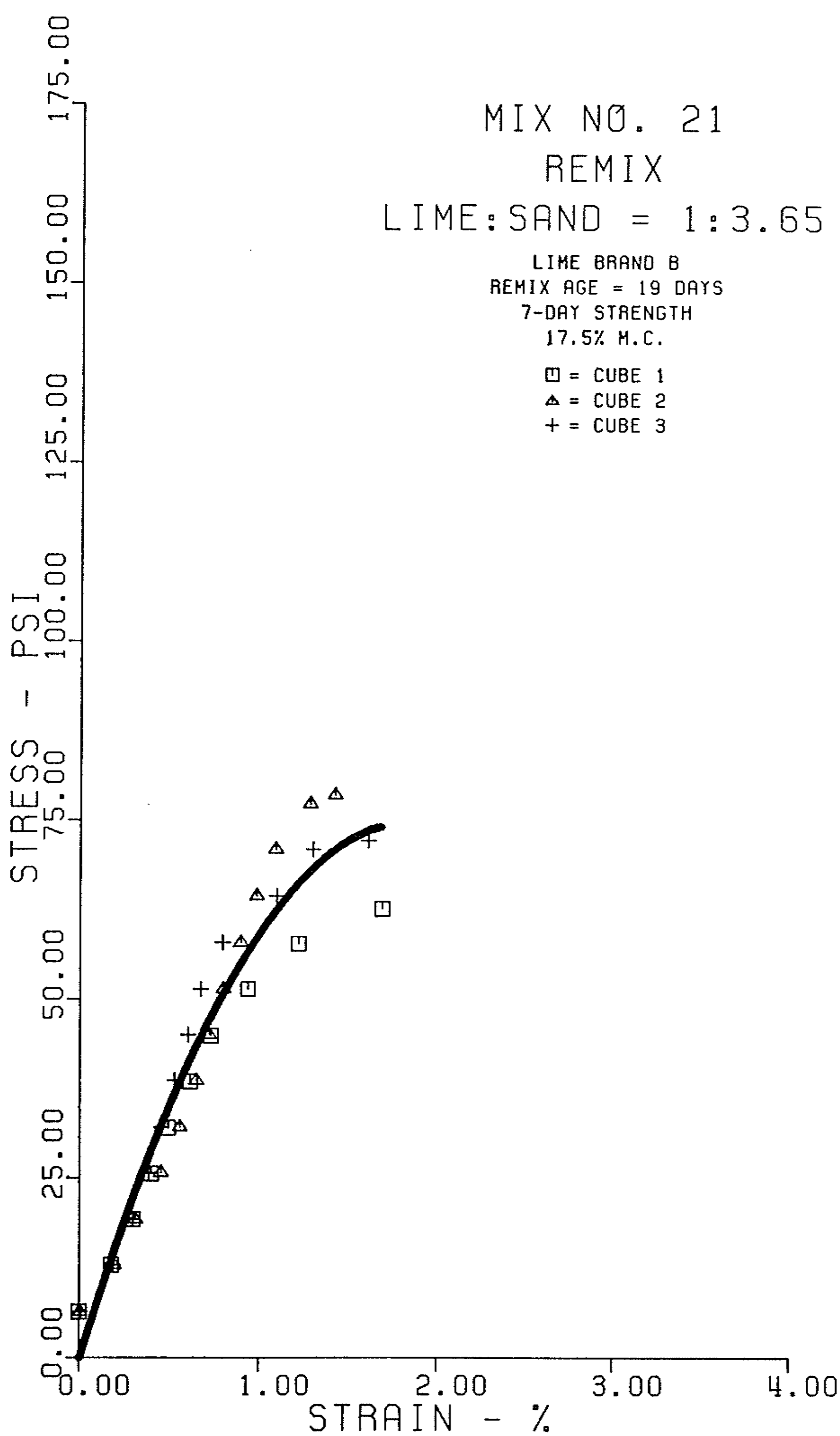


Figure 45: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 21

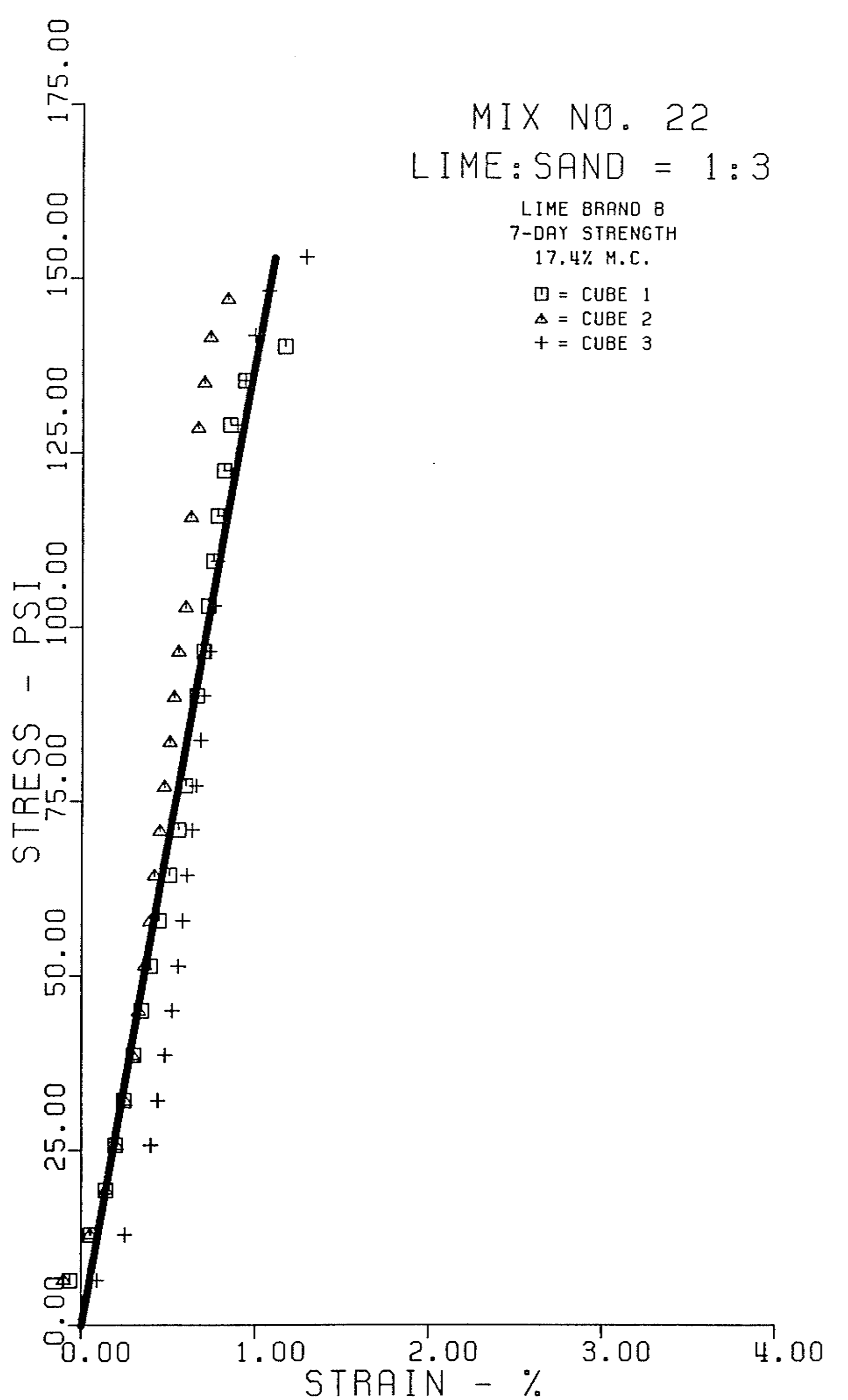


Figure 46: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 22

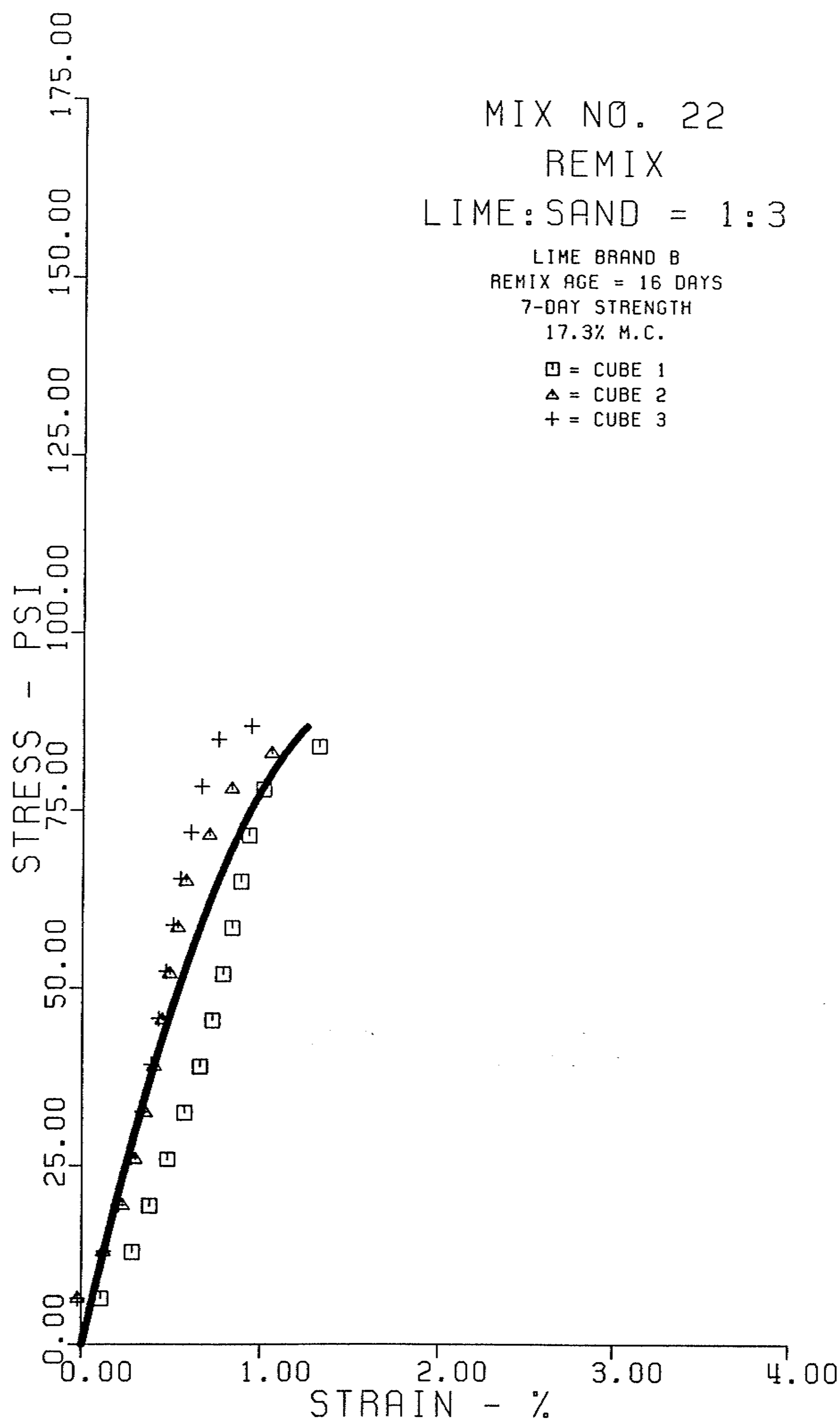


Figure 47: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 22

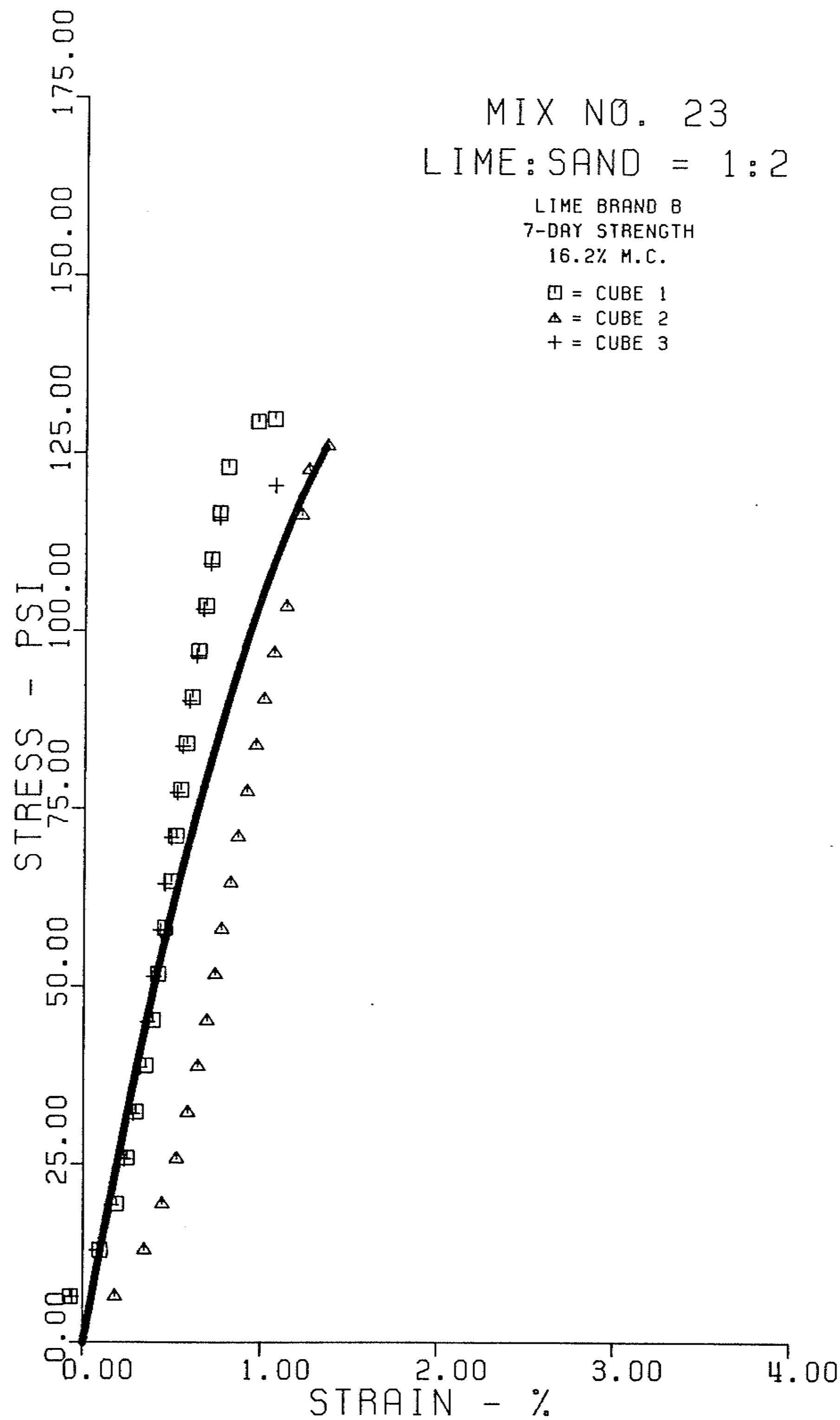


Figure 48: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 23

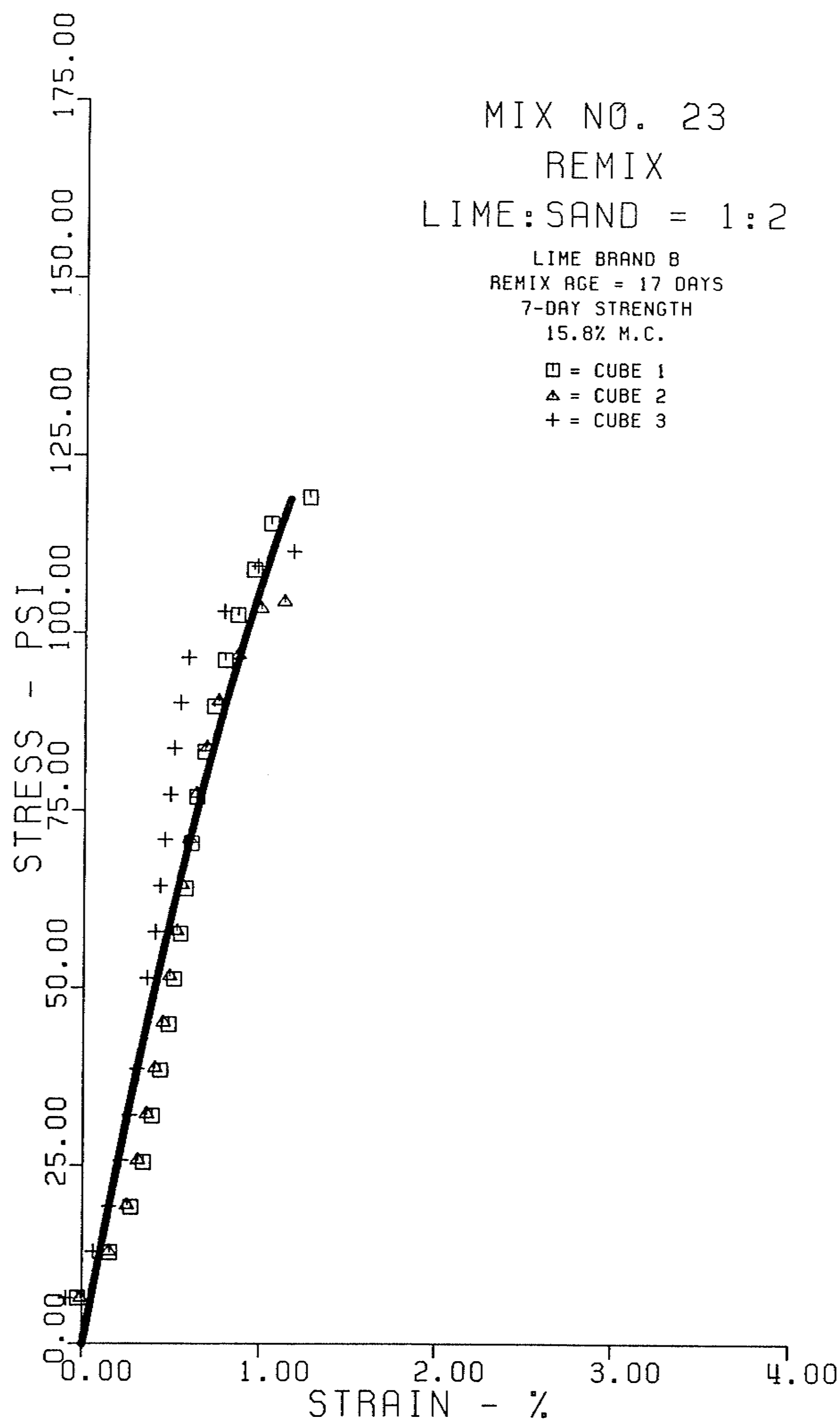


Figure 49: Computer Plot Showing the Seven-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 23

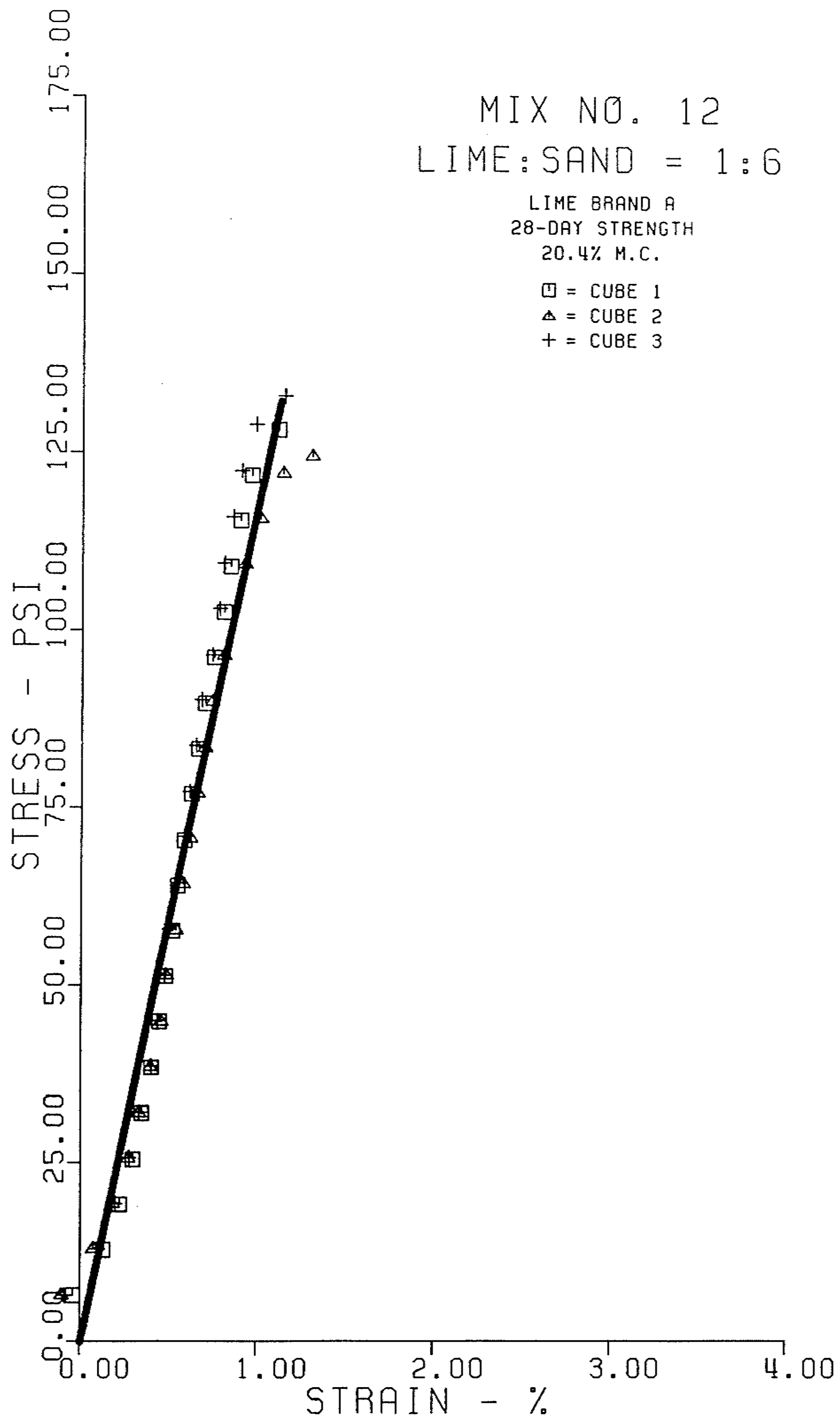


Figure 50: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 12

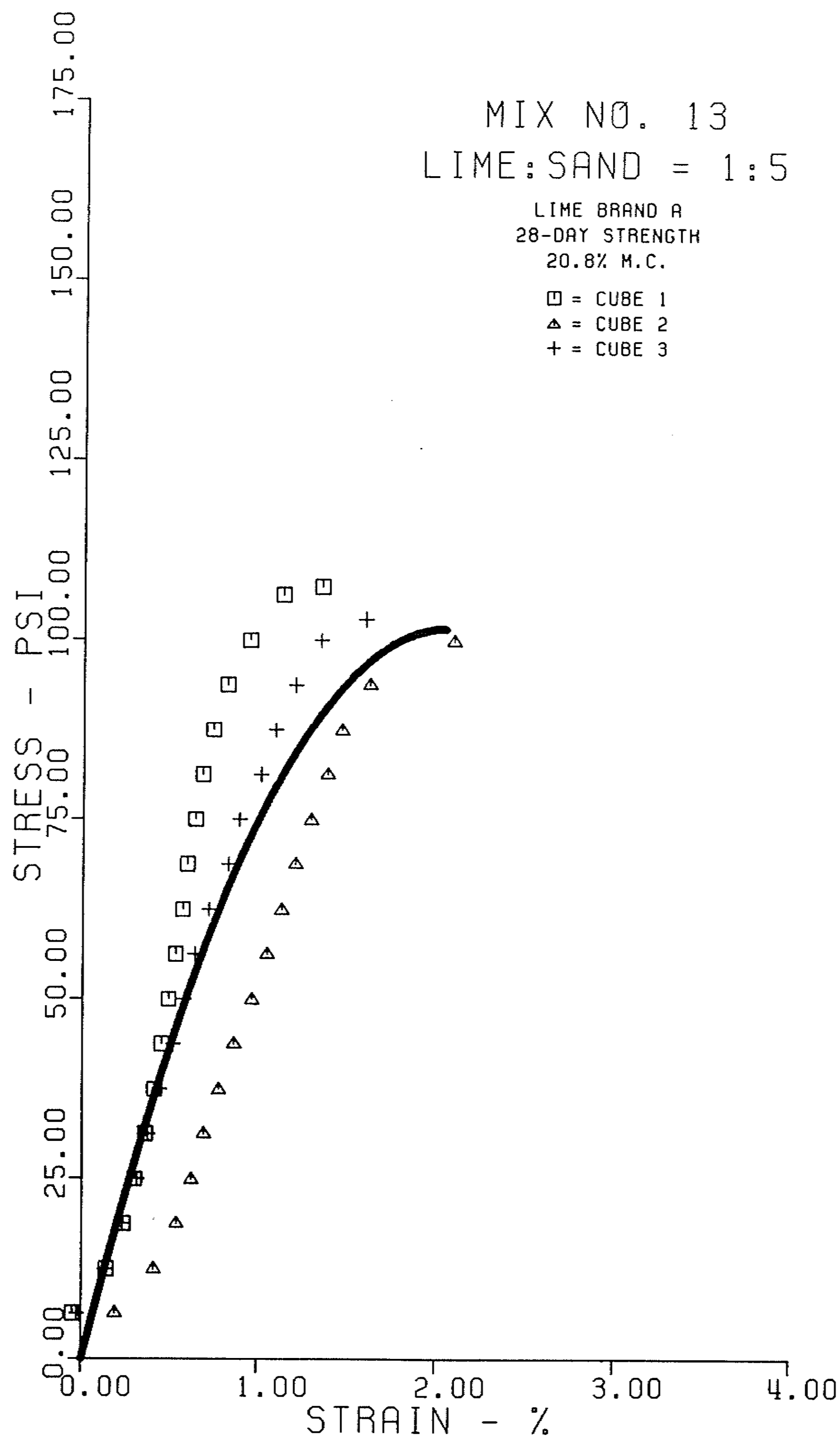


Figure 51: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 13

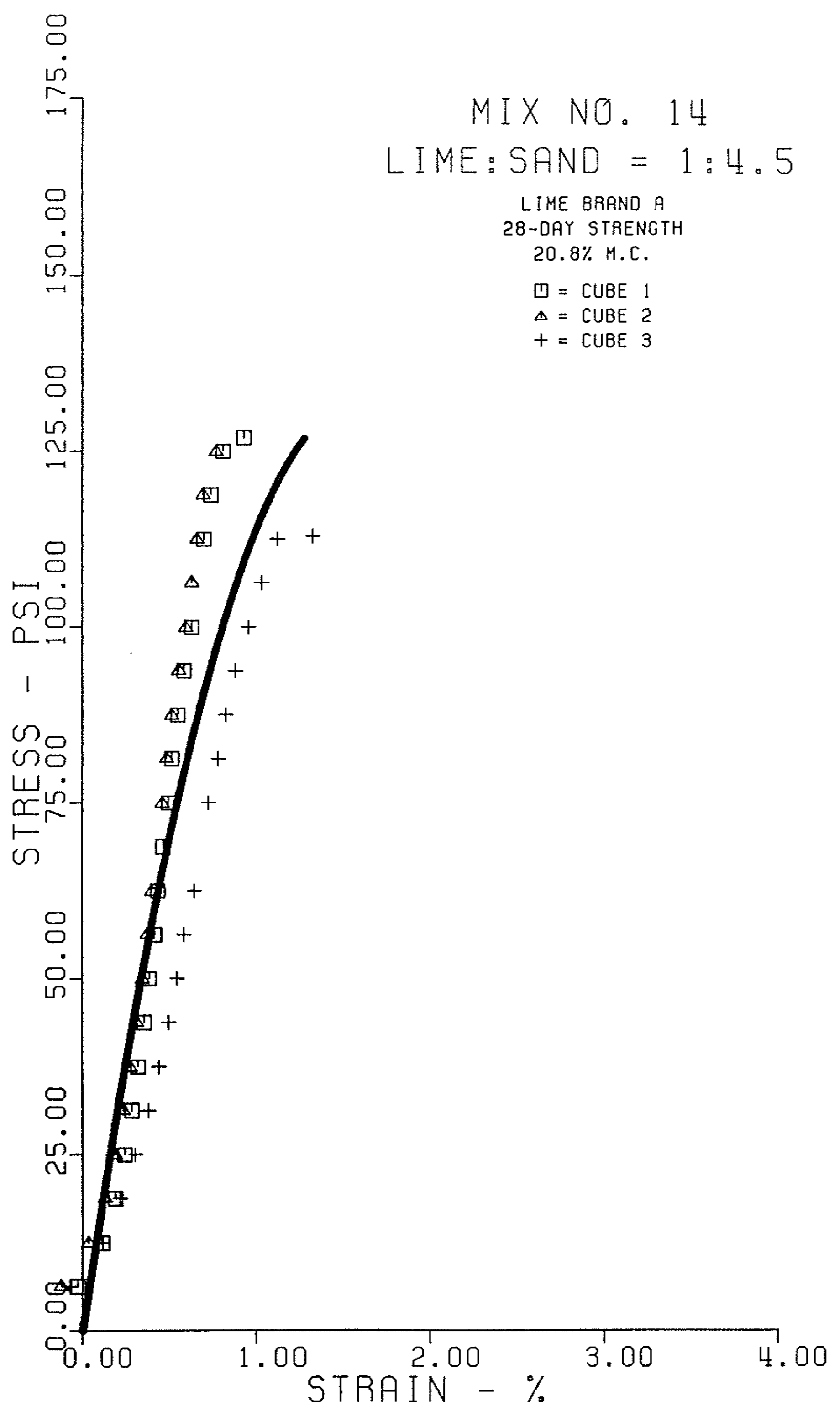


Figure 52: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 14

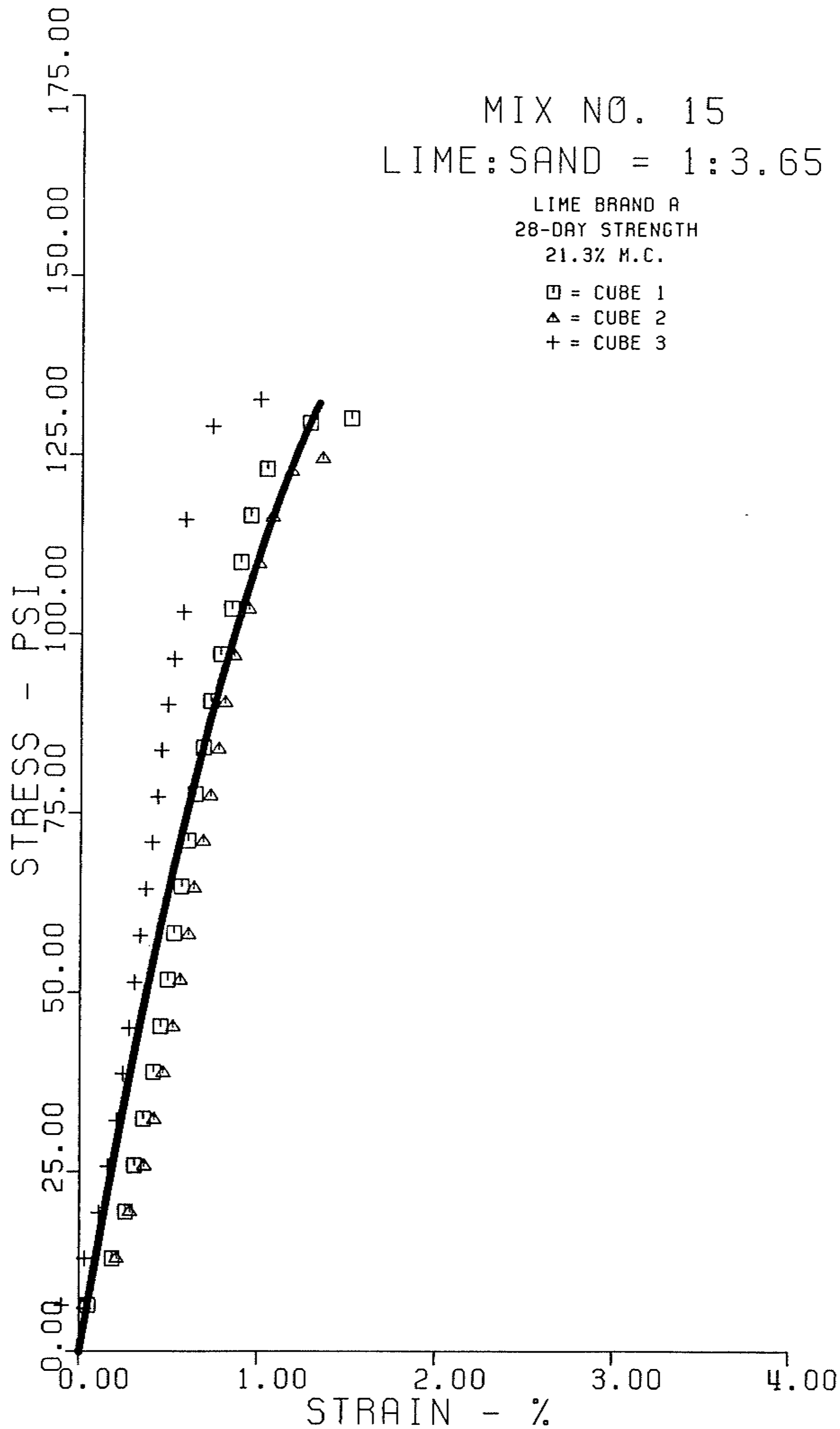


Figure 53: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 15

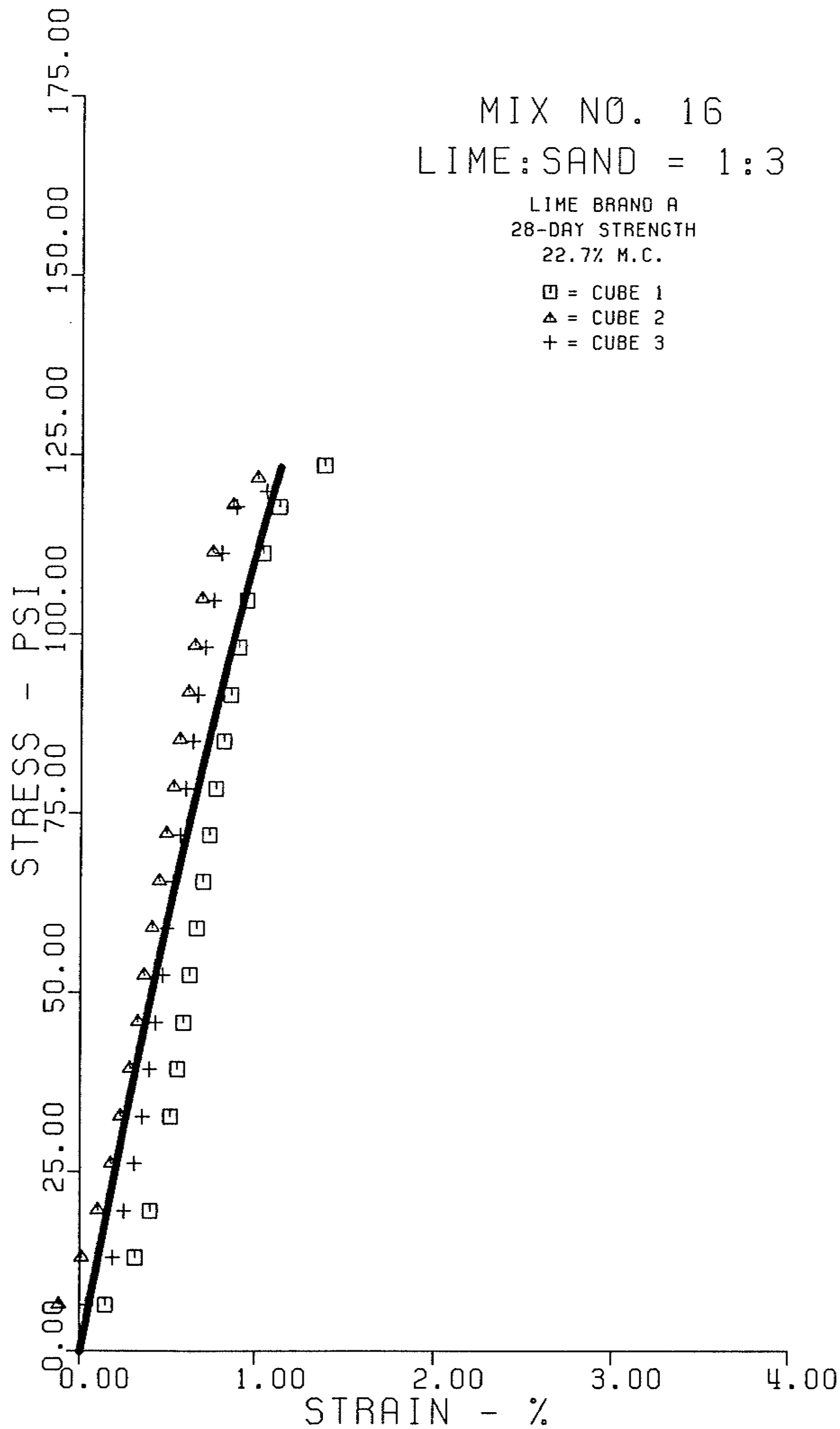


Figure 54: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 16

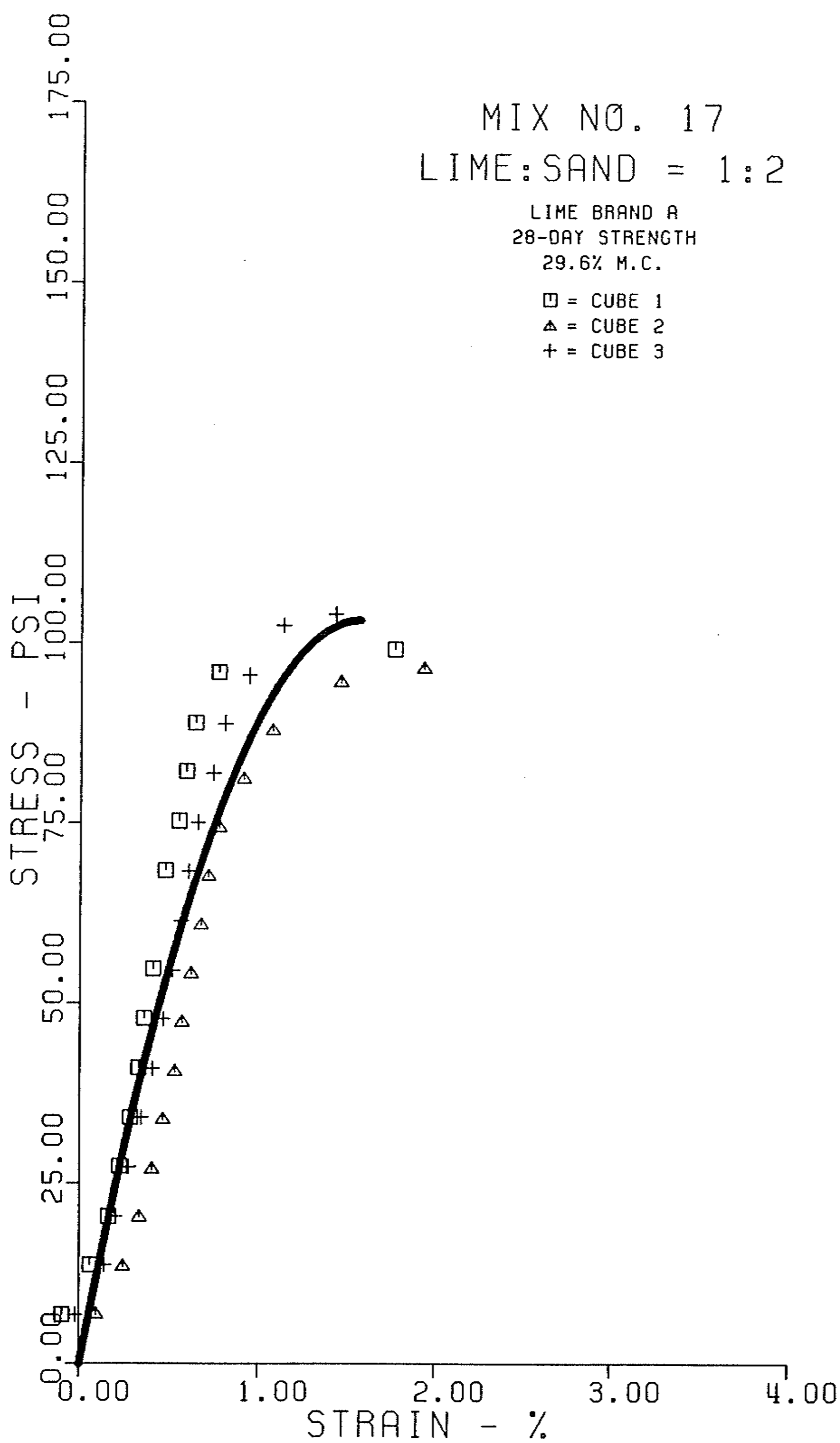


Figure 55: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 17

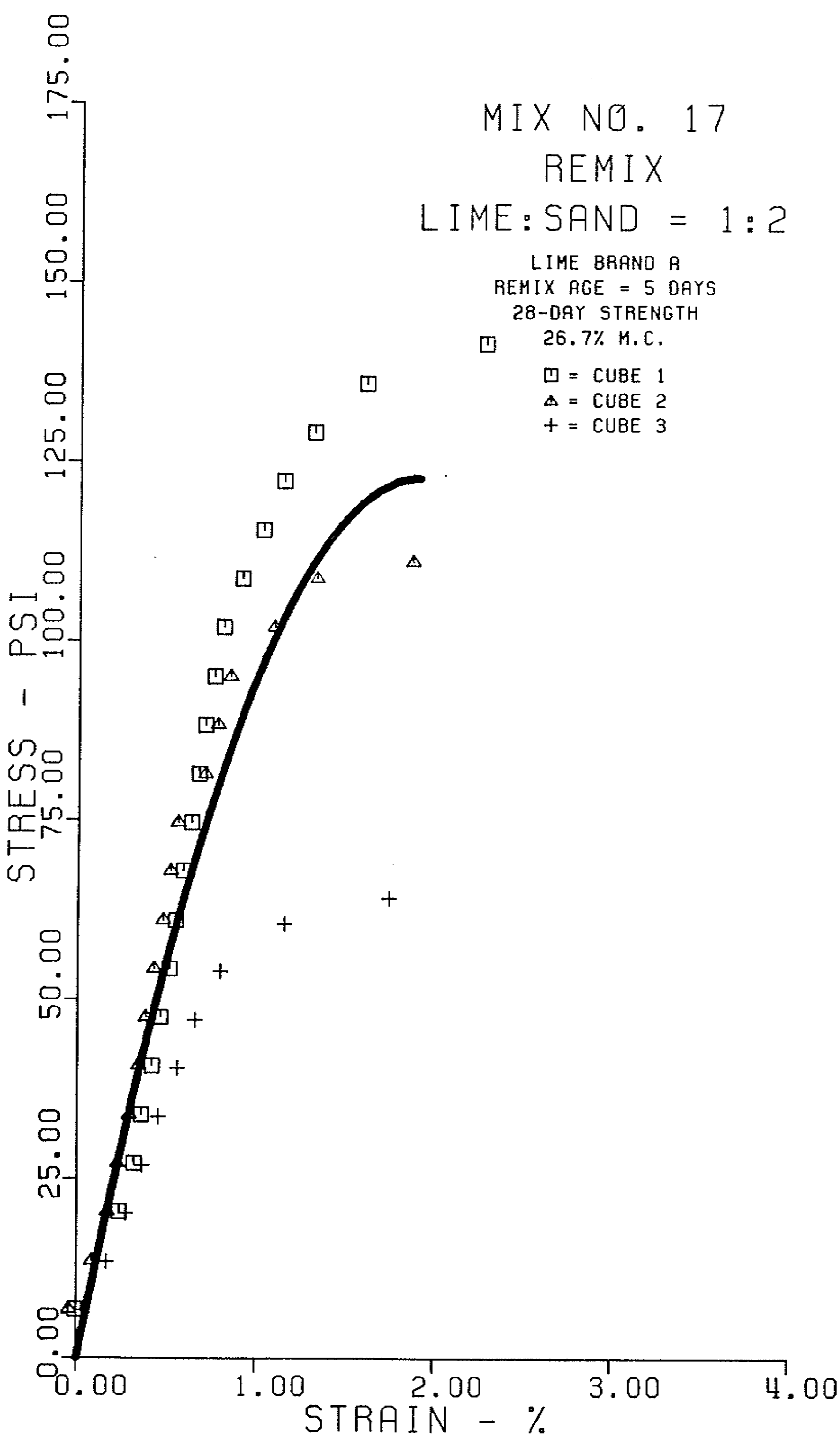


Figure 56: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 17

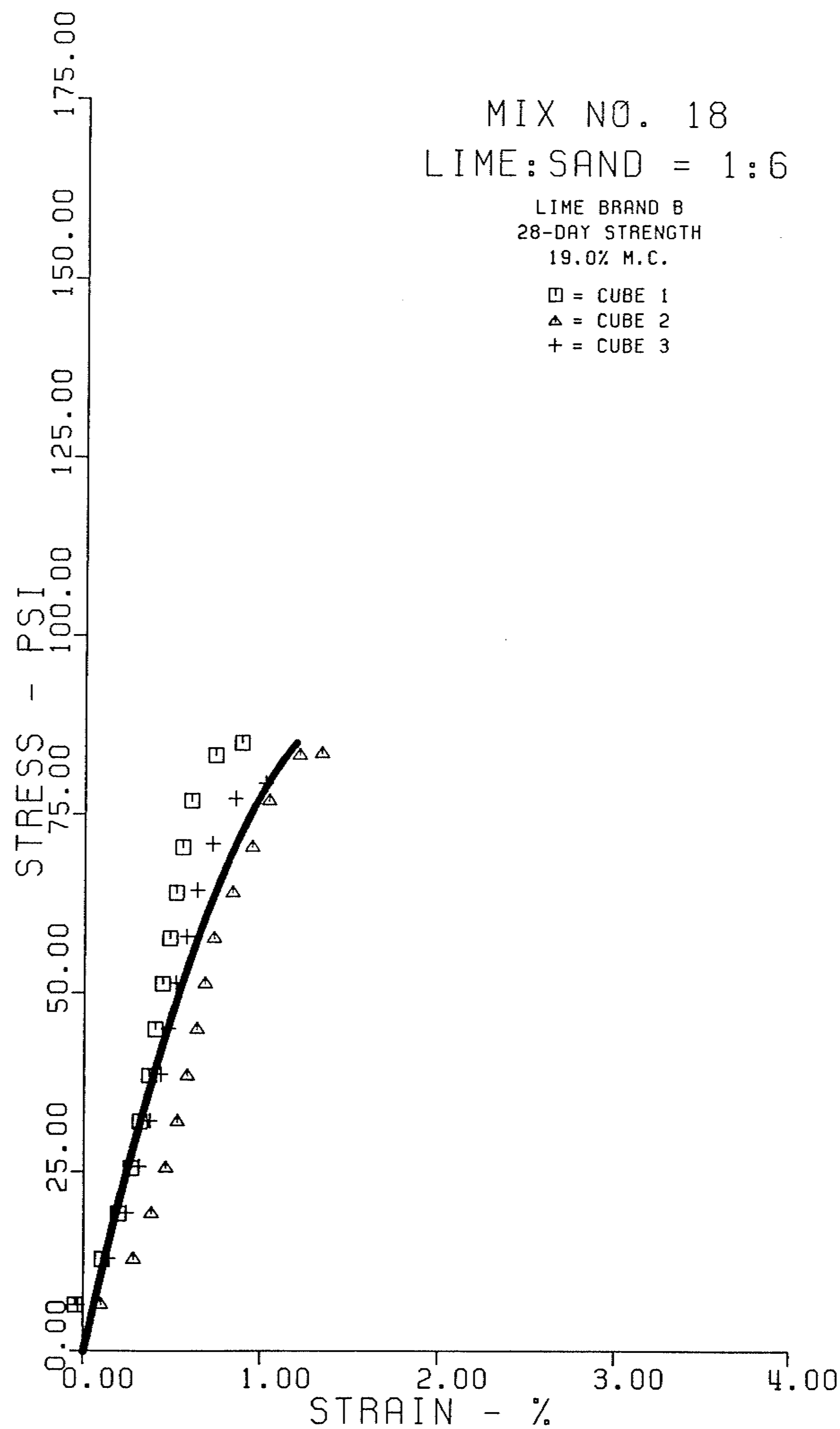


Figure 57: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 18

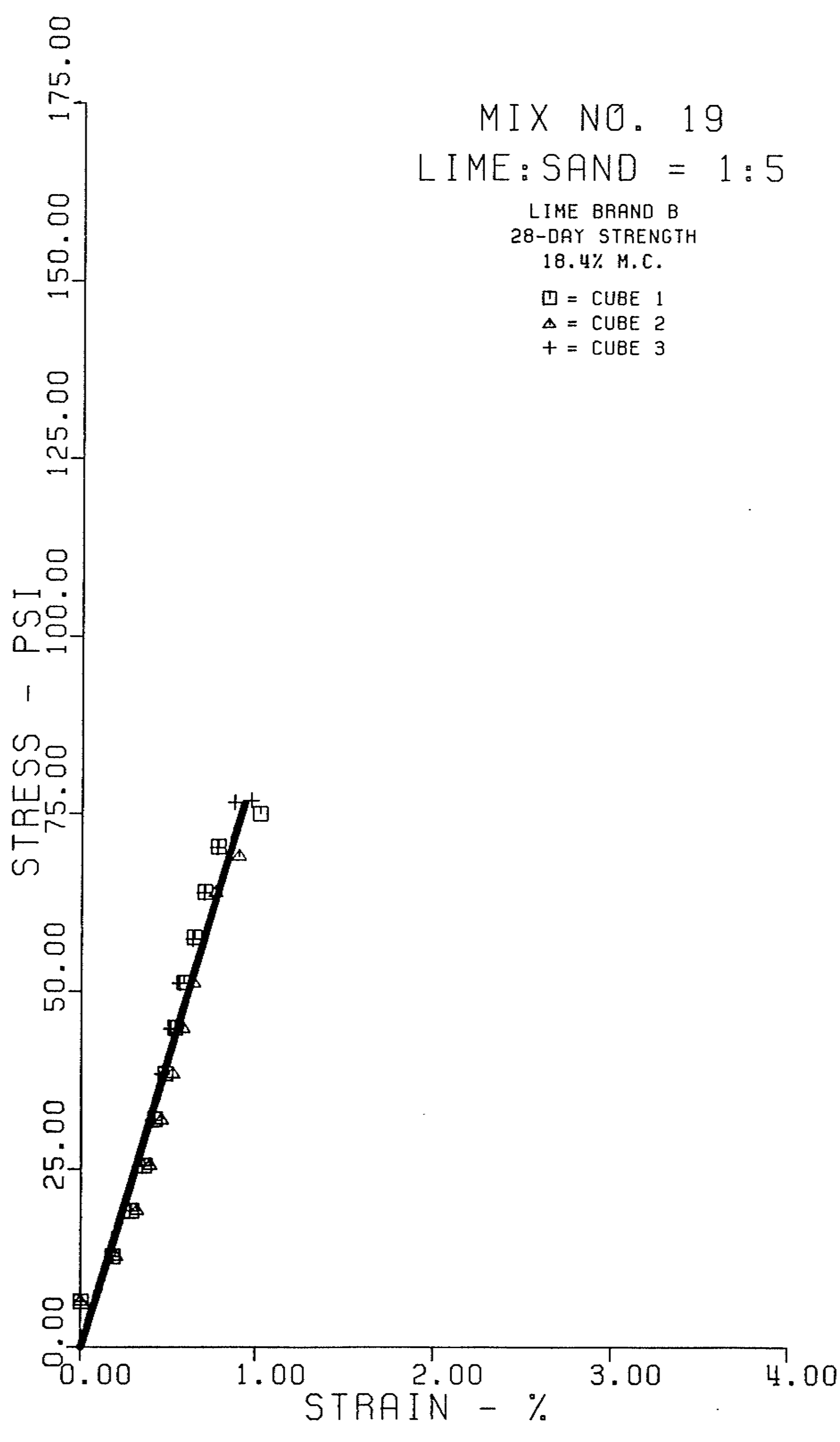


Figure 58: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 19

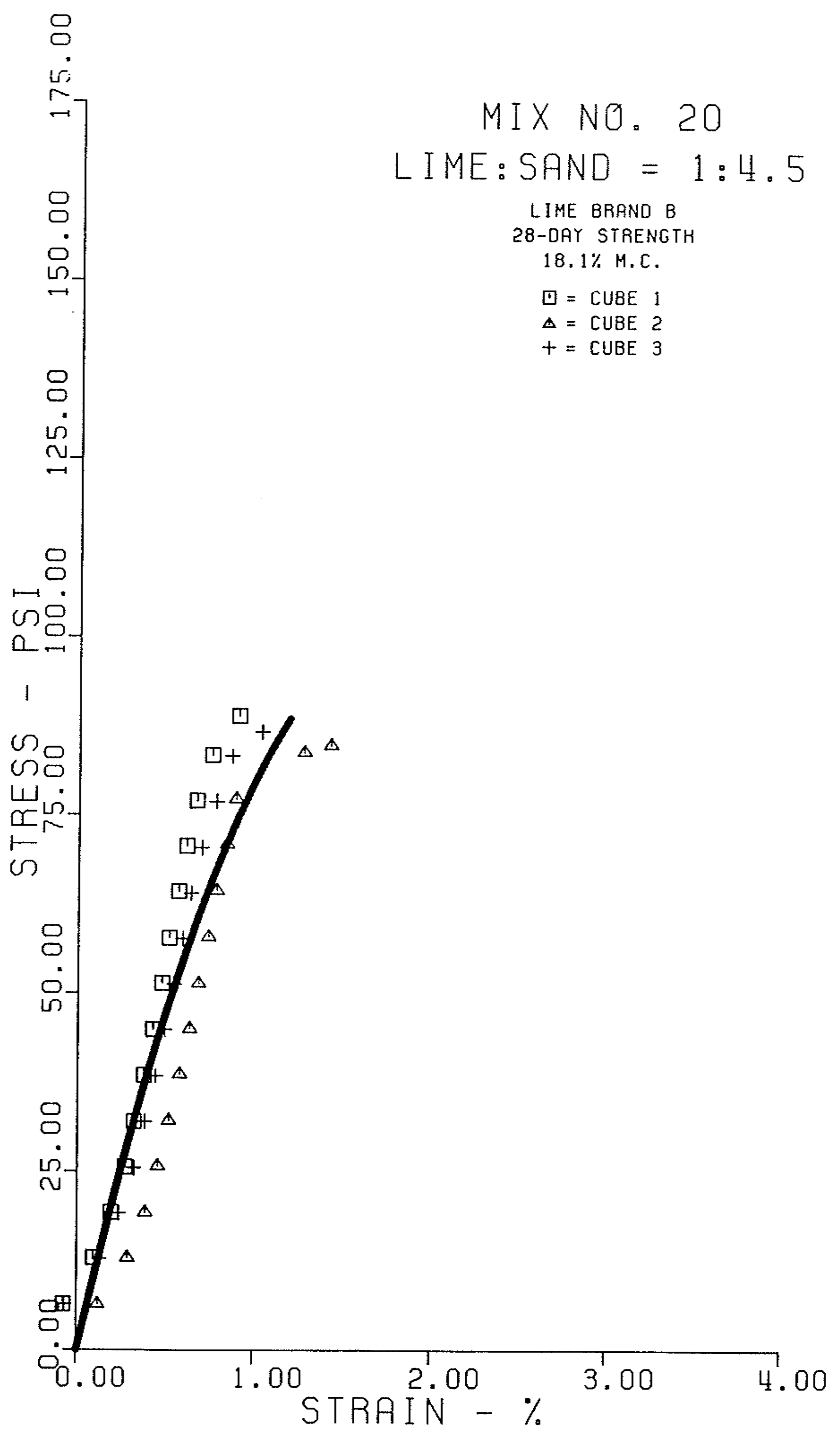


Figure 59: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 20

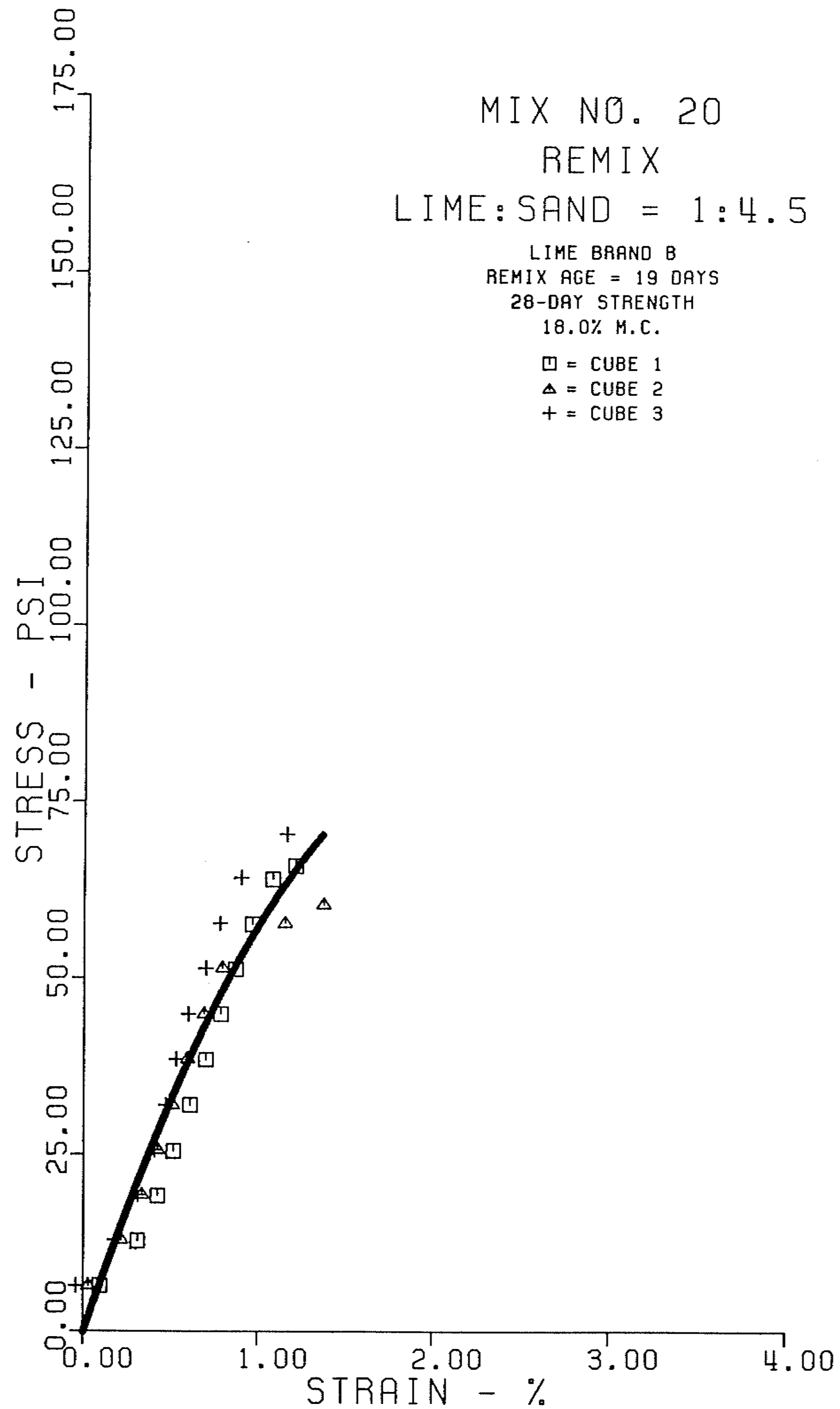


Figure 60: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 20

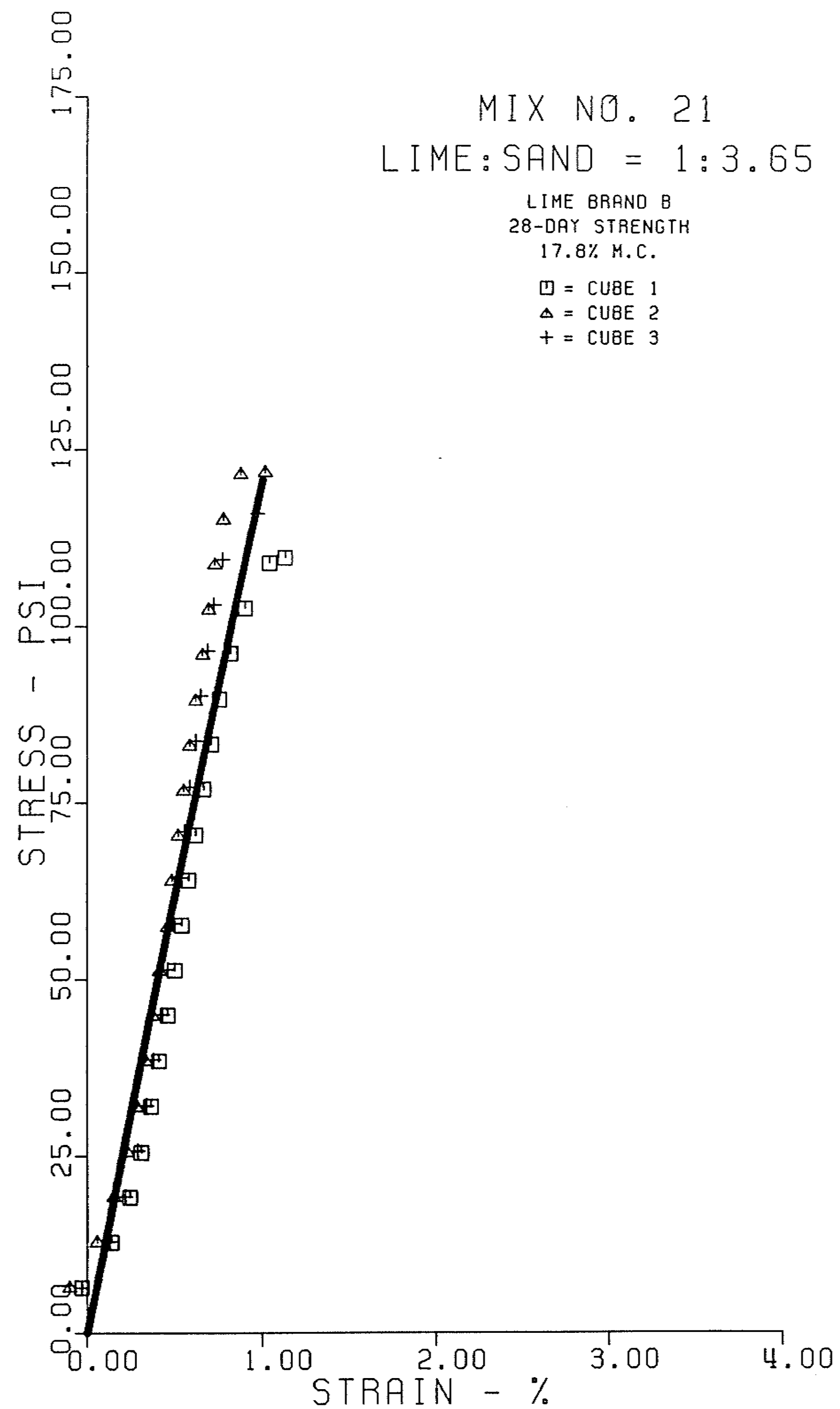


Figure 61: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 21

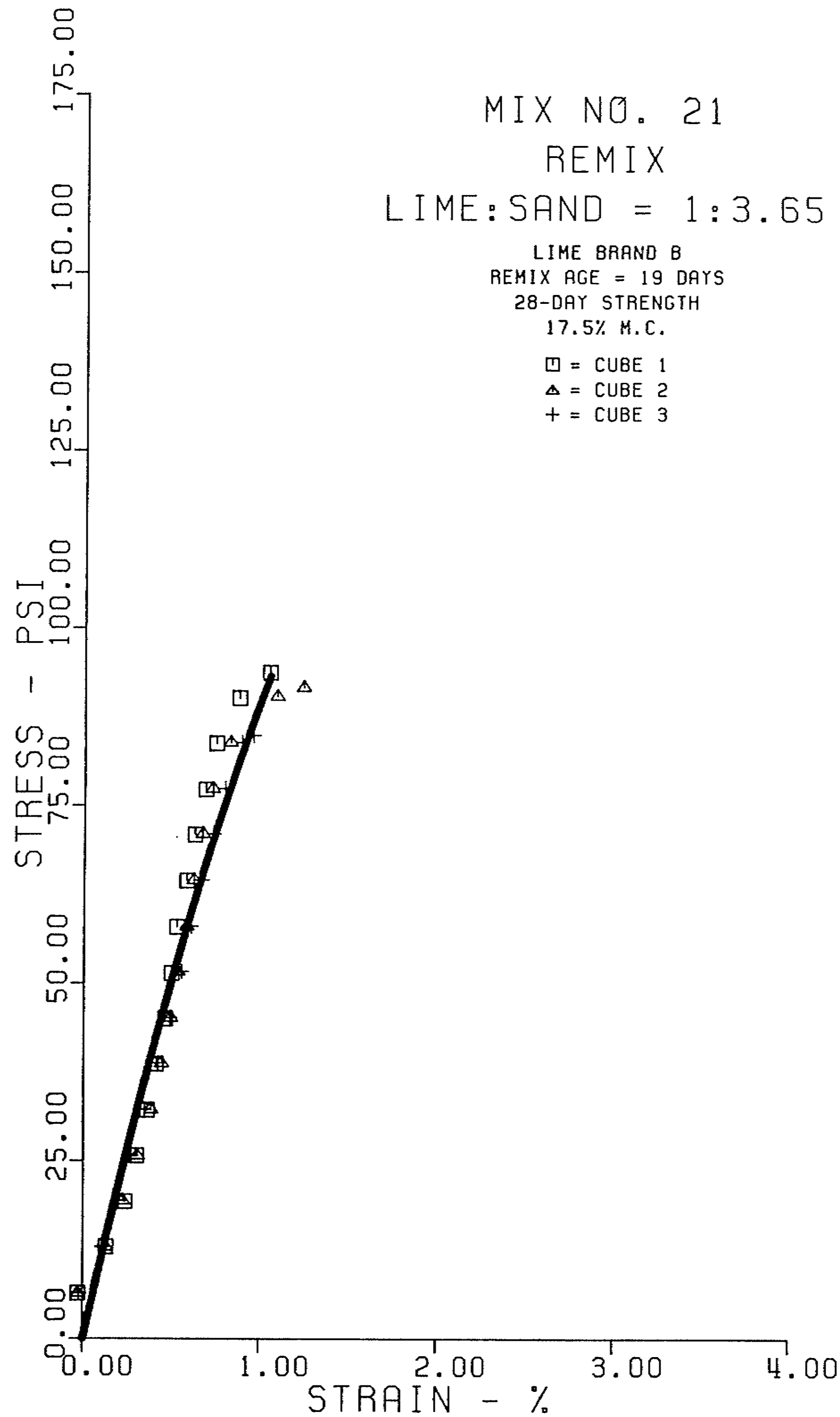


Figure 62: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 21

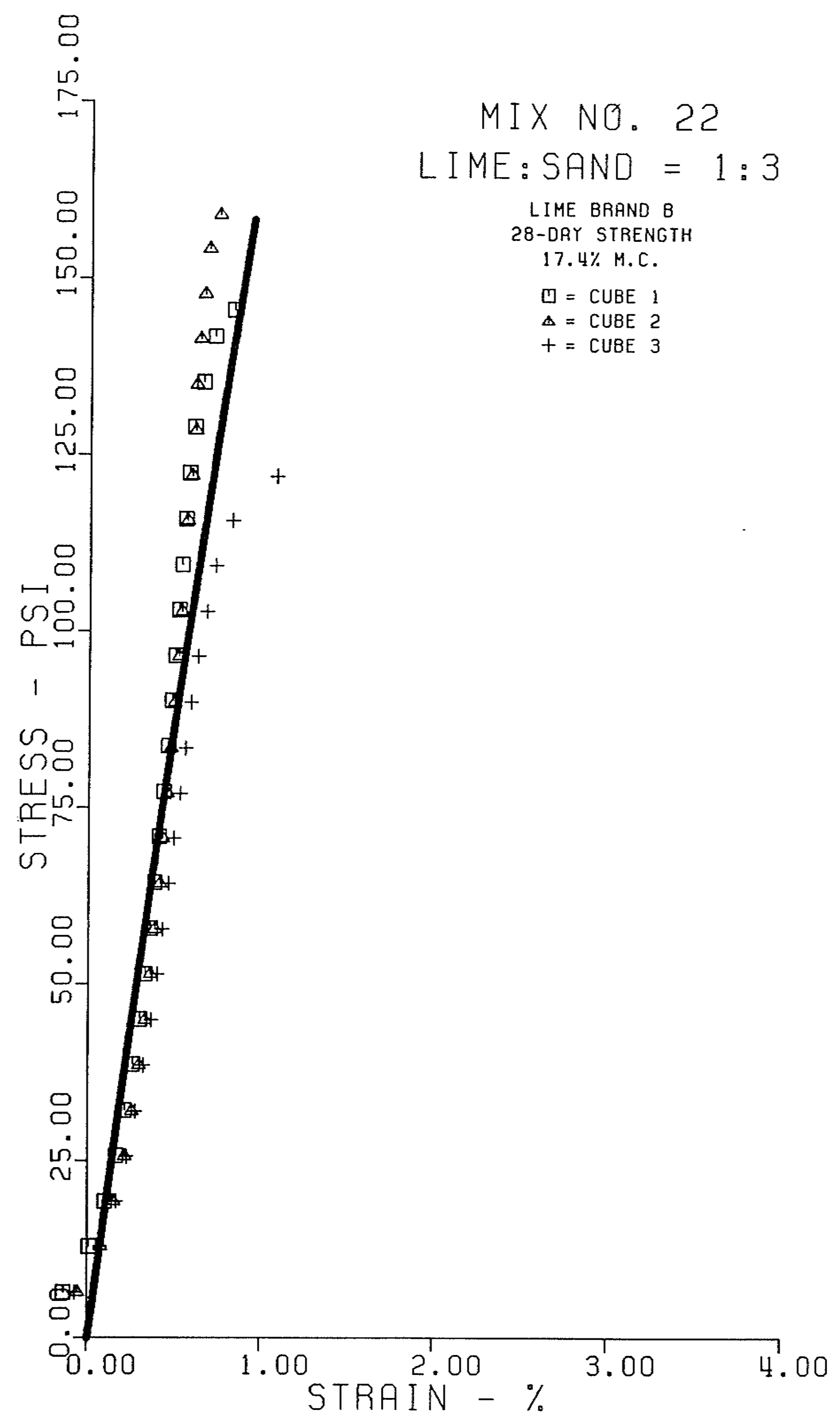


Figure 63: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 22

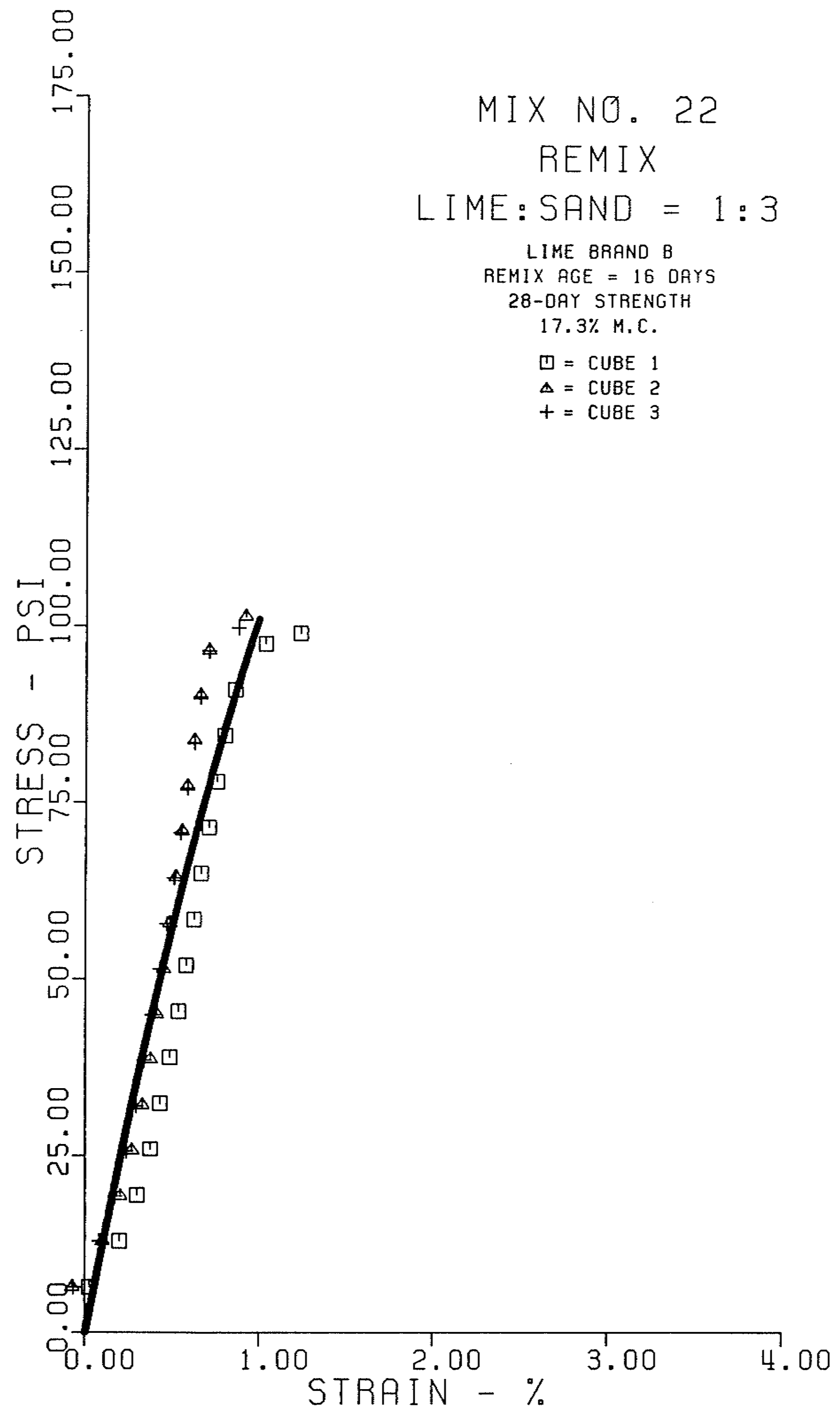


Figure 64: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 22

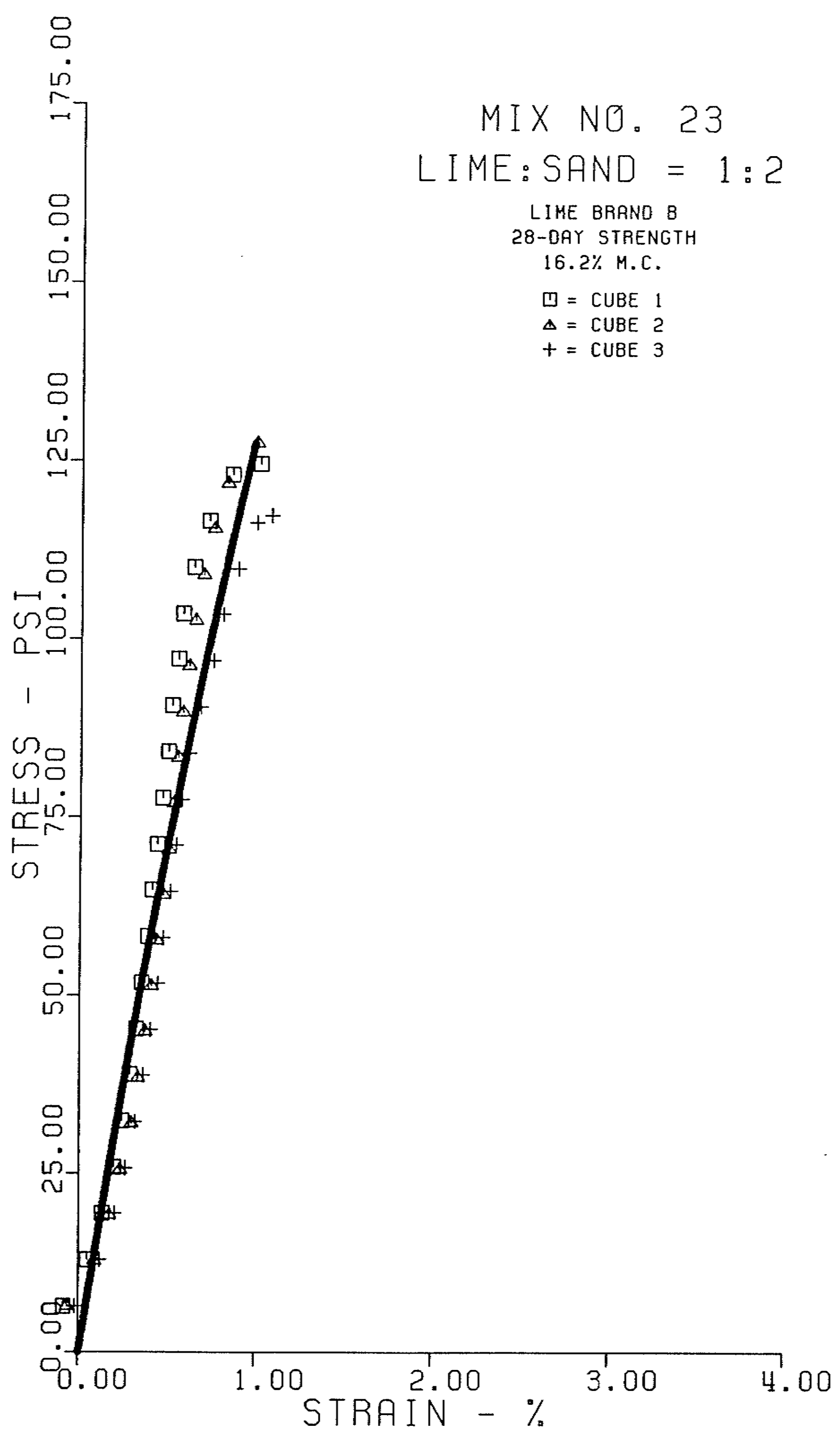


Figure 65: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Mix No. 23

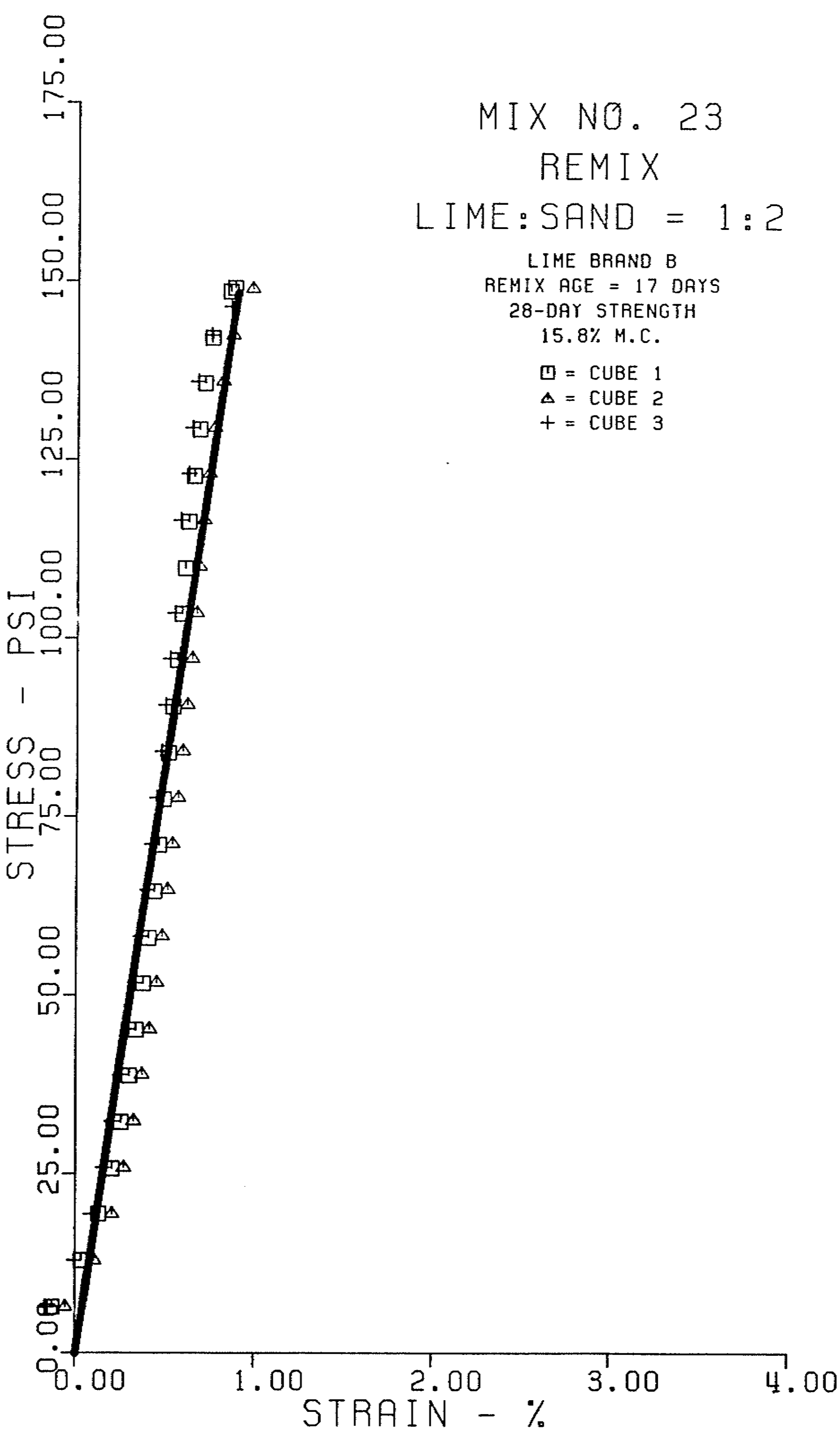


Figure 66: Computer Plot Showing the 28-Day Compressive Strength and Failure Characteristics of Lime-Sand Mortar Remix No. 23

described by the curves given in Figures 33 to 66. From these figures, different combinations of the curves were put together for four different studies: 1) lime-sand ratio studies, 2) remix strength studies, 3) seven- and 28-day strength studies, and 4) lime brand studies.

The purpose of the above respective studies was to get an indication of how, or if, the compressive strength and failure characteristics changed: 1) with the change in the lime-sand ratio, 2) with mixes that have hardened, been crushed and remixed, 3) with time, and 4) between two different lime brands for the lime-sand ratios tested at the age of seven and 28 days.

The above studies were plotted out through the use of a computer plotting program. A copy of this program is listed in Appendix G as Computer Program No. 8. This program is similar to Computer Program No. 5 of Appendix G with exception that it was modified for use with the lime-sand mortar mixes. Modifications were required primarily due to the different plotting scales. The computer plots giving the lime-sand ratio studies are shown in Figures 67 to 70, while the remix strength studies are given in Figures 71 to 80. Plots showing the remaining two studies are given in Appendix J, Figures J-1 to J-31, pages 471 to 501.

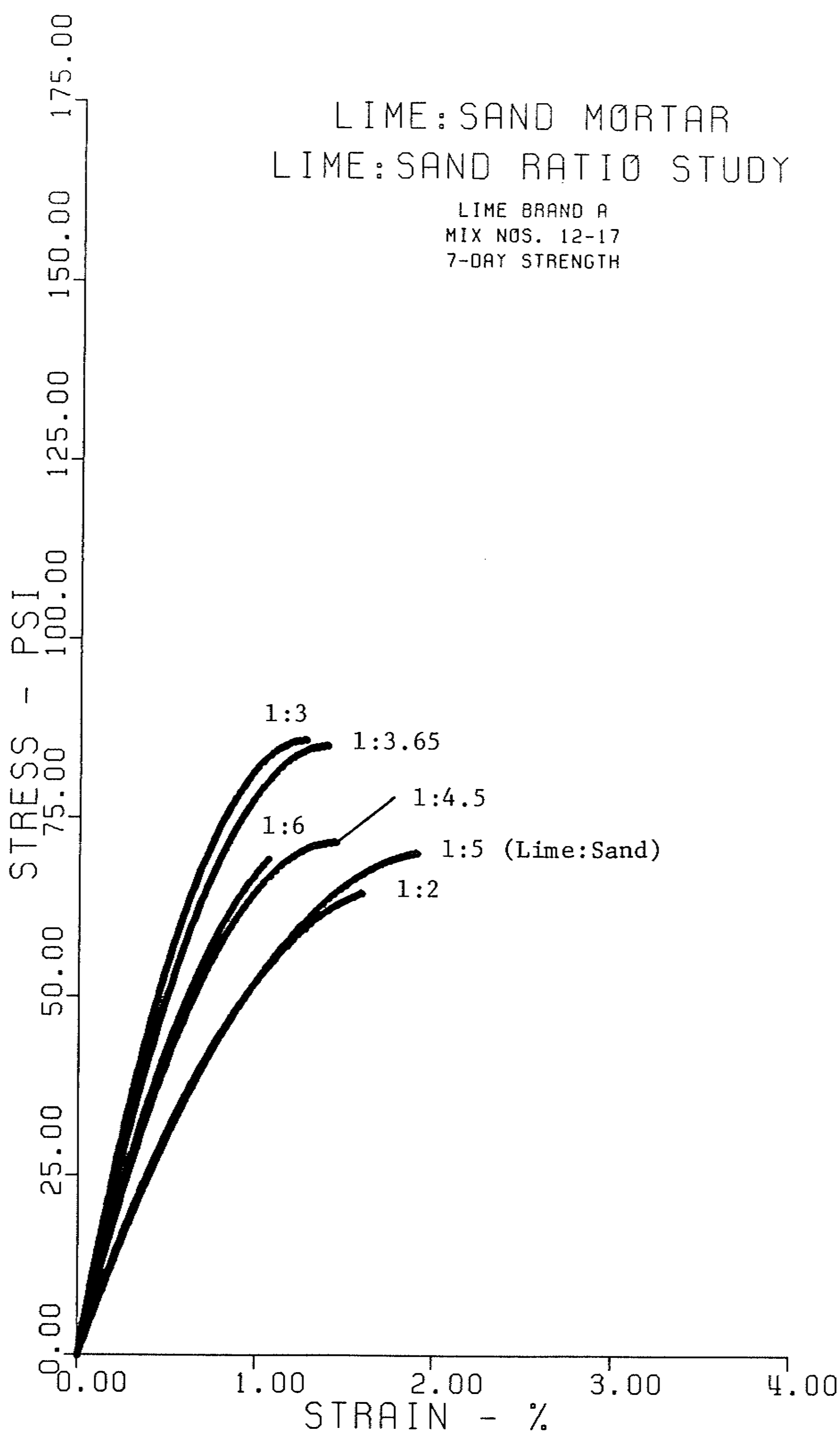


Figure 67: Lime-Sand Ratio Study Plot for Lime-Sand Mortar Mixes Containing Lime Brand A at the Seven-Day Compressive Strength

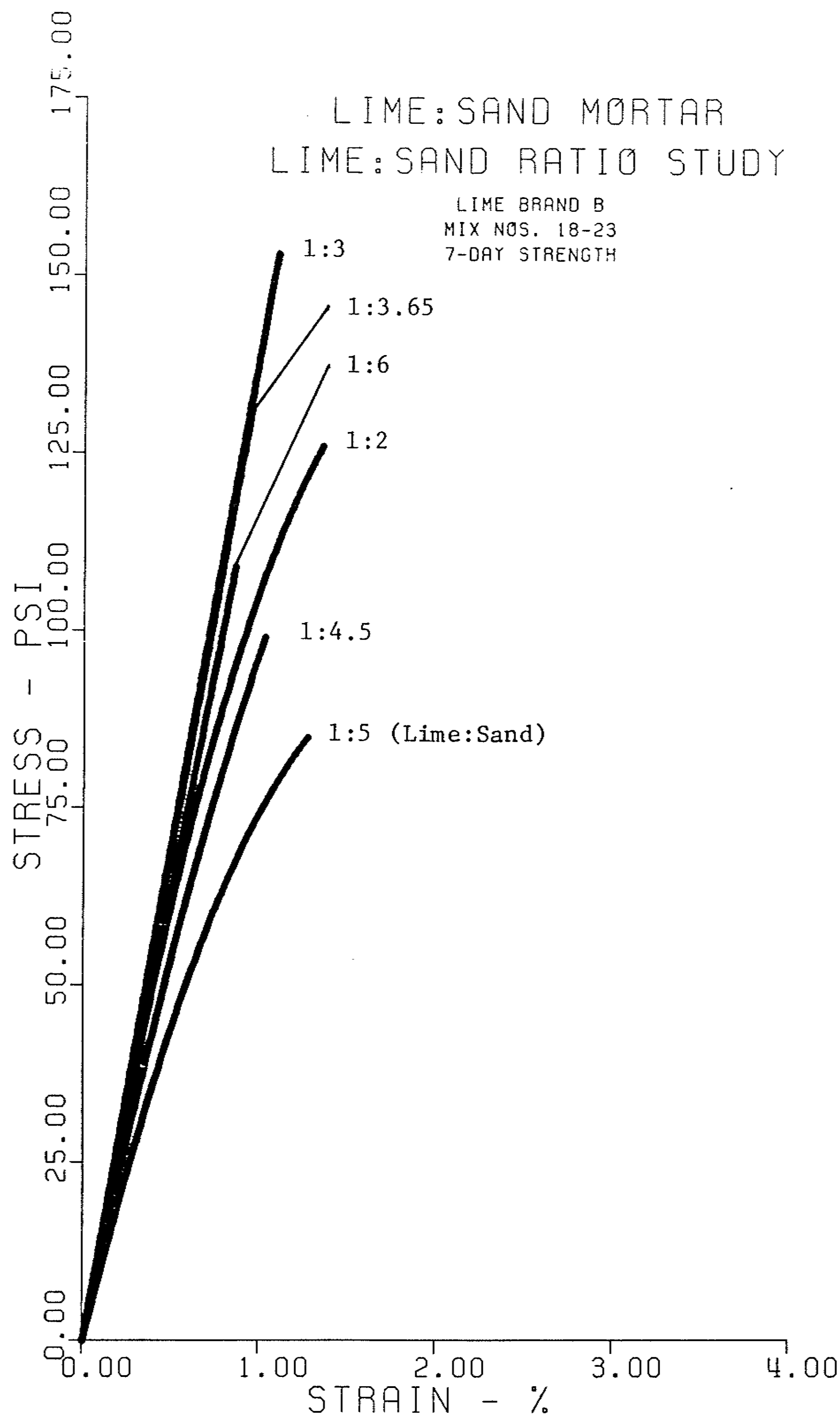


Figure 68: Lime-Sand Ratio Study Plot for Lime-Sand Mortar Mixes Containing Lime Brand B at the Seven-Day Compressive Strength

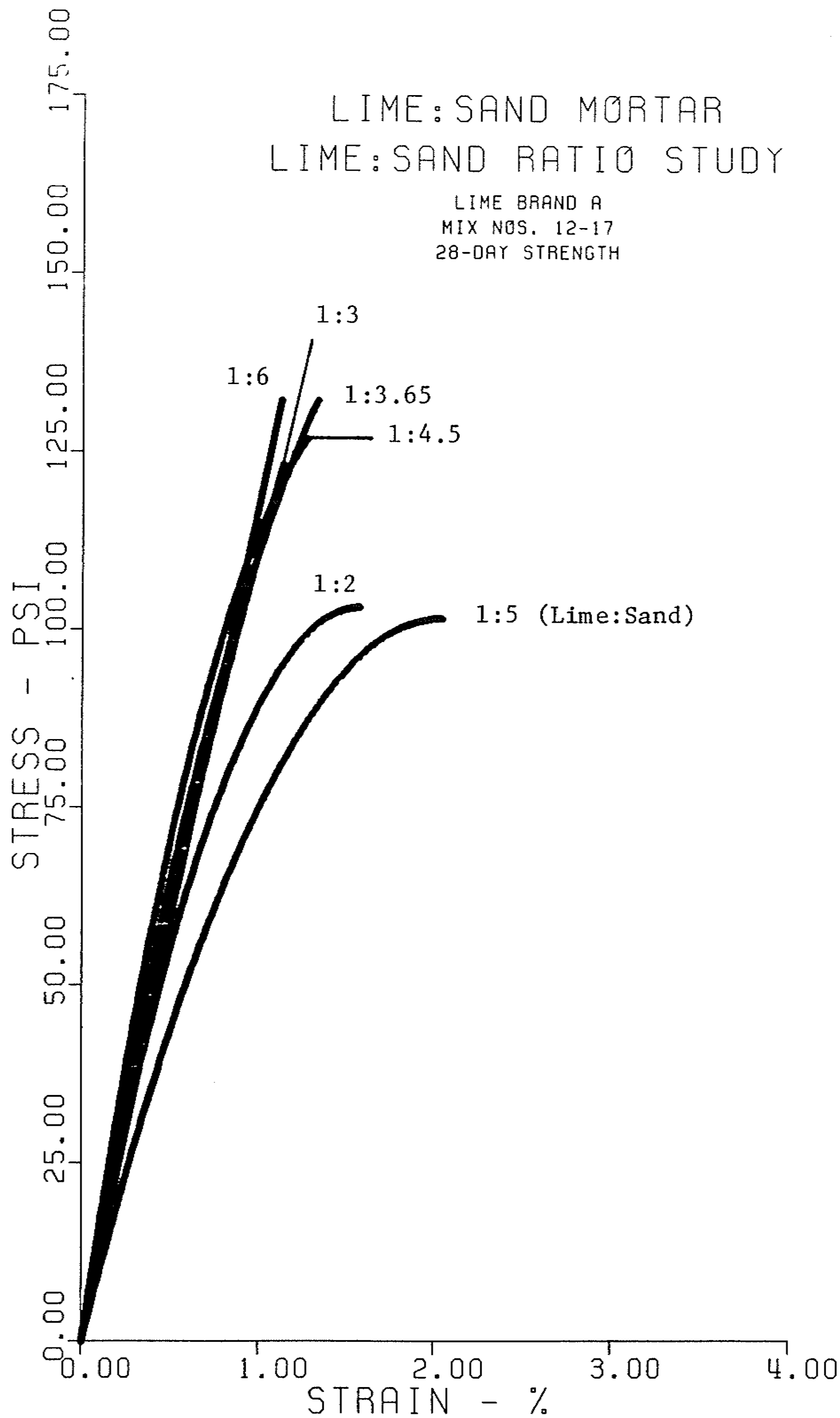


Figure 69: Lime-Sand Ratio Study Plot for Lime-Sand Mortar Mixes Containing Lime Brand A at the 28-Day Compressive Strength

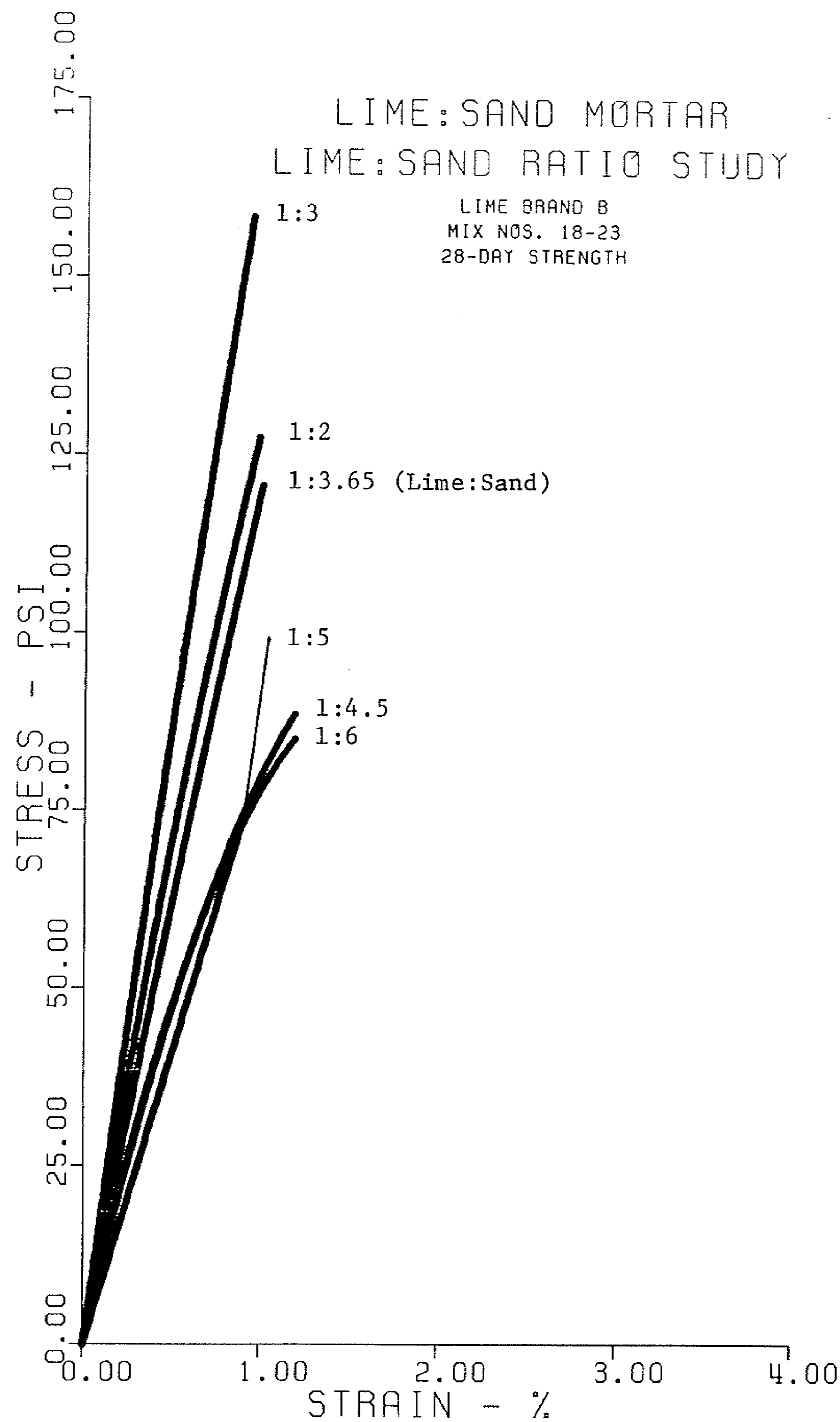


Figure 70: Lime-Sand Ratio Study Plot for Lime-Sand Mortar Mixes Containing Lime Brand B at the 28-Day Compressive Strength

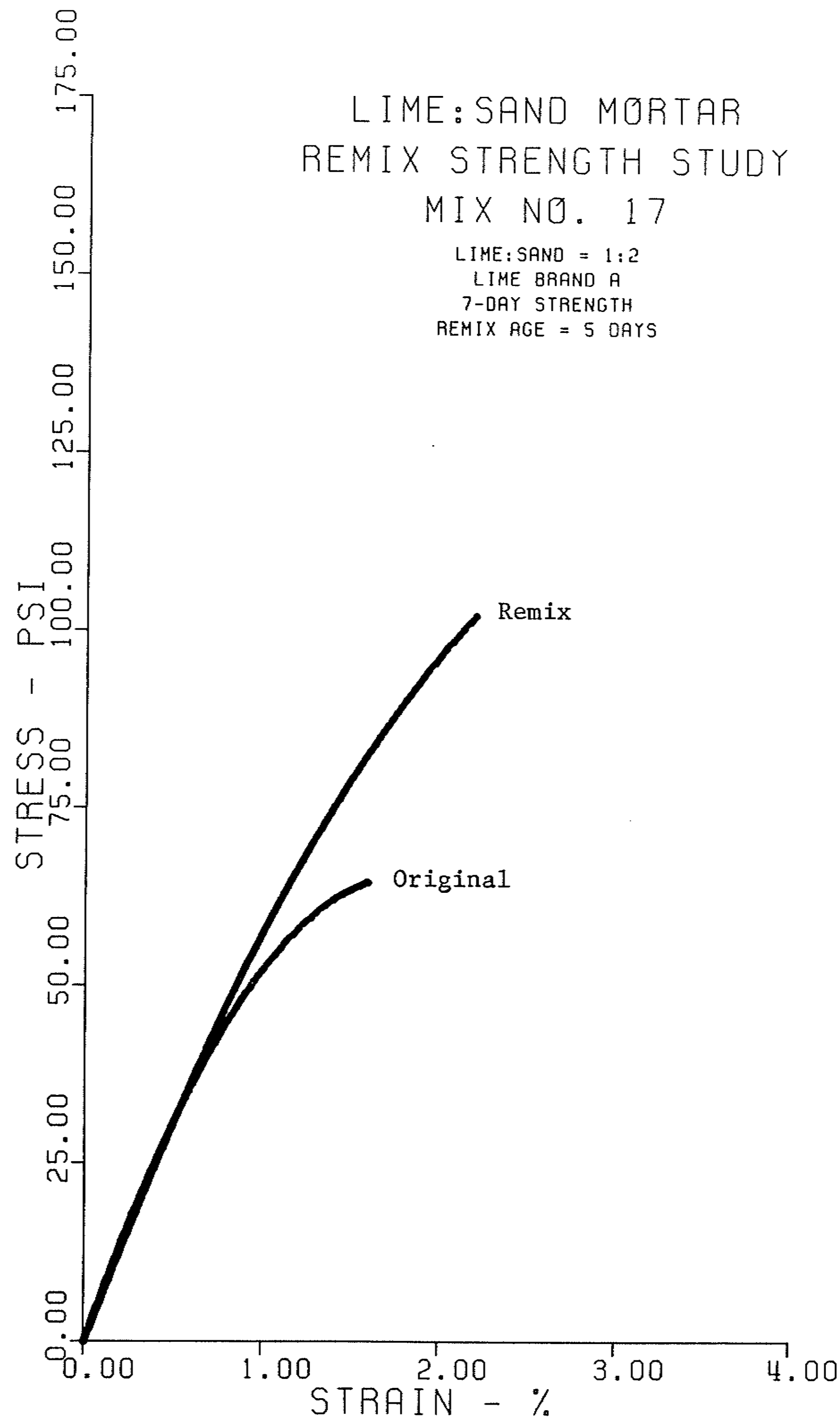


Figure 71: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 17 at the Compressive Strength of Seven Days

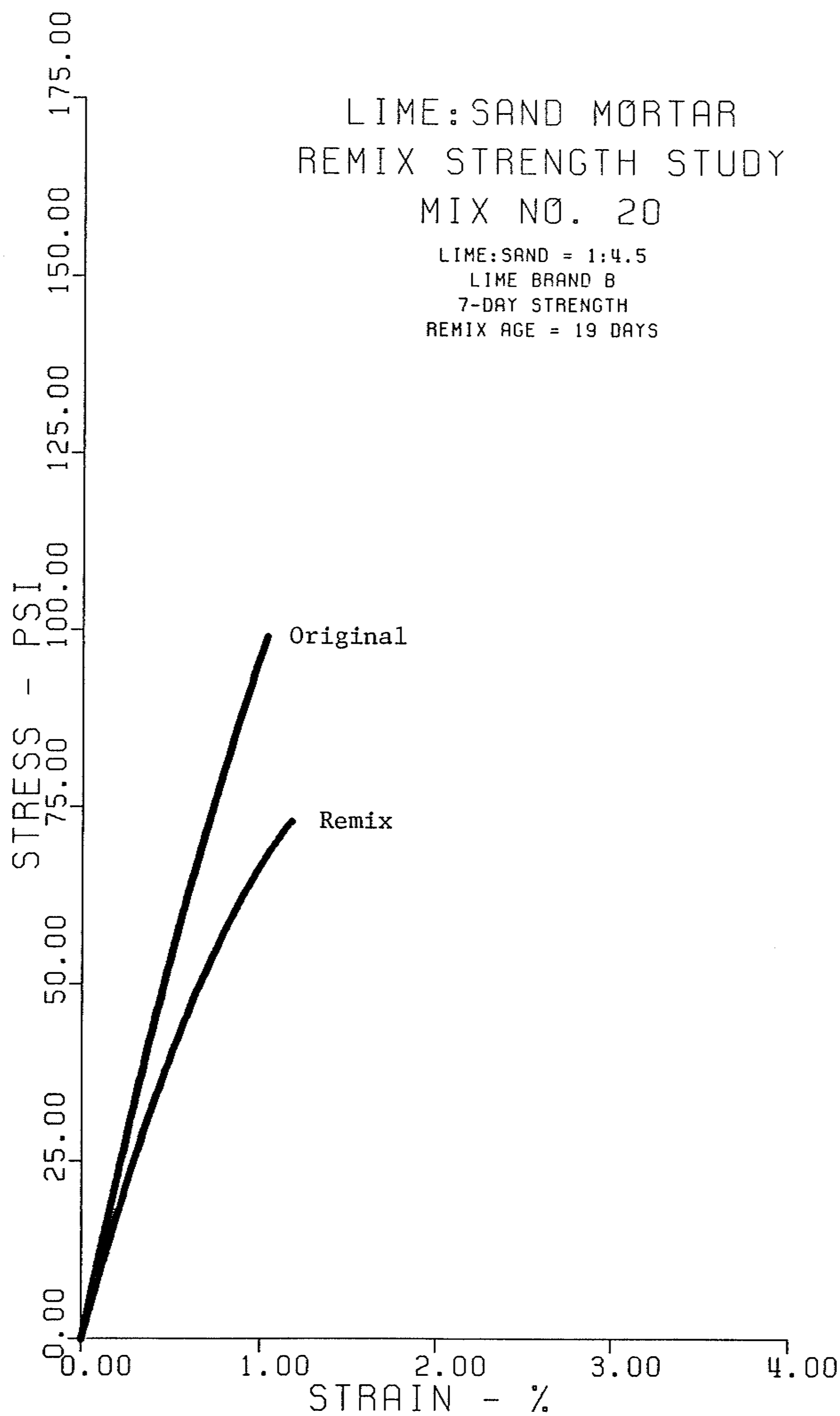


Figure 72: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 20 at the Compressive Strength of Seven Days

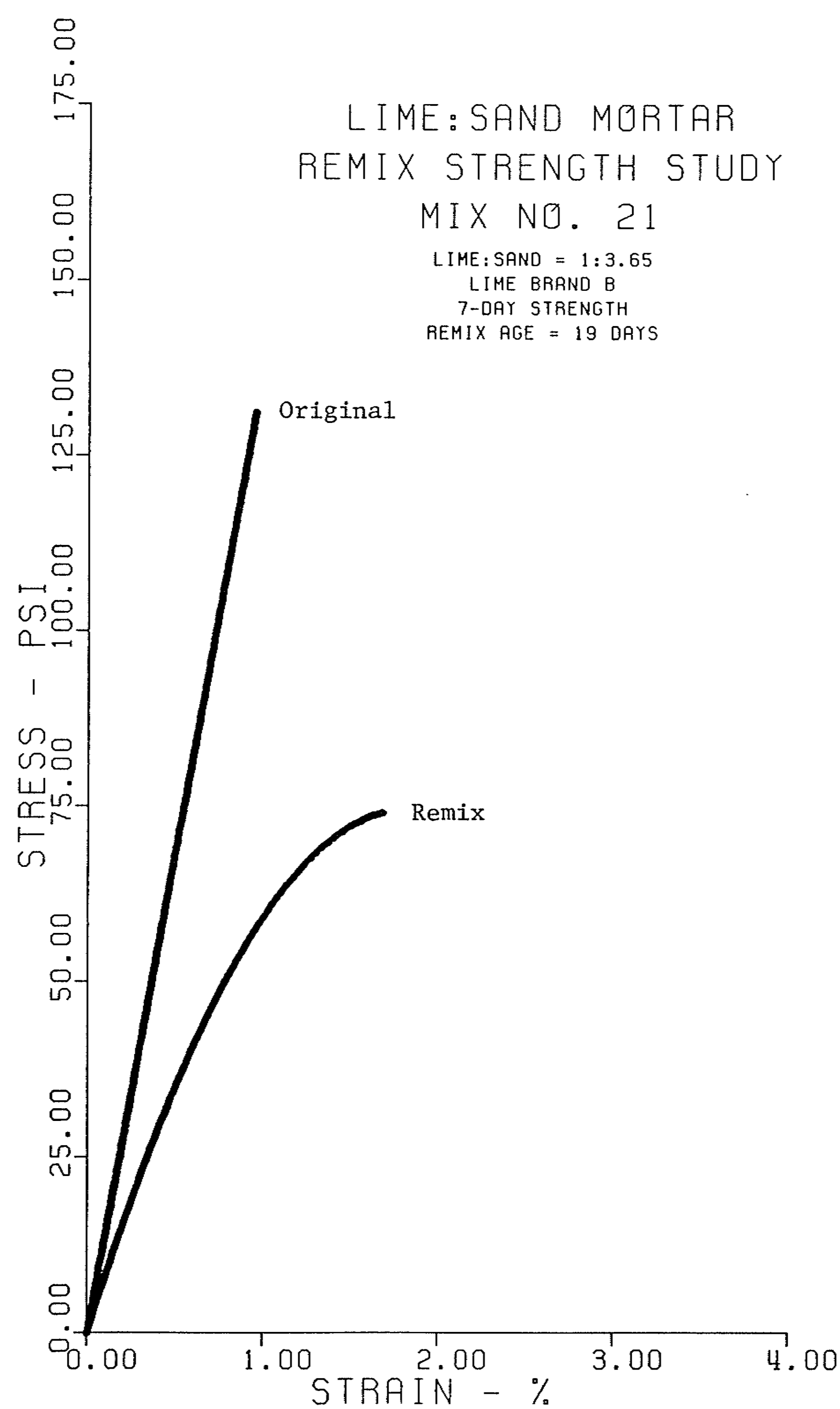


Figure 73: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 21 at the Compressive Strength of Seven Days

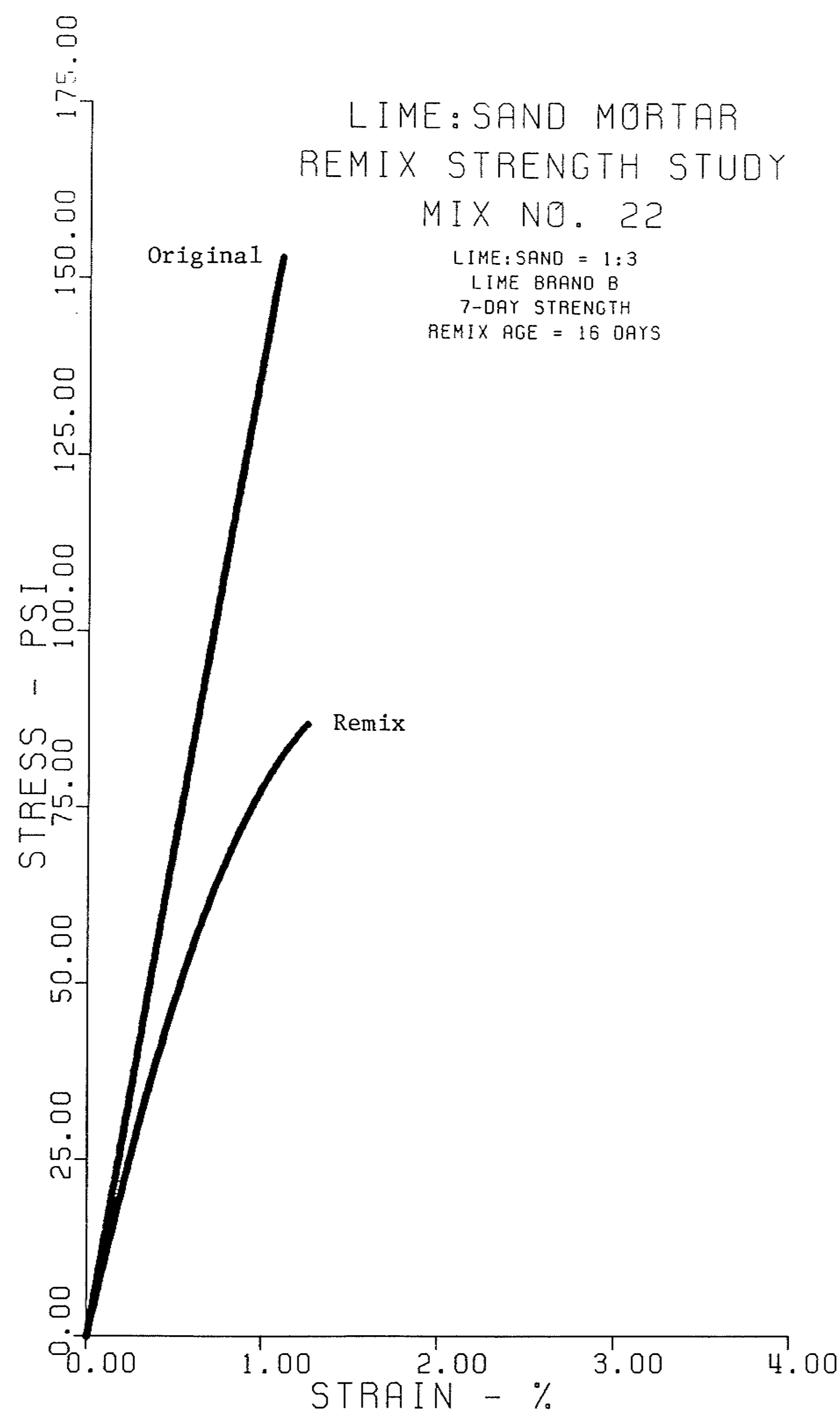


Figure 74: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 22 at the Compressive Strength of Seven Days

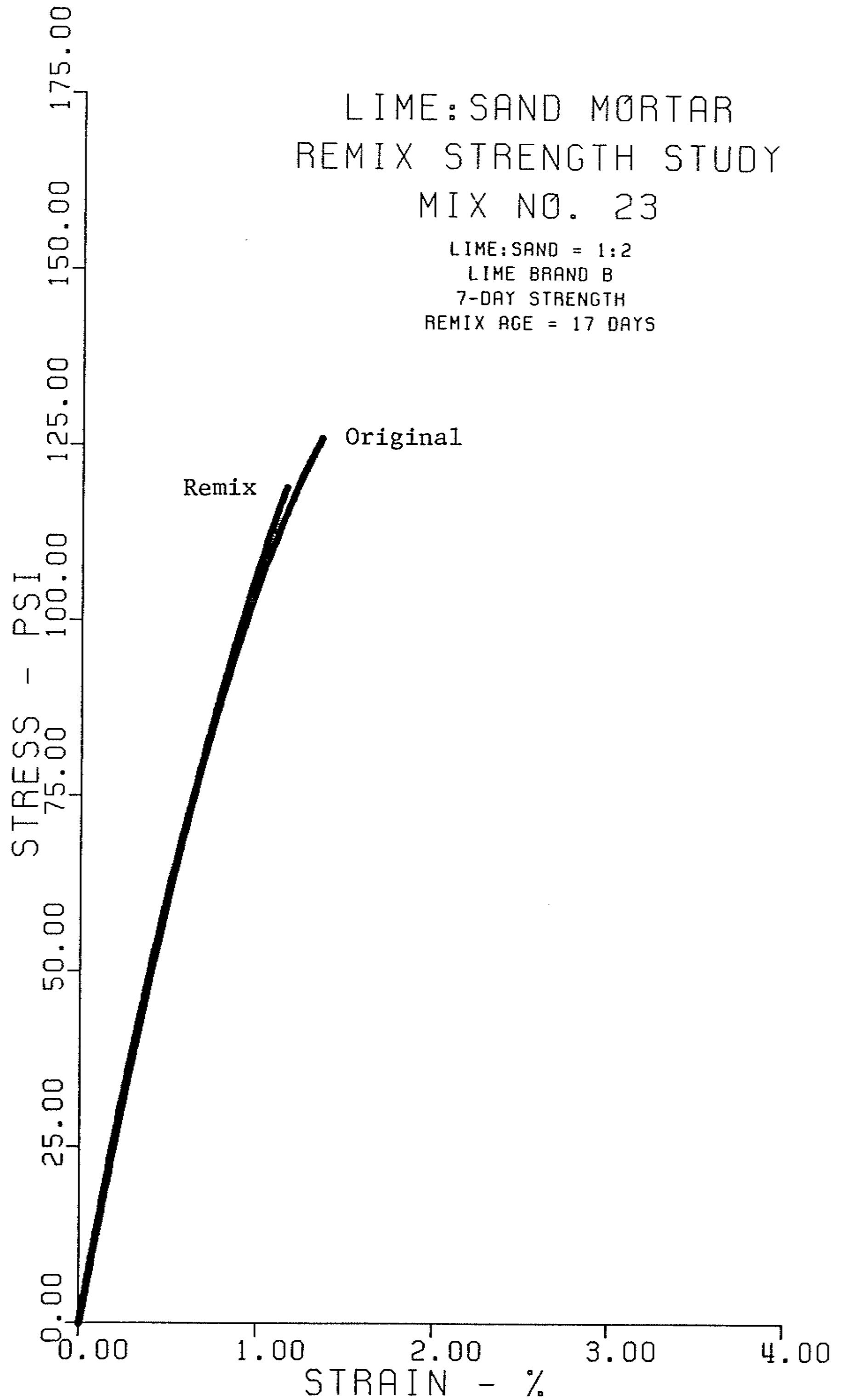


Figure 75: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 23 at the Compressive Strength of Seven Days

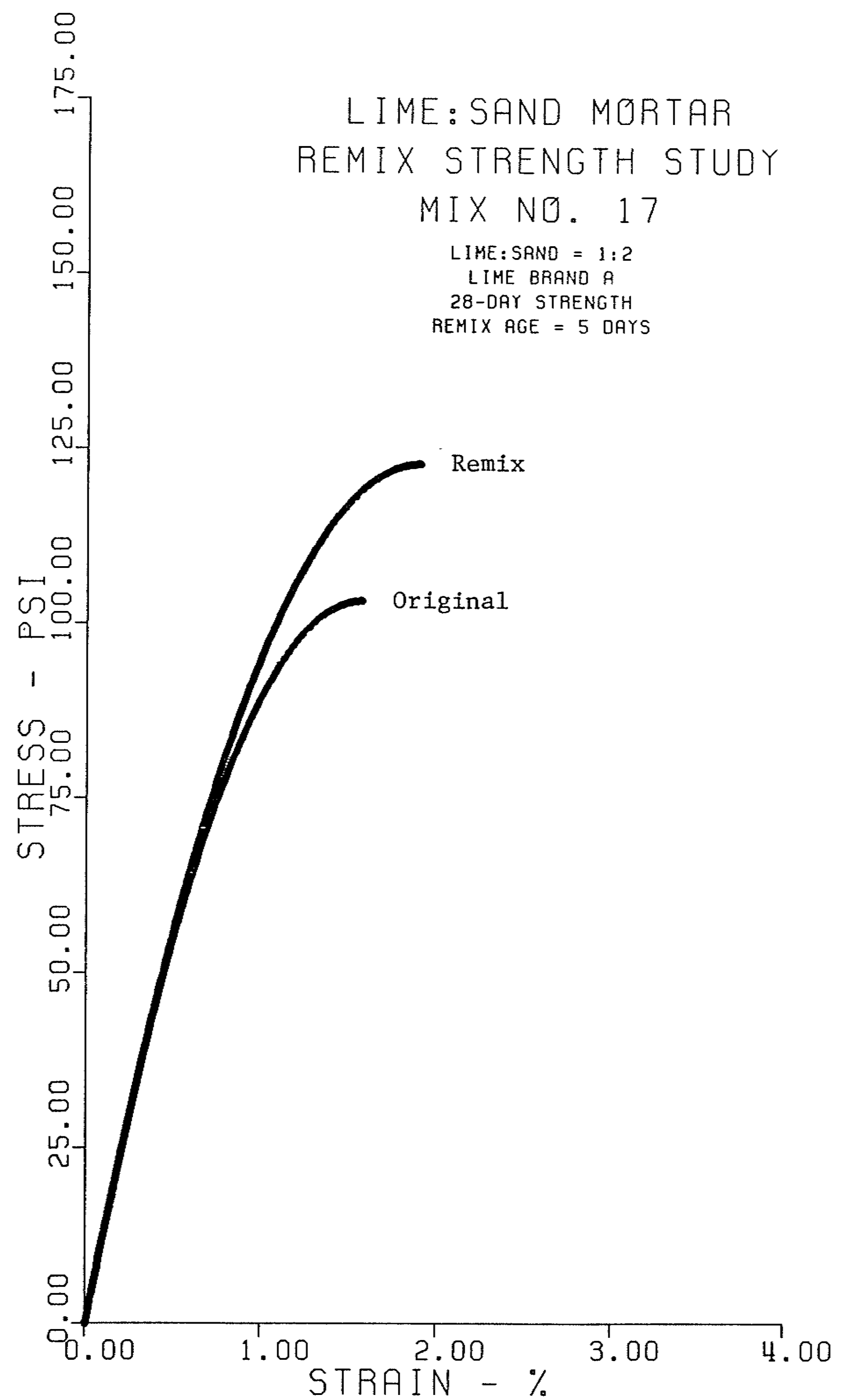


Figure 76: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 17 at the Compressive Strength of 28 Days

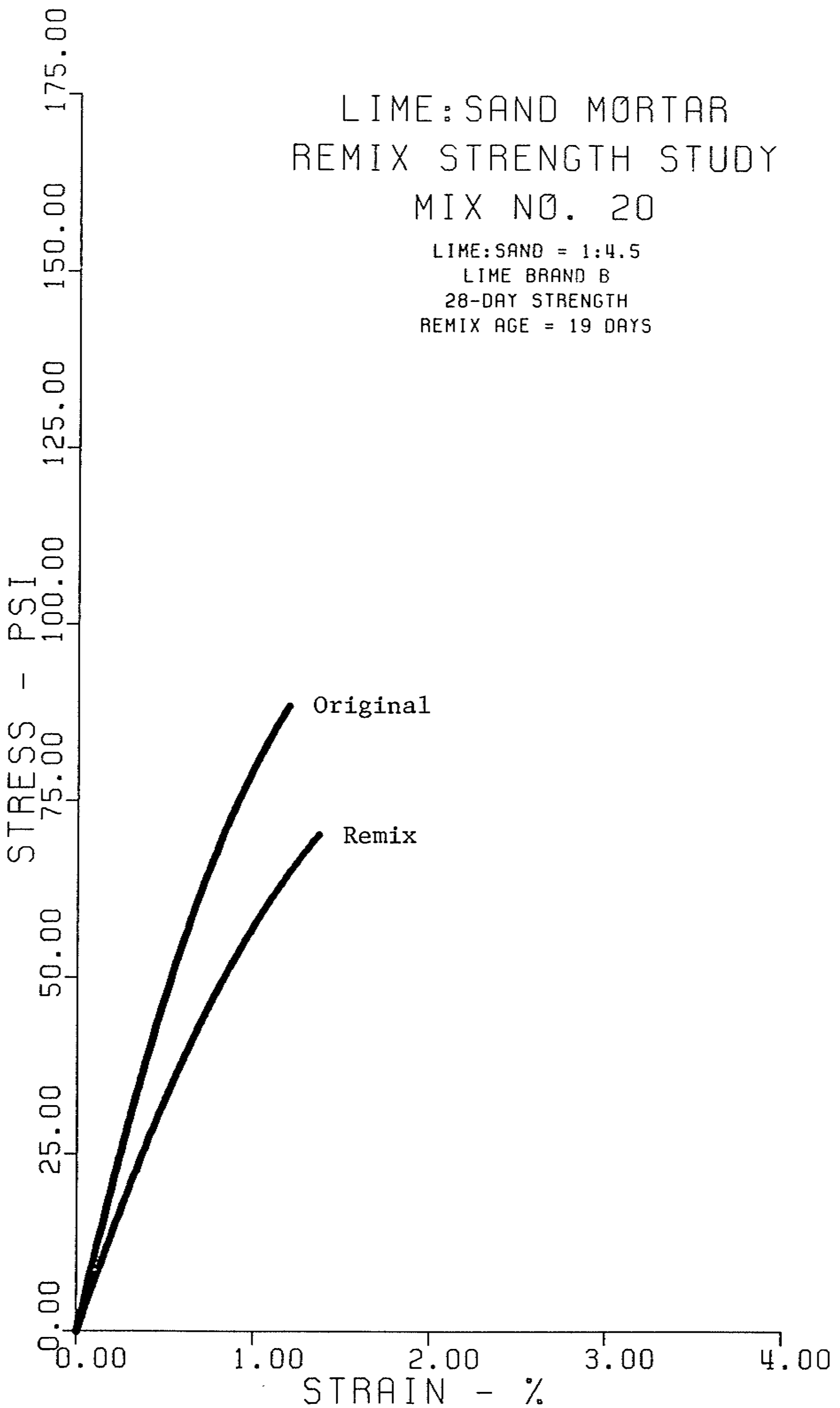


Figure 77: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 20 at the Compressive Strength of 28 Days

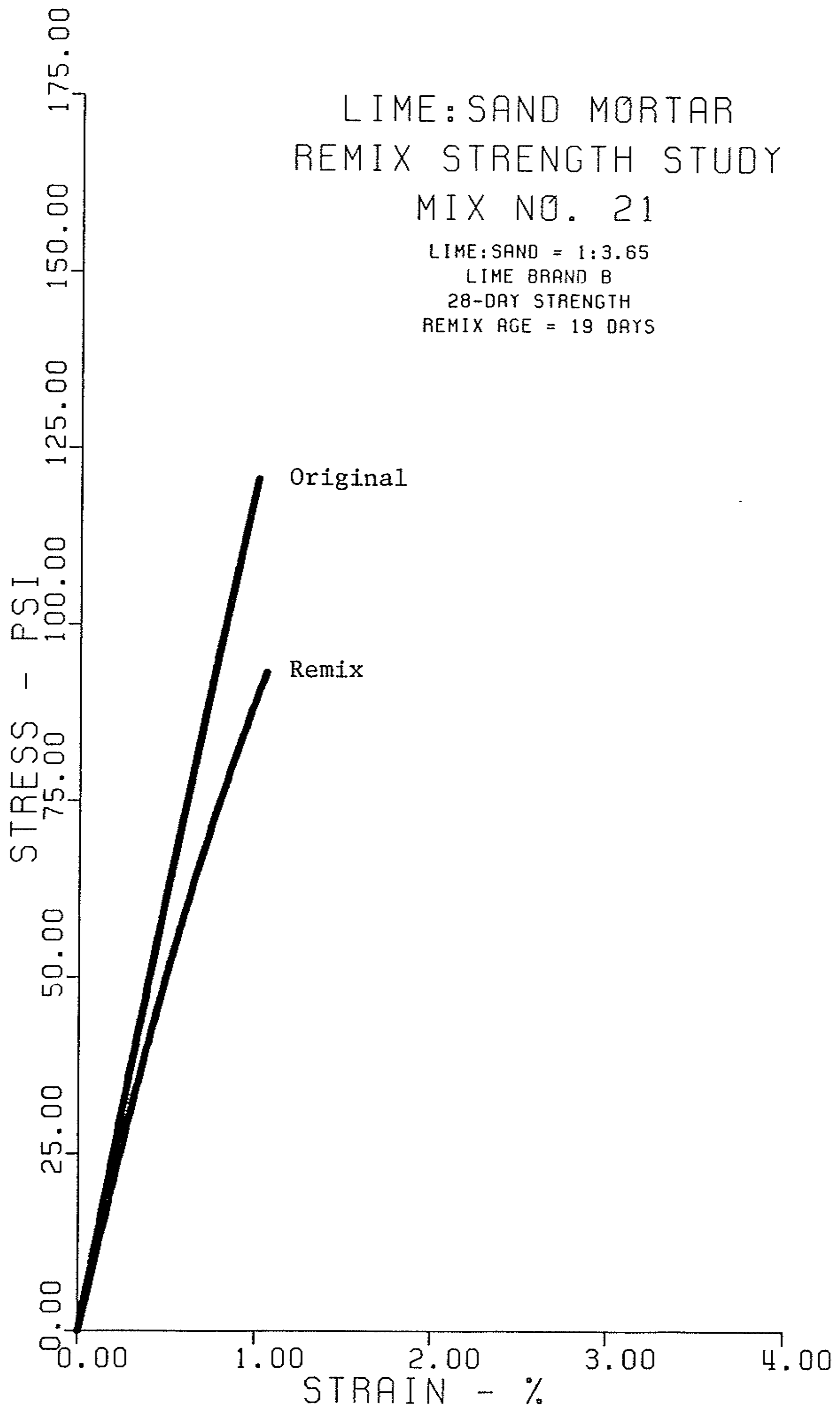


Figure 78: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 21 at the Compressive Strength of 28 Days

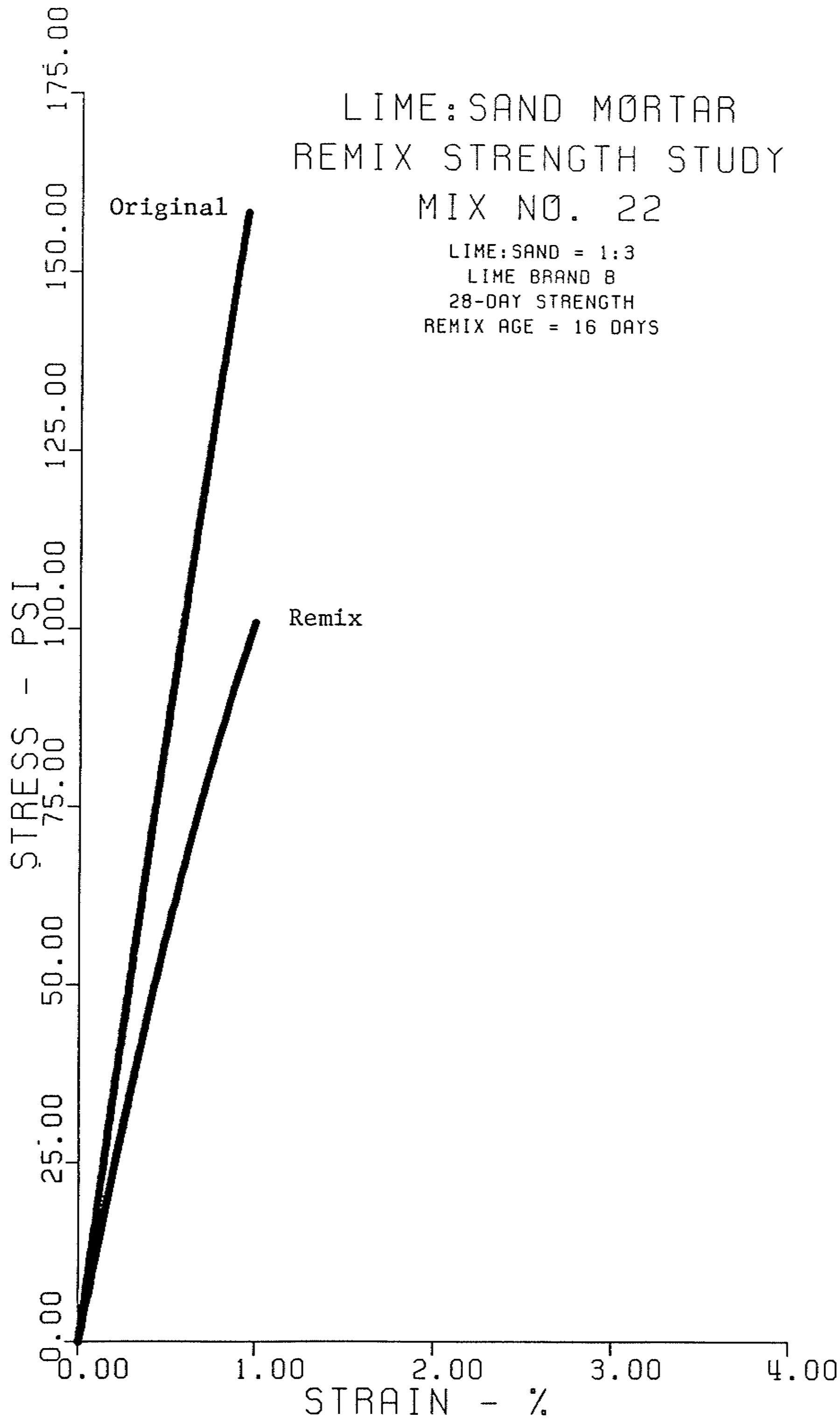


Figure 79: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 22 at the Compressive Strength of 28 Days

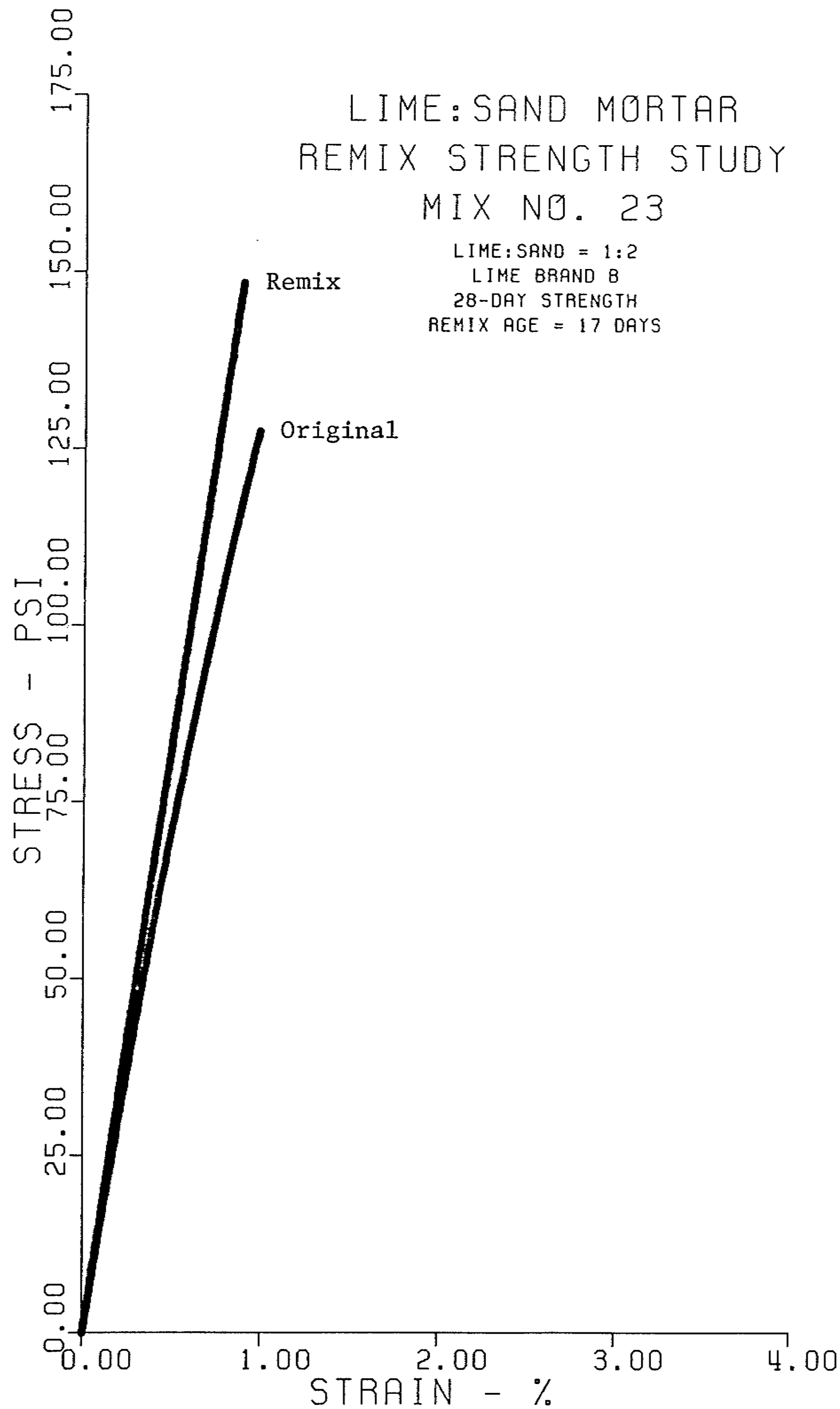


Figure 80: Remix Strength Study Plot for Lime-Sand Mortar Mix No. 23 at the Compressive Strength of 28 Days

4.2.4 Material Compressive Properties

From the representative computer plots of Figures 33 to 66, pages 163 to 196, material compressive properties of the lime-sand mortar mixes were acquired. Properties tabulated were the maximum strain and stress, the moduli of elasticity, modulus of elastic resilience and the moduli of toughness.

4.2.4.1 Maximum Strain and Stress

Table XXIV lists the maximum compressive strain and stress values of each lime-sand mortar mix as defined by the best-fit curves in Figures 33 to 66, pages 163 to 196.

To get an indication of how the maximum stress/mortar strength values changed with the lime-sand ratio, computer plots showing this change were developed. For the original mixes, one plot was made for lime Brand A and another one for lime Brand B. A third plot was made for the remix mixes of lime Brand B. Each of these plots included the seven- and the 28-day strengths. These plots are shown in Figures 81 to 83. An example run of the computer program used to plot out these figures is given in Appendix G, listed as Computer Program No. 9.

Table XXIV

Maximum Compressive Strain and Stress of Lime-Sand Mortar Mixes[1]

Lime Brand	Mix No.	Age (days)	Maximum Compressive Strain (%)	Maximum Compressive Stress (psi.)
A	12	7	1.06	69
		28	1.12	132
	13	9	1.90	70
		28	2.04	102
	14	8	1.44	72
		28	1.27	127
	15	9	1.39	85
		28	1.33	132
	16	8	1.27	86
		28	1.13	123
	17	8	1.59	65
		28	1.57	103
	17-R	7	2.20	102
		28	1.90	123

Table XXIV

(Continued)

Lime Brand	Mix No.	Age (days)	Maximum Compressive Strain (%)	Maximum Compressive Stress (psi.)
	18	7	0.86	109
		28	1.19	85
	19	7	1.27	85
		28	0.93	77
	20	7	1.03	99
		28	1.19	89
	20-R	8	1.17	73
		28	1.36	70
	21	7	0.95	131
		28	1.00	121
B	21-R	8	1.68	74
		28	1.05	93
	22	7	1.10	153
		28	0.94	158
	22-R	7	1.25	87
		28	0.99	101
	23	7	1.35	126
		28	0.98	127
	23-R	7	1.15	119
		27	0.89	148

Note: R indicates remix.

[1] In the compression tests as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

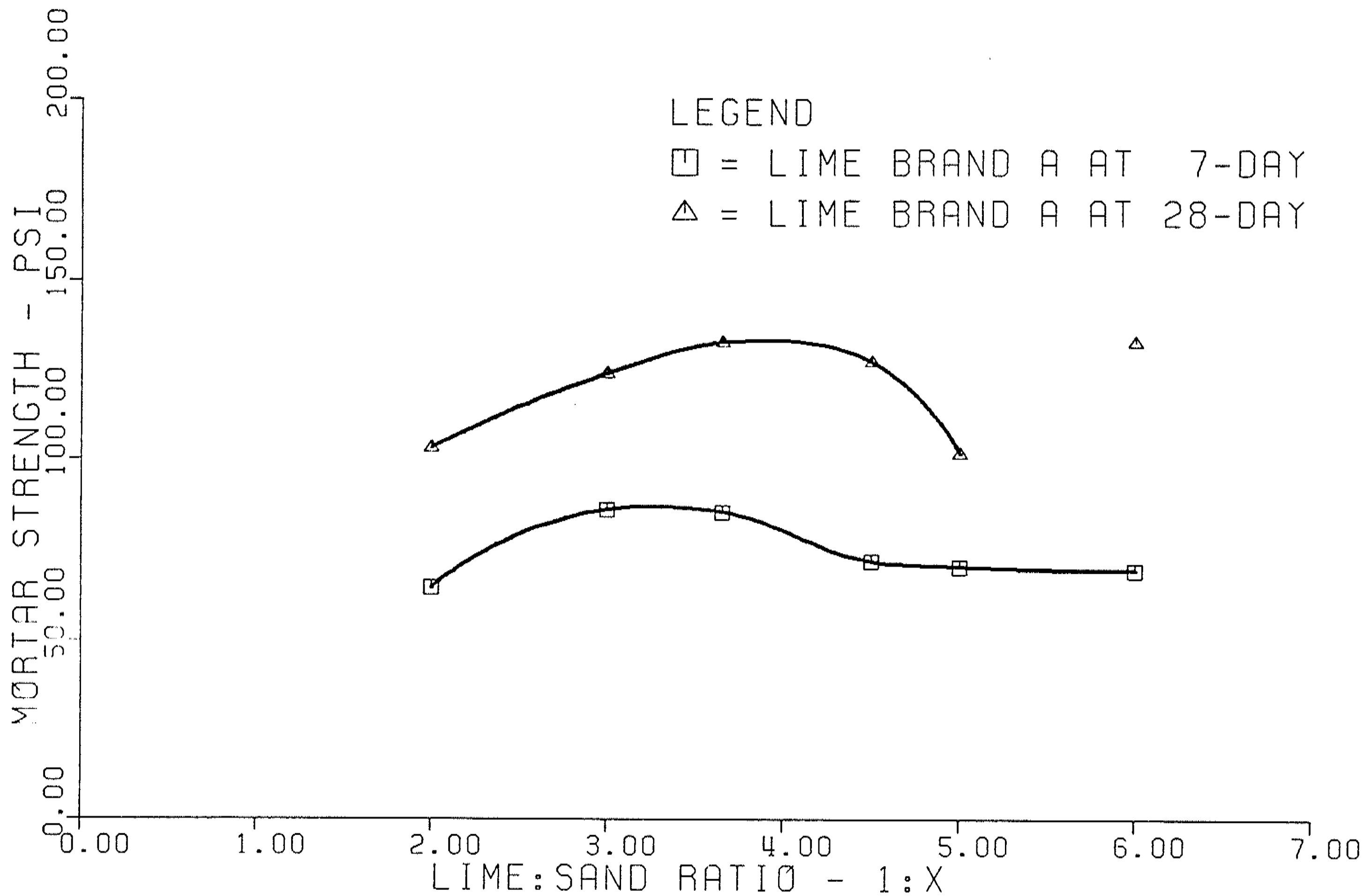


Figure 81: Mortar Compressive Strength Change with the Lime-Sand Ratio for Lime-Sand Mortar Mixes Containing Lime Brand A

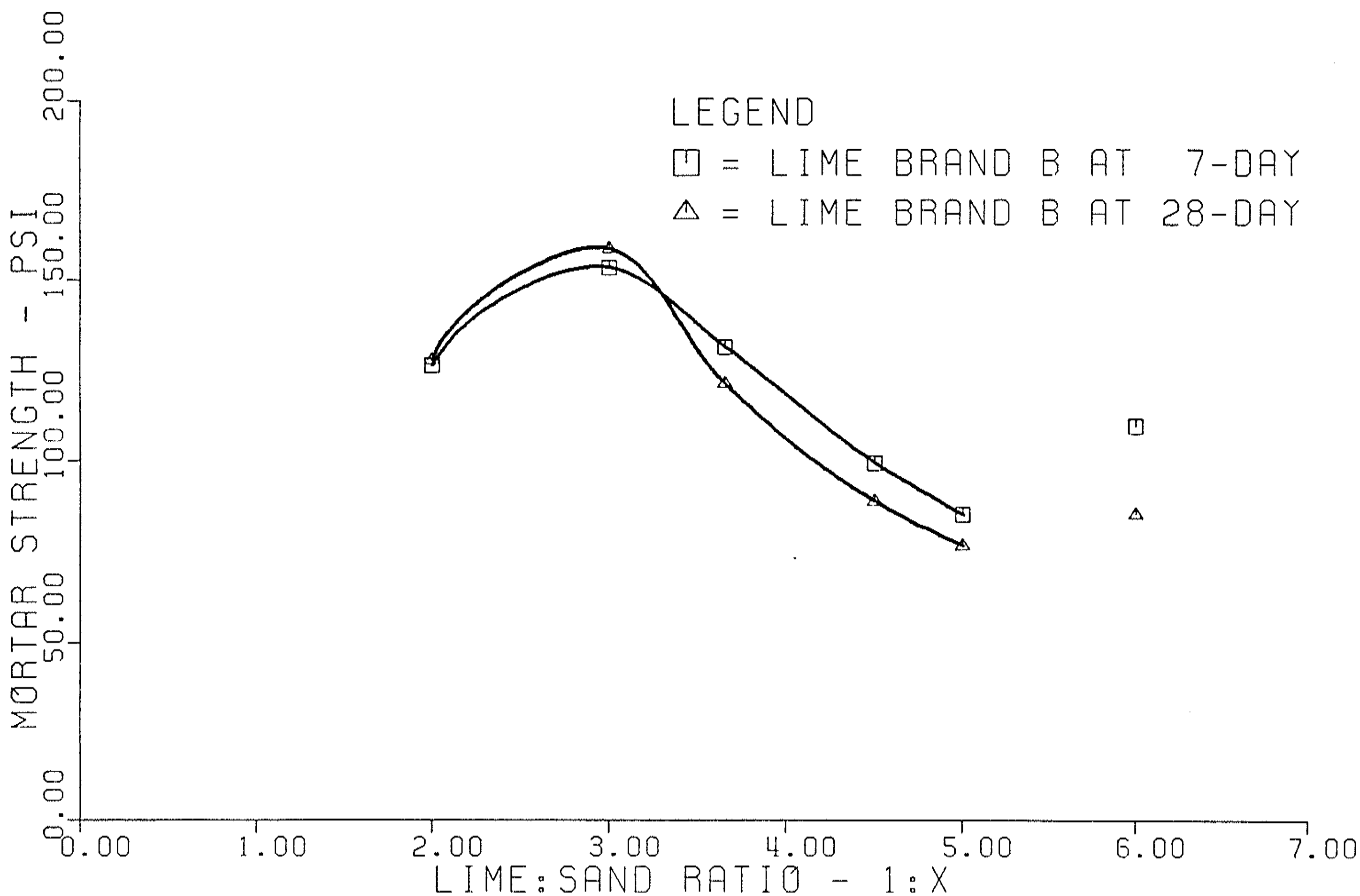


Figure 82: Mortar Compressive Strength Change with the Lime-Sand Ratio for Lime-Sand Mortar Mixes Containing Lime Brand B

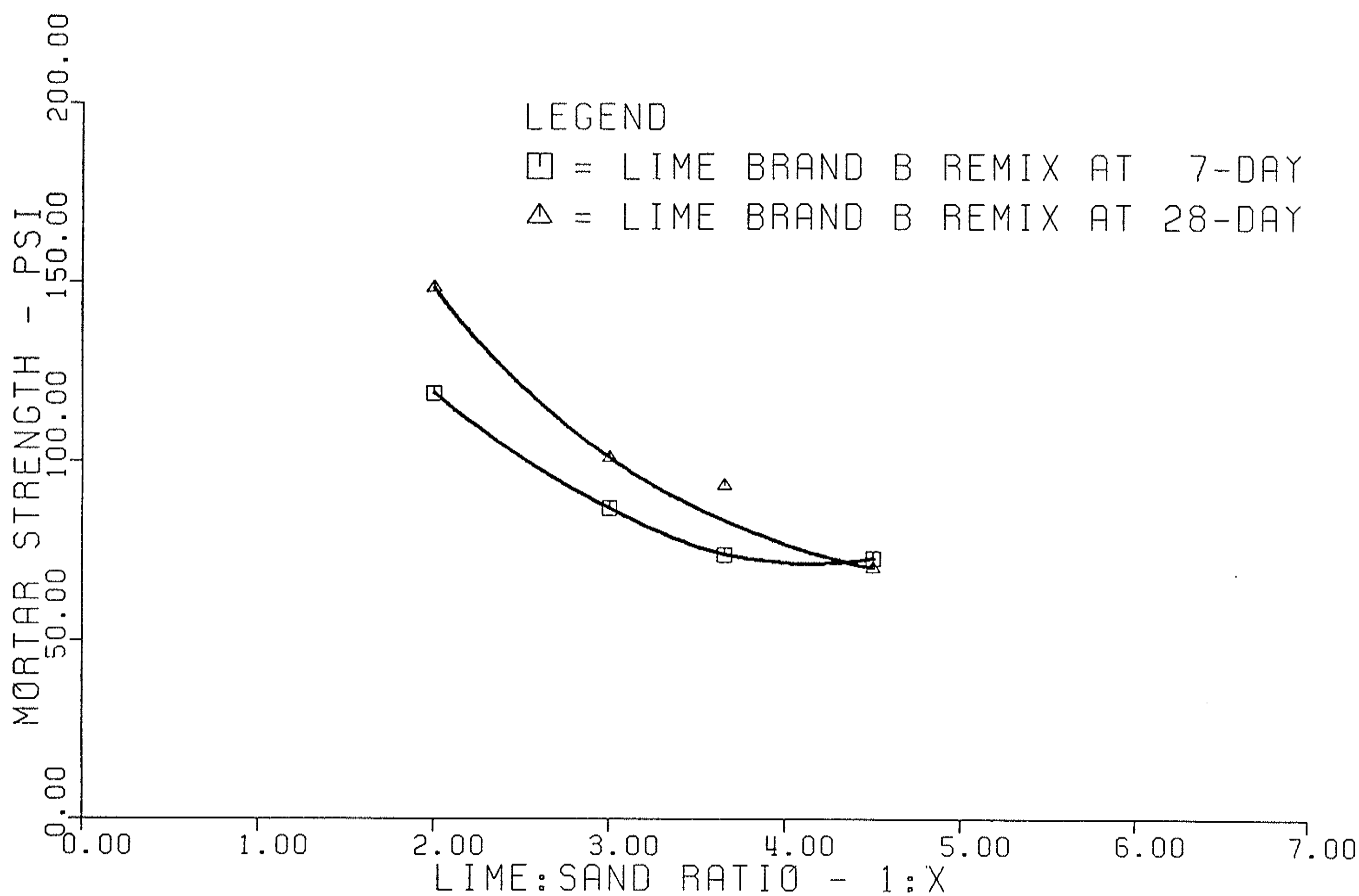


Figure 83: Mortar Compressive Strength Change with the Lime-Sand Ratio for Lime-Sand Mortar Remix Mixes Containing Lime Brand B

4.2.4.2 Moduli of Elasticity

For each lime-sand mortar mix, the initial tangent modulus of elasticity (E_o) and the secant modulus of elasticity (E_m) were calculated. These calculations were performed using the computer printout of the best-fit curve plotting data points representing the curves of Figures 33 to 66, pages 163 to 196. The definitions of E_o and E_m are the same as that for the clay mortar mixes (page 130). Resultant values of E_o and E_m for the lime-sand mortar mixes are in Table XXV.

4.2.4.3 Modulus of Elastic Resilience

The modulus of elastic resilience for the lime-sand mortar mixes was calculated using the same procedure as that described for the clay mortar mixes (pages 132 to 135). Both continuously curved and totally linear stress-strain curves existed for the lime-sand mortar mixes. Using the procedure mentioned above, the whole area under the totally linear stress-strain curve represents elastic resilience. Checking with Table XXIII, pages 161 to 162, Mix Nos. 18 and 21 in the seven-day test and Mix Nos. 12, 19 and 23-R in the 28-day test had stress-strain curves that are totally linear. Table XXVI list the modulus of elastic resilience values for each lime-sand mortar mix, as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

4.2.4.4 Moduli of Toughness

As with the clay mortar mixes, two measures of toughness were calculated for each lime-sand mortar mix, the modulus of toughness (T) and the modified modulus of toughness (T'). The definitions of these two moduli were discussed with the clay mortar mixes (pages 135 to 138). Table XXVII list the T and T' values for each lime-sand mortar mix, as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

Table XXV

Moduli of Elasticity for Lime-Sand Mortar Mixes[1]

Lime Brand	Mix No.	Age (days)	Modulus of Elasticity -- (psi.) Initial Tangent E_o	Secant[2] E_m
A	12	7	11,000	8,966
		28	11,808	n.a.
	13	9	7,000	5,949
		28	10,000	8,509
	14	8	10,000	8,527
		28	17,000	14,344
	15	9	12,000	10,440
		28	14,000	12,885
	16	8	14,000	11,590
		28	13,000	12,122
	17	8	7,000	6,188
		28	13,000	11,242
	17-R	7	7,000	5,862
		28	14,000	11,043

Table XXV

(Continued)

Lime Brand	Mix No.	Age (days)	Modulus of Elasticity -- (psi.) Initial Tangent E_o	Secant[2] E_m
	18	7	12,666	n.a.
		28	11,000	9,770
	19	7	10,000	8,873
		28	8,232	n.a.
	20	7	12,000	10,901
		28	11,000	9,568
	20-R	8	9,000	8,166
		28	7,000	6,494
	21	7	13,801	n.a.
		28	13,000	12,557
B	21-R	8	8,000	6,961
		28	12,000	10,332
	22	7	14,000	13,985
		28	18,000	17,639
	22-R	7	11,000	9,688
		28	13,000	11,827
	23	7	14,000	12,257
		28	16,000	14,412
	23-R	7	13,000	12,243
		27	16,676	n.a.

Notes: 1) R indicates remix;
2) n.a. indicates not applicable.

[1]In the compression tests as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

[2]Based at one-half the maximum stress indicated by the best-fit curves of Figures 33 to 66, pages 163 to 196.

Table XXVI

Modulus of Elastic Resilience (R_e) for Lime-Sand Mortar Mixes[1]

Lime Brand	Mix No.	Age (days)	R_e $\frac{in.-lbs.}{in.^3}$
A	12	7	0.066
		28	0.738
	13	9	0.103
		28	0.153
	14	8	0.076
		28	0.141
	15	9	0.087
		28	0.169
	16	8	0.080
		28	0.156
	17	8	0.085
		28	0.118
	17-R	7	0.222
		28	0.171

Table XXVI

(Continued)

Lime Brand	Mix No.	Age (days)	R_e $\frac{in.-lbs.}{in.^3}$
	18	7	0.469
		28	0.092
	19	7	0.102
		28	0.360
	20	7	0.112
		28	0.103
	20-R	8	0.082
		28	0.094
	21	7	0.622
		28	0.146
	21-R	8	0.098
B		28	0.105
	22	7	0.209
		28	0.177
	22-R	7	0.098
		28	0.108
	23	7	0.162
		28	0.140
	23-R	7	0.145
		27	0.657

Note: R indicates remix.

[1]In the compression tests as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

Table XXVII

Moduli of Toughness for Lime-Sand Mortar Mixes[1]

Lime Brand	Mix No.	Age (days)	Modulus of Toughness -- $\frac{\text{in.-lbs.}}{\text{in.}^3}$ T	Modified T'
A	12	7	0.44	0.22
		28	0.74	0.0
	13	9	0.86	0.51
		28	1.38	0.87
	14	8	0.69	0.43
		28	0.98	0.51
	15	9	0.79	0.49
		28	1.02	0.40
	16	8	0.73	0.46
		28	0.74	0.16
	17	8	0.65	0.35
		28	1.08	0.67
	17-R	7	1.29	0.54
		28	1.56	1.02

Table XXVII

(Continued)

Lime Brand	Mix No.	Age (days)	Modulus of Toughness -- $\frac{\text{in.-lbs.}}{\text{in.}^3}$ T	Modified T'
	18	7	0.47	0.0
		28	0.60	0.28
	19	7	0.63	0.27
		28	0.36	0.0
	20	7	0.55	0.14
		28	0.61	0.25
	20-R	8	0.50	0.20
		28	0.55	0.19
	21	7	0.62	0.0
		28	0.62	0.06
	21-R	8	0.80	0.45
B		28	0.54	0.17
	22	7	0.84	0.01
		28	0.77	0.07
	22-R	7	0.65	0.31
		28	0.55	0.15
	23	7	0.99	0.43
		28	0.67	0.16
	23-R	7	0.76	0.21
		27	0.66	0.0

Note: R indicates remix.

[1]In the compression tests as defined by the best-fit curves of Figures 33 to 66, pages 163 to 196.

Chapter V

DISCUSSION

If a clay or a lime-sand mortar were to be used, what constituent materials are required and in what proportion would they be needed to give a good quality mortar? The testing performed in this study attempted to provide the solutions.

With reference to the results of the testing performed on these two types of mortars, an examination was carried out so as to see what constituent materials and in what proportion was best overall in satisfying the essential properties for a good quality mortar. As appropriate, the examination is related to stackwall construction. Essential properties for a good quality mortar are detailed in Appendix A.

5.1 CLAY MORTAR

An examination of each essential property for a good quality mortar (see Appendix A) is performed with respect to all of the clay mortar mixes. From this, an indication as to what constituent materials and in what proportion they would be required has been sought.

5.1.1 Workability

At the possible expense of providing good workability in the clay mortar mixes, by design, the minimal amount of water was used in each mix. This was done so as to minimize the amount of volumetric shrinkage which is associated with the drying of clay.

Using the flow test as an indicator to the workability of the mortar, Table VI, page 88 shows that with exception of Mix No. 1, all of the clay mortar mixes had a flow/workability approximately one-half or 50 percent of that used for conventional mortars (see Definitions). Mix No. 1, which had no lime content, had the lowest flow/workability at about 0.09 or nine percent of that used in conventional mortars (see Definitions). This small flow value is in part due to the lower moisture content (based as a percentage of the clay solids only, not the total dry solids) of Mix No. 1 (see Table VII, pages 89 to 90). The higher moisture content of the remaining mixes was required largely due to the addition of dry lime to the mixture.

With respect to the flow test results, it is indicated that the addition of lime to a clay mortar is beneficial in terms of improving the property of workability. This leaves Mix No. 1 out as a possible mix candidate. The other 10 lime-containing mixes are still possible mix candidates.

Intuitively, both positive and negative features were detected with respect to the property of workability. The positive features for the clay mortar were: 1) while spreading, the water did not separate nor did the solid materials segregate out of the mix, 2) the mixture clung onto vertical surfaces, and 3) the mortar had a consistency that would extrude readily from joints without dropping as the building unit was placed and at the same time had body so that it could support courses of units without undergoing excessive distortion. The negative features were: 1) relative to conventional mortars (see Definitions), clay mortar was not easy to spread -- it required a degree of effort, and 2) the mortar was adhesive to the trowel which would create a problem for a mason in filling joints without undue effort and time.

5.1.2 Water Retention

A water retention test was not performed for any of the clay mortar mixes. It is noted though, that because clay has a natural water holding characteristic, moderate water retentivity did exist.

5.1.3 Bond

Appendix A states that in general, a mortar will form a good bond in masonry if it possesses high workability, high water retention, high strength and low air content. Other factors affecting bond are volume changes and resilience.

The clay mortar mixes were previously discussed as having low workability and presumably having moderate water retentivity. Higher strengths were attained for Mix Nos. 1 to 5 (see Table X, page 131), with Mix No. 2 having the highest at 871 psi. Measurements of air content were not performed.

The high volumetric shrinkage that occurred upon drying of all the clay mortars (see Figure 3, page 93, or Tables F-I to F-XII in Appendix F, pages 339 to 350), is seen as a negative factor for good bonding. Listed in Tables XIII and XIV, pages 136 and 137 is the modulus of elastic resilience for each clay mortar mix. Examination of these two tables shows that the mix with the highest elastic resilience is Mix No. 2.

From the above discussion on bond, clay mortar may have problems in providing a good bond in masonry work. However, out of all the clay mortar mixes, the most favourable appears to be Mix No. 2.

5.1.4 Strength

A graphical illustration of how the compressive strength and failure characteristics changed with changes of a single mortar component is illustrated in the Lime Study, Sand Study and Fibre Study plots, Figures 23 to 25, pages 126 to 128. From these study plots, the most favourable proportions of dry materials were 3 percent hydrated lime, 33.3

percent sand and 1.75 percent fibres. The combination of these materials with respect to the base weight measurement of one unit of dry clay corresponds to Mix No. 2.

A comparison of the compressive strength and failure characteristics of the dry-cured Mix No. 5^A with the moist-cured Mix No. 5^B is illustrated in the Moisture Curing Study, Figure 26, page 129. From this figure, it is shown that in terms of the compressive strength and failure characteristics, there was no great advantage to the moisture curing process (specimens kept in the moisture curing room for about the first two weeks) for a clay mortar mix.

The mortar strength required for stackwall construction is discussed in Appendix K. From this appendix, it is stated that the minimum laboratory compressive strength required for a one- and two-storey stackwall houses should theoretically be 47 and 94 psi. respectively. Appendix K also recommends a maximum strength of 180 to 460 psi.; the exact figure in this range is determined by the species of wood used as a building unit in stackwall (see Table K-I, page 512). The above strength values were assumed to be the 28-day compressive strengths as tested on two-inch cube specimens in the laboratory.

Table X, page 131 lists the maximum compressive strain and stress reached by the clay mortar mixes as determined by the best-fit curves of Figures 4 to 15, pages 105 to 116.

All of the clay mortar mixes met the minimum strength requirement. With respect to the maximum strength recommendation, Mix Nos. 1 to 5 (both 5^A and 5^B) exceeded this upper limit while Mix Nos. 6 to 11 did not.

If the maximum strength allowed was ignored, Mix No. 2 would be chosen as the best mix since it had the highest compressive strength at 871 psi. Mix Nos. 6 to 11 had strengths that were within the strength limits given by Appendix K. Of these, Mix Nos. 6 and 9 would be chosen as the best mixes since the other mixes had considerably lower stiffness. The compressive strengths of Mix Nos. 6 and 9 were respectively recorded as 344 and 304 psi.

5.1.5 Autogenous Healing

No attempt was made to determine if any or all of the clay mortar mixes had the property of autogenous healing.

5.1.6 Elasticity and Flexibility

A mortar that has high elasticity and flexibility is preferable in masonry work (see Appendix A). Elasticity will be judged by examining the modulus of elastic resilience (see Tables XIII and XIV, pages 136 and 137) of each mix. Flexibility will be judged by examining the moduli of toughness (see Tables XV and XVI, pages 139 and 140) of each mix.

As previously discussed with the property of bond, the mix with the highest elastic resilience/elasticity was Mix

No. 2. Examining Tables XV and XVI, pages 139 and 140, the highest moduli of toughness/flexibility values also occurred with Mix No. 2.

It is expected then that Mix No. 2 will provide the highest elasticity and flexibility out of all the clay mortar mixes.

5.1.7 Efflorescence

The efflorescence potential of mortar is dependent primary on its workability and the materials of which it is composed (see Appendix A). With exception to Mix No. 1, all of the clay mortar mixes had approximately the same workability (as indicated by their flow test results -- see Table VI, page 88), the same components, and the same source of materials; this would indicate that Mix Nos. 2 to 11 all had the same efflorescence potential. Except for being devoid of lime, Mix No. 1 also had the same kind and source of materials, but with its lower workability (see Table VI, page 88), it use is seen as unfavourable.

5.1.8 Durability

A mortar mix that is favoured in providing a good bond will in general provide masonry work that has good durability. This stems from the fact that a mortar with good bonding characteristics will create a wall that is watertight; this will reduce the migration of water into the masonry work which will in effect reduce the potential for efflorescence to occur and reduce the destructive effects of freezing water.

Referring back to the discussion on bond, the mix chosen as having the best bonding potential was Mix No. 2. In turn, this means that Mix No. 2 has the best potential in creating masonry work that has good durability.

There is however only one true test of durability -- the test is of time. Mortar in-situ, exposed to the environmental elements over time, is the only sure test of durability.

5.1.9 Volumetric Changes

Two kinds of drying shrinkage were expected with the use of clay as a major mortar component. The first kind was anticipated during the initial drying stage, shortly after being placed in the wall. After this, once the clay mortar is set in a wall and exposed to the environmental conditions, a second kind of drying shrinkage can occur during the wetting and drying cycles.

Two methods of approach were taken to eliminate or to minimize the expected shrinkage of clay mortar. The first approach was the addition of lime to the mixes. A second approach, performed with Mix No. 5, was a moisture-curing process.

During the initial drying stage, all of the clay mortar mixes with and without lime experienced high volumetric shrinkage. This is indicated in Figure 3, page 93, or Tables F-I to F-XII, pages 339 to 350, where drying shrinkage took place during the first eight days of exposure to laboratory air. After this age, the volume of the specimens remained stable at about 56 percent of their original volume. Mix No. 5 with moisture curing showed no shrinkage while in the moisture curing room, but once put out into the laboratory air, the shrinkage behaviour was similar to that of Mix No. 5 with no moisture curing.

If this amount of shrinkage were to take place around the masonry units, it would cause a loss of bond resulting in leaky walls. In stackwall construction the leaky walls would allow wetting and drying cycles of the logs and insulation which would lead to the deterioration of the building. If the salt(s) for efflorescence (see Appendix A) were to exist in the clay mortar materials, the leaky wall would also increase the potential for efflorescence to occur.

To correct the initial drying shrinkage characteristic of clay mortars in stackwall construction, the joints would have to be refilled a number of times till the shrinkage gap was reduced to the point where it could be filled with caulking, as would be the case with conventional mortar [51, pp. 44 and 61].

This high volumetric shrinkage was also foreseen as a problem in the construction of the corners of a stackwall building. In stackwall construction it is very important to have the corners constructed so that they are plumb, square (as it would be in any other type of building) and to have the timbers parallel to each other [51, p. 39]. The reason for this is that the corners are used as reference points so as to build the walls plumb and straight [51, p. 41]. With the high volumetric shrinkage experienced with the clay mortar, distortion of the corners would be inevitable resulting in complications during stackwall construction.

At present, if clay mortar were to be used in stackwall construction, it is suggested that it not be used in the corners, but only in the wall portion. In the corners, a mortar that has a fairly low volumetric shrinkage upon drying should be used instead. In order for this to work, the two mortars would have to be compatible. An example of compatibility would be similar compressive strength and failure characteristics. Conventional mortar (see Definitions) presently used for stackwall construction [51, p. 20] has proven to provide satisfactory corners. Therefore, one theoretical mode of construction would be to use a conventional mortar in the corners that is compatible with the clay mortar forming the remaining part of the stackwall.

Although the volumetric shrinkage during the initial drying stage was not prevented through the use of lime in the clay mortar, it is possible that the volume change during the wetting and drying cycles may be stabilized. To determine if this is valid, laboratory or field tests on assemblage or wall panels of stackwall would have to be performed.

5.1.10 Economy

As explained in Appendix A, there are two costs to consider when dealing with mortar, the initial cost and the secondary costs. The secondary cost factors will be considered first.

Clay mortars cling to vertical surfaces well which implies that little mortar would be wasted due to droppings during construction. The setting characteristic of clay mortars was also considered slow enough so that labour time spent in retempering (see Definitions) would be minimal. These are two positive economic factors.

The clay mortars were designed with a low flow/ workability. This feature means more time to mix and lay the mortar. The clay mortar mixes also have high volumetric shrinkage upon drying. Subsequently, refilling of mortar into the shrinkage gaps would have to be performed theoretically a number of times till the gap at the joint is small enough to caulk. With each filling, additional labour time and material would be required. If labour and/or material is part of the stackwall construction cost, the low flow/ workability and the high volumetric shrinkage of clay mortar become negative economic features.

Surface cracks were noted to exist on the clay mortar specimens. If such cracks appeared on the walls of stack-wall, additional labour and material cost would be involved to fill them up. Even if these costs are very small, an examination of the notes taken on the mixes in Appendix H will determine which mix/mixes had the most favourable crack distribution.

The original top surface of the specimens was assumed to best correspond to the wall surface since they are both exposed to the air at the initial stage of drying. From Appendix H, it is noted that for Mix Nos. 5^B and 7 to 11, the cracks were evenly distributed on the specimens. The remaining mixes, Mix Nos. 1 to 5^A and 6, had cracks only near the bottom of the specimens but none near or at the top; these are the most favourable mixes to use in terms of the crack distribution pattern.

The mix that looks the most promising in terms of providing the best durability will require the least amount of maintenance work. This mix would be an economic asset since maintenance work usually involves some considerable expenditure. The previous discussion on durability pointed out that the best potential in creating masonry work with good durability is Mix No. 2. Mix No. 2 is also among the mixes that are favourable to use in terms of crack distribution.

From the discussion of the secondary economic factors, for a clay mortar, it is suggested that Mix No. 2 be used.

At present, the Northern Housing Committee [51] suggests that a conventional mortar (see Definitions) be used for stackwall construction. In particular, a Portland cement:lime:sand (P.C.:L:S) ratio of 2:1:6 is stated in Reference 51 [page 20]. The initial cost of this mortar and clay mortar Mix No. 2 is calculated in Appendix L; these calculations were based on a number of assumptions and a range of prices found in Winnipeg, Canada as of June, 1987.

For the conventional mortar above, it was calculated in Appendix L that the cost is \$3.27 to \$4.35 per cubic foot. With clay mortar Mix No. 2, the cost was calculated to be \$0.29 to \$0.44 per cubic foot. Referring to Table L-II of Appendix L, page 523, the cost of clay mortar Mix No. 2 is 0.09 to 0.10 times that of the above conventional mortar. From this comparison, there is a definite initial cost advantage in using the clay mortar Mix No. 2 over the conventional mortar presently suggested for stackwall construction.

5.1.11 Appearance

The following discussion on appearance will assume that consistent workmanship is applied with all of the clay mortar mixes. This will leave only the characteristics of the mortars to be judged for appearance. The original top surface of the specimens was assumed to best correspond to the wall surface since they are both exposed to the air at the initial stage of drying.

Mix No. 1 had a dark greyish brown colour. The remaining clay mortar mixes were grey. These colours were considered acceptable.

Examination of the pre-testing notes in Appendix H, reveals that with exception to Mix No. 5^B, the original top surface of the specimens had a surface texture that was smooth with some roughness. For Mix No. 5^B, slight bumps were noticed. The mixes absent of bumps are preferred.

The sight of cracks on the exterior surface of the mortar is an appearance factor to consider. It was noted with the discussion of economy that clay mortar Mix Nos. 1 to 5^A and 6 had no cracks near or at the top of the specimens. In terms of appearance, these are favourable mixes.

Considering together the surface texture and cracks, Mix Nos. 1 to 5^A and 6 best satisfy the property of appearance.

5.1.12 <u>Summary</u>

Reviewing the discussion material made with respect to the essential properties for a good quality mortar, the most promising clay mortar is Mix No. 2, i.e. 33.3% sand, 1.75% fibres, 3% hydrated lime, and 140% water, all proportioned by dry weight to one unit of dry clay.

The clays used in this study came from one area and had similar properties (see Appendix B). It is realized that the composition and properties of clay can vary from one area to another; this may have the effect of creating a clay mortar that has different properties (see Appendix A) from that of the clays used in this study. Although this may occur, it is the adequacy of a mortar that is of importance. It is important to remember that an adequate mortar is one that behaves satisfactorily (see Appendix A), not one that has high strength. A mortar that behaves satisfactorily does not need improvement.

5.2 LIME-SAND MORTAR

An examination of each essential property for a good quality mortar (see Appendix A) is performed with respect to all of the lime-sand mortar mixes. From this, an indication as to what lime-sand ratio to use is obtained. The performance of the remix mixes relative to the original mixes is also examined.

5.2.1 Workability

Using the flow test as an indicator to the workability of the mortar, Table XVIII, page 143 shows that all of the lime-sand mortar mixes had a flow/workability within or close to the range (105 to 115 percent) specified by CSA A8-1970, Article 7.9.5.3 [15, p. 29]. The average flow of all the mixes was 112 percent.

As the lime content increased in a lime-sand mortar mix, the workability of the material with the trowel increased. With respect to the requirements for good workability, as discussed in Appendix A, only one requirement was not met by all of the mixes. None of the mixes had body so that they could support many courses of masonry units without undergoing distortion. This one negative feature becomes unimportant though if rapid construction is not utilized, as is usually the case for stackwall construction.

5.2.2 Water Retention

A water retention test was not performed for any of the lime-sand mortar mixes. An indication of good water retentivity was evident though, since it took a few days for the leftover pile of mortar to dry out. Although the mortar stayed damp for this time, some hardening did take place suggesting that further construction could take place.

An indirect indication of good water retention was seen from the Vicat tests performed for Mix Nos. 14 and 17. The time needed for the required 10 millimetre settlement was respectively 29 and 37 hours. Water retention capabilities of lime is further supported in literature [38,40,48,68].

5.2.3 Bond

Appendix A states that in general, a mortar will form a good bond in masonry if it possesses high workability, high water retention, high strength and low air content. Other factors affecting bond are volume changes and resilience.

The lime-sand mortar mixes were previously described as having good workability and good water retention.

Figures 81 to 83, pages 215 to 217, shows how the mortar strength changed with the lime-sand ratio. Referring to Figure 81, page 215, the highest strength of the lime Brand A mortar mixes is indicated at the lime:sand ratios of 1:3.2 and 1:3.9 for the seven- and 28-day tests respectively; the average of these two ratios is 1:3.6. For lime Brand B, Figure 82, page 216 indicates that the highest strength will occur at the lime:sand ratio of 1:2.9 for both the seven- and 28-day tests. Figure 83, page 217 shows that for the remix mixes of lime Brand B, the highest seven- and 28-day strength occurred at the lime:sand ratio of 1:2. For reason of providing good bond through a higher strength mortar, a lime:sand ratio in the range from 1:2 to 1:3.6 is suggested from the strength tests.

Measurements of air content were not performed for any of the lime-sand mortar mixes; it was noted though, that upon breaking up of the leftover piles of dried mortar for the remix mixes, the material in the cross-section was porous.

The low volumetric shrinkage that took place upon drying for all of the lime-sand mortar mixes (see Table XX, page 146) is seen as a positive factor for good bonding.

The modulus of elastic resilience for all of the lime-sand mortar mixes is listed in Table XXVI, pages 222 to 223. An examination of the original mixes in this table show that there is not a large change in the elastic resilience with the change in the lime-sand ratio of a mix. The difference between the lowest and the highest modulus of elastic resilience recorded in Table XXVI, pages 222 to 223, is 0.672 in.-lbs./in.^{3}.

For lime Brand A, the highest elastic resilience for the seven- and 28-day tests occurred at the lime:sand ratios of 1:5 and 1:6 respectively; for lime Brand B, the corresponding lime:sand ratios are 1:3.65 and 1:5 respectively. This would indicate that a lime:sand ratio in the range from 1:3.65 to 1:6 is favourable in providing the higher elastic resilience. It is noted though, that the change in the elastic resilience with the change of the lime-sand ratio of a mix is small.

With respect to the remix mixes of lime Brand B, the modulus of elastic resilience increased as the lime concentration increased. The elastic resilience of the remix mixes were in general lower than that of the corresponding original mixes with exception at the lime:sand ratio of 1:2.

At this ratio, the elastic resilience of the remix mixes were higher than the original mixes with exception to lime Brand B at the seven-day test where the elastic resilience was just below that of the original mix. This indicates that if a similar or even a higher degree of elastic resilience is desired in a remix mix as compared to its original mix, a lime:sand ratio of 1:2 is required. Since the change in the elastic resilience from mix to mix or remix to remix is small, a remix mix with a lower lime concentration does not necessarily mean that it will lack in adequate or compatible elastic resilience.

In terms of strength, a lime:sand ratio in the range of 1:2 to 1:3.6 is suggested to provide a better bonding mortar. However, in terms of resilience, a lime:sand ratio in the range of 1:3.65 to 1:6 is suggested. The fact that the change in elastic resilience with the change in the lime-sand ratio is small coupled with the fact that a remix mix with a lime:sand ratio of 1:2 provides a mortar that has a resilience close to or higher than that of the original mix, a lime:sand ratio in the range of 1:2 to 1:3.6 is suggested for a better bonding mortar.

5.2.4 Strength

A graphical illustration of how the compressive strength and failure characteristics changed with the change in the lime-sand ratio is illustrated in the Lime-Sand Ratio Study plots, Figures 67 to 70, pages 198 to 201. In general, the lime:sand ratios that appear to be the most favourable in these figures range from 1:2 to 1:3.65.

The compressive strength and failure characteristics of the remix mixes as compared to the original mix is illustrated in the Remix Strength Study plots, Figures 71 to 80, pages 202 to 211. From these figures, it is shown that the remix compressive strength and failure characteristics was similar to or better than that of the original mix only at the lime:sand ratio of 1:2. This held true for both lime Brands A and B. For mixes with lower lime concentrations, the original mixes had a strength that was superior to that of the remix.

The mortar strength required for stackwall construction is discussed in Appendix K. From this appendix, it is stated that the minimum laboratory compressive strength of mortar required for a one- and two-storey stackwall house should theoretically be 47 and 94 psi. respectively. Appendix K also recommends a maximum strength of 180 to 460 psi.; the exact figure in this range is determined by the species of wood used as a building unit in stackwall (see Table K-I, page 512). The above strength values were assumed to be the 28-day compressive strength requirements as tested on two-inch cube specimens in the laboratory.

Since both seven- and 28-day strength tests were performed for the lime-sand mortar mixes, a correlation between the two strengths is needed. Researchers have found that the 28-day strengths of mortars, regardless of lime content, average about 60 percent higher than seven-day strengths [12]. This can be written as:

$$f'_{m_{28\text{-Day}}} = 1.6(f'_{m_{7\text{-Day}}})$$

or

$$f'_{m_{7\text{-Day}}} = 0.625(f'_{m_{28\text{-Day}}})$$

The above relationships between the seven- and 28-day strengths can be checked graphically and numerically. A graphical check between the seven- and 28-day strength of each lime-sand mortar mix is illustrated on computer plots in Appendix J, Figures J-1 to J-17, pages 471 to 487. Numerically, this relationship can be checked with the maximum compressive strain and stress results in Table XXIV, pages 213 to 214. For lime Brand A, the above relationship holds true on average, especially when using only the original mix results. With lime Brand B, on average of all the mixes, the seven- and 28-day strengths are approximately the same.

Despite the behaviour of the mixes of lime Brand B, the above relationship will be used to calculate the theoretically required seven-day strengths. Using the 28-day strength specifications of Appendix K, the minimum acceptable seven-day strength of mortar for a one- and two-storey stackwall house calculates to be 29 psi. (47 x 0.625) and 59 psi. (94 x 0.625) respectively.

Table XXIV, pages 213 to 214 lists the maximum compressive strain and stress reached by all of the lime-sand mortar mixes. From this table, it is seen that the minimum 28-day strength required for a one-storey stackwall house (47 psi.) was met by all of the original and remix mixes at both the seven- and 28-day tests.

For a two-storey stackwall house, the minimum seven- and 28-day strengths were previously stated as 59 psi. and 94 psi. respectively. An examination of Table XXIV, pages 213 to 214 shows that all of the original and remix mixes satisfied the calculated seven-day strength requirement (59 psi.). The 28-day strength requirement (94 psi.) however, was not met by all of the mixes. Mix Nos. 18, 19 and 20 of the original mixes and Remix Nos. 20-R and 21-R had 28-day strengths below the required strength of 94 psi.; Remix No. 21-R had a borderline 28-day strength of 93 psi. All of this indicates that for a lime-sand mortar to be used for a two-storey stackwall house, a lime:sand ratio in the range of 1:2 to 1:3.65 (Mix Nos. 15 to 17 of lime Brand A/Mix Nos. 21 to 23 of lime Brand B) will meet the 28-day strength requirement. This holds true for both the original and remix mixes.

It is interesting to note at this point how two different brands of lime (classified as being the same), when put into separate but identical lime-sand mortar mixes, can have different compressive strength and failure characteristics. This difference in compressive strength and failure characteristics is graphically illustrated in the Lime Brand Study computer plots of Appendix J, Figures J-18 to J-31, pages 488 to 501. The difference can be accounted for in a number of ways. Two different sources of lime may differ somewhat in material properties (see Appendix E for a brief description of the two lime brands used). Another reason could be an unintentional difference in the tamping pressure used during the moulding process.

With respect to the maximum strength recommended in Appendix K (180 to 460 psi.), none of the original or remix mixes exceeded this upper limit.

The recommended range of lime-sand ratios in terms of strength for a one- and two-storey stackwall house differ from one another. For a one-storey stackwall house, all of the mixes proved to have adequate strength, whereas for a two-storey stackwall house, limits were exceeded. So as to provide a unified lime-sand ratio of a lime-sand mortar for stackwall house construction, the range specified for a two-storey stackwall house will govern. In terms of strength, a lime:sand ratio in the range of 1:2 to 1:3.65 is suggested for stackwall construction.

5.2.5 Autogenous Healing

No attempt was made to determine if any or all of the lime-sand mortar mixes had the ability of performing autogenous healing. References 38, 48 and 68 point out though, that lime-sand mortars do have this property.

5.2.6 Elasticity and Flexibility

A mortar that has high elasticity and flexibility is preferable in masonry work (see Appendix A). Elasticity can be judged by examining the modulus of elastic resilience (see Table XXVI, pages 222 to 223) of each mix. Flexibility can be judged by examining the moduli of toughness (see Table XXVII, pages 224 to 225) of each mix.

As previously discussed with the property of bond, there were small differences in the elastic resilience/elasticity among all of the lime-sand mortar mixes. In spite of this fact, it was pointed out that the highest resilience/elasticity was reached with the lime:sand ratio ranging from 1:3.65 to 1:6. For a remix mix to have resilience/elasticity that is similar to or higher than the original mix, a lime:sand ratio of 1:2 is required.

A study of the moduli of toughness values reveals that there is no clear indication as to what range of lime-sand ratios provide the highest flexibility. Highest values occurred across the whole range of lime-sand ratios that were tested. In some instances, the values did not change significantly with the change in the lime-sand ratio; examples of this occurred with the modulus of toughness (T) at the 28-day age for the lime Brand B original and remix mixes. Some of the modified modulus of toughness values had figures that were near to and even at zero. In spite of the above, if a recommendation is to be made based on the frequency of occurrence rather than a general trend, the highest moduli of toughness/flexibility will occur with the lime:sand ratio ranging from 1:2 to 1:3.65.

For the reasons stated, the above lime-sand ratios discussed for higher elasticity and flexibility bear little weight on the final overall recommended ratio(s).

5.2.7 Efflorescence

The efflorescence potential of mortar is dependent primarily on its workability and on the materials of which it is composed (see Appendix A).

The workability of all the lime-sand mortar mixes was approximately the same (as indicated by their flow test results in Table XVIII, page 143); this similarity means that with respect to workability, an equal efflorescence potential exists among all of the mixes/lime-sand ratios.

With respect to the materials, each mix contained the same components: hydrated lime, sand and water. Two brands of lime were used to form two sets of mixes; the efflorescence potential between these two sets may not be equal as the source of the two lime brands were different (see Appendix E). However, the potential in each set remained constant since the source of lime used for each mix/lime-sand ratio was the same. The source of the sand and water remained constant for all of the mixes; this indicates no differential efflorescence potential among the mixes due to the sand or water.

5.2.8 <u>Durability</u>

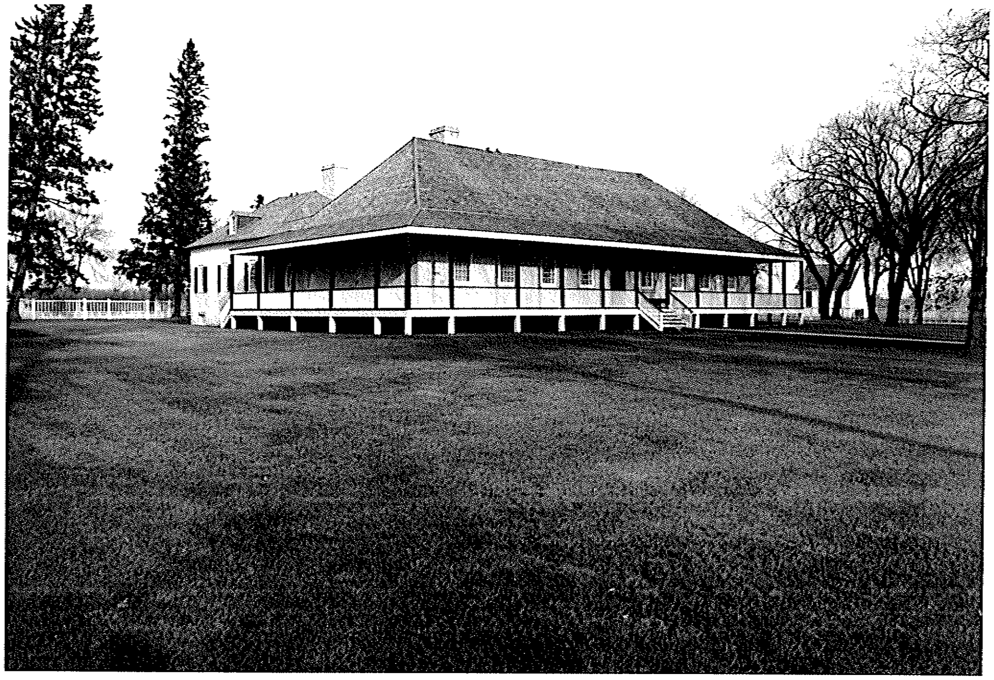
A mortar mix that is favoured in providing a good bond will in general provide masonry work that has good durability. This stems from the fact that a mortar with good bonding characteristics will create a wall that is watertight; this will reduce the migration of water into the masonry work which will in effect reduce the potential for efflorescence to occur and reduce the destructive effects of freezing water.

Referring back to the discussion on bond, the range of lime:sand ratios suggested as having the best bonding potential were 1:2 to 1:3.6. In turn, this means that the same range of lime-sand ratios has the best potential in creating masonry work that has good durability.

The true test of durability is time. Masonry structures built with a straight lime-sand mortar in its in-situ condition exposed to the environmental elements over many years would create such a test. Examples of such structures can found locally in Manitoba, Canada.

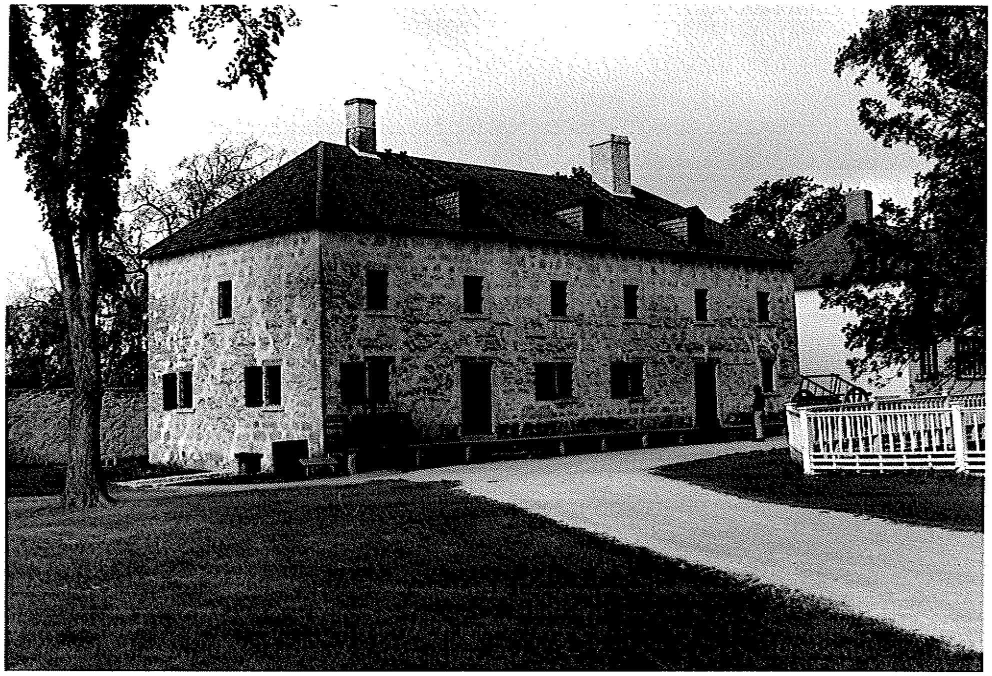
South of Selkirk, Manitoba at the Lower Fort Garry National Historic Park, all of the original masonry construction was done with a straight lime-sand mortar and limestone building blocks. Associated with this fort, three examples of this type of construction will be given: 1) the central building known as the Big House, built in 1832 (Photograph 19), 2) the fur loft and saleshop which was among the first buildings constructed inside the fort sometimes prior to 1874 (Photograph 20), and 3) the walls surrounding the fort which have an average height of 7.5 feet which were completed around 1848 (Photograph 21). Photograph 22 shows a close-up view of an original lime-sand mortar joint that is typical of the masonry structures at this fort; specifically this photograph was taken of a joint on the south wall of the fur loft and saleshop with a macro 1.5 magnification lens. The above structures are presently in good condition serving as part of a National Historic Park.

The St. Andrews Anglican Church located between Winnipeg and Selkirk, Manitoba is another example of lime-sand mortar and limestone building blocks construction (Photograph 23). Built during the period of 1845 to 1849, this church still stands in sound condition and continues to be the focus of an active parish life.



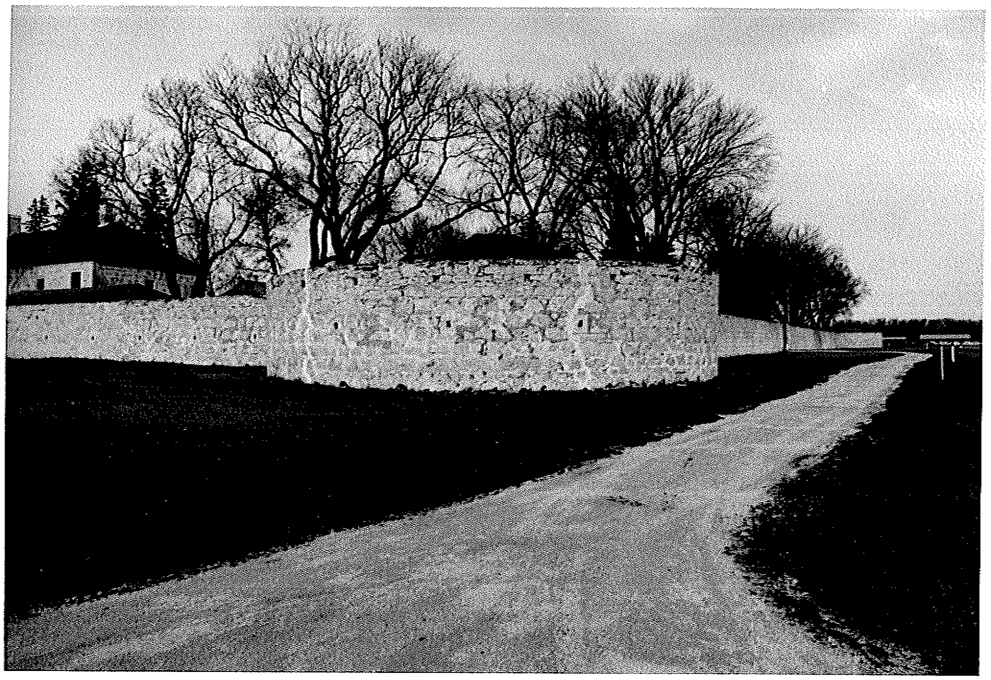
Photograph 19: The Big House at the Lower Fort Garry National Historic Park, Manitoba, Canada

At the intersection of Main Street and Centre Avenue of Stonewall, Manitoba there exist a number of buildings constructed with lime-sand mortar and limestone building blocks. At this site there exist a library, a bank and a retail store (Photographs 24 to 26 respectively). The library was built in 1914. It is assumed that the other buildings were constructed about the same time. All of these buildings still appear to be in good condition and are still in full use.



Photograph 20: Fur Loft and Saleshop at the Lower Fort Garry National Historic Park, Manitoba, Canada

Noting the age of the above examples and the fact that these structures have been exposed to the harsh environmental weather conditions of Manitoba, it is without a doubt that masonry structures built with a lime-sand mortar are durable. There are probably numerous other examples to prove that lime-sand mortars produce durable structures, but with the advent of Portland cement, they have become less prevalent. It should be noted here that Portland cement was introduced to mortar to provide fast setting and high early

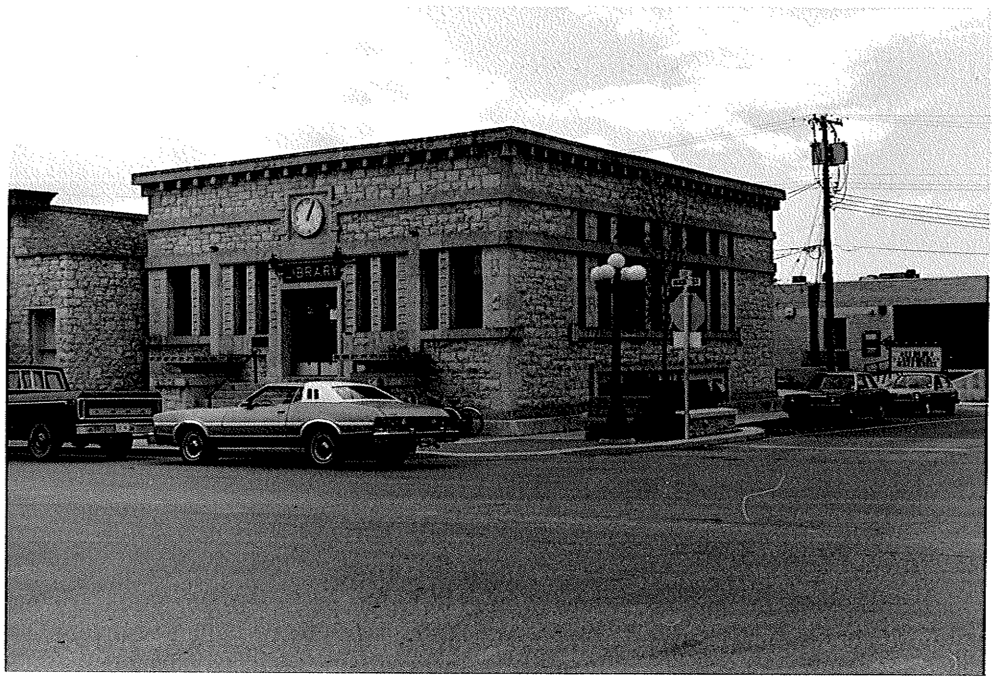


Photograph 21: The Walls Surrounding the Lower Fort Garry National Historic Park, Manitoba, Canada

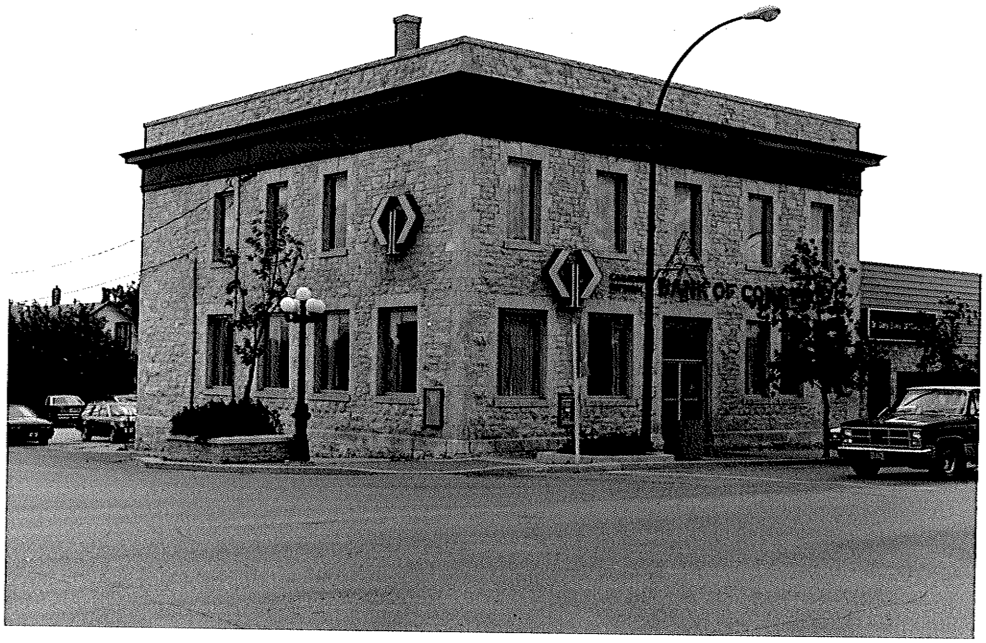
strength so that construction can proceed at a rapid pace. It was not introduced for the purpose of ultimate high mortar or masonry assemblage strength [12].

Photograph 22: Close-Up of a Typical Lime-Sand Mortar Joint of Fur Loft and Saleshop (South Wall) in Photograph 20, Page 254 -- Lens: Macro 1.5 Magnification

Photograph 23: St. Andrews Anglican Church North of Winnipeg, Canada



Photograph 24: Library in Stonewall, Manitoba, Canada



Photograph 25: Bank in Stonewall, Manitoba, Canada

Photograph 26: Retail Store in Stonewall, Manitoba, Canada

5.2.9 Volumetric Changes

Only one kind of volume change/volumetric shrinkage was expected with the use of a lime-sand mortar. This was expected to occur during the initial drying stage, shortly after being placed in the wall.

Table XX, page 146 lists the volumetric shrinkage that took place for all of the lime-sand mortar mixes. The degree of shrinkage which occurred for the remix mixes was approximately the same as that occurred for the original mixes. From this table it is seen that the shrinkage that took place up to the seven-day age was approximately the same for all of the mixes; this was also true at the 28-day age. The average volumetric shrinkage at the seven- and 28-day age was approximately four and five percent respectively. From these figures it appears that the majority of the shrinkage took place in the first week of drying.

In stackwall construction, a certain amount of shrinkage of the mortar is considered acceptable as part of the construction process [51, pp. 44 and 61]. The magnitude of volumetric shrinkage reported above for the lime-sand mortar mixes is considered to be within the acceptable amount. Shrinkage causing distortion of the corners or requiring subsequent refilling of mortar at the log-mortar joints should not occur with lime-sand mortar. Caulking around the logs as prescribed in Reference 51 [pp. 44 and 61] would however be necessary.

5.2.10 Economy

As explained in Appendix A, there are two costs to consider when dealing with mortar, the initial cost and the secondary costs. The secondary costs are considered first.

The cross-section of dried lime-sand mortar was noted to be porous. Although not proved, it appeared that the degree of porosity was greater that what exists in conventional mortar (see Definitions). Since conventional mortar is presently used in stackwall construction [51, p. 20], this characteristic of lime-sand mortars may prove to develop a better insulated wall. Economic benefit from this would be realized when the stackwall house/building is in use through savings in heating and/or cooling costs.

All of the lime-sand mortar mixes were found to have good workability. This feature means that the labour time required to mix and lay the mortar will be at a minimum. This in turn will minimize the labour cost, if it exists. Having good workability, the mortar clung onto vertical surfaces well, which implies that only small amounts of mortar would be wasted due to droppings. Even if droppings occur, there is some positive indications that dried lime-sand mortar can be remixed (see discussion on other mortar properties). If remixing is possible, further economic advantage is seen.

The lime-sand mortar mixes were found to have slow setting characteristics. If labour cost is a factor, this leads to an economic benefit since the possible time spent in retempering (see Definitions) would be minimal. This benefit will be seen only if the pace of construction is not rapid as the slow setting will restrict the number of courses of building units that can be built up at a time. In the case of stackwall construction, this benefit will in most cases be applicable.

The average volumetric drying shrinkage experienced by the lime-sand mortar mixes at the 28-day age was five percent (see Table XX, page 146). This is relatively low. With this magnitude of shrinkage, caulking at each stackwall joint, as prescribed by the Northern Housing Committee [51, pp. 44 and 61], can probably be done with no prior refilling of mortar. This becomes an economic benefit if labour and material costs are a factor in refilling of mortar into shrinkage gaps.

The mixes that are the most promising in terms of providing the best durability will require the least amount of maintenance work. Since maintenance work usually involves some considerable expenditure, the use of such a mix would be an economic asset. From the previous discussion, it was predicted that the best potential in creating masonry work with good durability was with the lime:sand ratios ranging from 1:2 to 1:3.6.

From the discussion of the secondary economic factors, it is suggested that a lime:sand ratio in the range of 1:2 to 1:3.6 be used.

At present, the Northern Housing Committee [51] suggests that a conventional mortar (see Definitions) be used for stackwall construction. In particular, a Portland cement:lime:sand (P.C.:L:S) ratio of 2:1:6 is stated in Reference 51 [page 20]. The initial cost of this mortar and of a selected number of lime-sand mortar mixes is calculated in Appendix L; these calculations were based on a number of assumptions and a range of prices found in Winnipeg, Canada as of June, 1987.

For the conventional mortar above, it was calculated in Appendix L that the initial cost is $3.27 to $4.35 per cubic foot. Also in this appendix is the calculated initial cost of lime-sand mortars with the lime:sand ratios of 1:2, 1:3 and 1:3.5. The respective cost of these mortar ratios is $2.22 to $3.64, $1.63 to $2.57 and $1.46 to $2.26 per cubic foot. Referring to Table L-II, page 523 of Appendix L, the cost of the above respective lime-sand mortars is 0.68 to 0.84, 0.50 to 0.59 and 0.45 to 0.52 times that of the conventional mortar. From this comparison, there is a definite initial cost advantage in using a lime-sand mortar over the conventional mortar presently suggested for stackwall construction.

5.2.11 <u>Appearance</u>

The following discussion on appearance assumes that consistent workmanship is applied with all of the lime-sand mortar mixes. This leaves only the characteristics of the mortars to be judged for appearance. The original top surface of the specimens was assumed to best correspond to the wall surface since they are both exposed to the air at the initial stage of drying.

All of the lime-sand mortar mixes were brownish-white (beige), a colour that is considered quite acceptable.

The surface texture of the specimens of lime Brand A differed somewhat from that of lime Brand B. For lime Brand A, all of the surfaces of the specimens had a smooth finish that was not susceptible to rubbing or scratching. With lime Brand B, the original top surface of the specimens also had a smooth texture but at lower lime concentrations, sand grains were released when rubbed or scratched. When the lime concentration increased to the lime:sand ratio of 1:3 and higher, the top surface became resistant to losing sand grains upon the action of rubbing or scratching; this held true for the remix mixes as well.

In terms of appearance, a surface that is smooth and not susceptible to simple rubbing or scratching is desirable. Therefore, a lime:sand ratio of 1:3 is suggested. A lime:sand ratio of 1:2 would also be satisfactory but since it has a higher concentration of lime, the initial cost of the mortar is higher.

5.2.12 Summary

Reviewing the discussion made with respect to the essential properties for a good quality mortar, with both the hydrated lime and sand measured in a dry state, the most promising lime-sand mortar mixes lie with the lime:sand ratios ranging from 1:2 to 1:3.6. For the purpose of simplifying numbers for discussion and for field use, the ratio of 1:3.6 will be rounded off to 1:3.5 in the end conclusions.

The ratio of 1:3 is favoured since it was at this lime concentration where a satisfactory surface texture became assured. Below this concentration of lime, at the lime:sand ratio of 1:3.65, the surface texture was on the borderline of being acceptable. The ratio of 1:3 is also somewhat between the range given above giving an intuitive feeling of safety from using a bit more cementitious material (lime) than the bare suggested minimum.

If dried mortar droppings and/or left-over piles of mortar are broken up and remixed, and if similar or better mortar properties to that of the original mix are required, results indicate that a higher concentration of lime should be used; the results suggest a lime:sand ratio of 1:2. If a lime:sand ratio of 1:2 is used in anticipation of using remixed mortar, a careful cost analysis should be done. The analysis should realize that the use of a lime:sand ratio of 1:2 will have a higher initial cost than with the ratio of 1:3 (see Appendix L). To be cost effective, this increase in cost should be lower than the amount saved in using remixed mortar.

The mortar properties of a remixed mortar with a lime:sand ratio of 1:3 were shown to be somewhat of lower quality than its original counterpart. If this degree of difference is proven to be insignificant and compatible in a wall with the original mortar, then a single ratio recommendation of 1:3 could be used irrespective of whether remixing would take place. If the difference is proven to be significant, then perhaps the remix mortar could still be used in some way that could be demonstrated to be acceptable. Two theoretical ideas of how this may be done are: 1) to incorporate relatively small amounts of remix into batches of original mix mortar, or 2) to add additional lime to a remix mortar; the amount added should be cost-effective. It is noted that these two ideas are theoretical and that neither one was proven to be an acceptable practice.

Chapter VI

CONCLUSIONS

The object of this study was to seek a lower-cost and more readily accessible mortar to be used for stackwall construction. For such a mortar, the required constituents and their proportion was sought. To provide a satisfactory mortar, the essential properties for a good quality mortar that are discussed in Appendix A were considered. Four different kinds of mortars were examined.

6.1 CLAY MORTAR

1. The composition of materials found the most favourable for a clay mortar was 33.3% sand, 1.75% fibres, 3% hydrated lime, and 140% water (as used in Mix No. 2), all proportioned by dry weight to one unit of dry clay.
2. The cost of the clay mortar above is 0.09 to 0.10 times that of the conventional mortar which is presently suggested for stackwall construction (see Appendix L).
3. Clay mortar has faults with respect to the properties of workability and volumetric changes; these faults in turn were predicted to create problems with the property of bond.

4. No benefit was seen with the moisture curing process of clay mortar.
5. Relative to conventional mortars (see Definitions), a high amount of effort and time is required to prepare a clay mortar mix (see Table III, page 37).

6.2 <u>LIME-SAND MORTAR</u>

1. A range of volumetric proportions were found to be acceptable for a lime-sand mortar. For each unit volume of dry hydrated lime, two to three and one-half units of dry sand can be used. The lime:sand ratio of 1:3 is suggested.
2. There were positive indications that lime-sand mortar that has dried out can be remixed. If remixing is to take place, a lime:sand ratio of 1:2 in the original mix is presently suggested; in the future the ratio of 1:3 may prove to be adequate.
3. The costs of lime-sand mortars with lime:sand ratios of 1:3 and 1:2 are respectively 0.50 to 0.59 and 0.68 to 0.84 times that of the conventional mortar which is presently suggested for stackwall construction (see Appendix L).
4. Dried lime-sand mortars is more porous in its cross-section than dried conventional mortar (see Definitions).

5. The slow-setting characteristic of lime-sand mortars will restrict the number of courses of building units that can be built up at a time; this is considered acceptable in stackwall construction.
6. The effort and time required to prepare a lime-sand mortar mix (see Table V, page 64) is judged to be the same as that of a conventional mortar (see Definitions).

6.3 SOIL-CEMENT MORTAR

No experimental work was performed with a soil-cement mortar, but it was discovered that:

1. The amount of cement required (19 percent or more by weight of soil -- as suggested by Reference No. 54) for a plastic silty-clay soil (soil available for experimental work) for an acceptable mortar is not economically feasible.
2. Addition and thorough blending of sand to a clay soil may reduce the amount of cement required in a soil-cement mortar; Gillard and Lee [36, pp. 67 to 81] suggest a volumetric proportion of 1:1:4.5 (Portland cement:clay:sand).

6.4 CEMENT-LIME MORTAR WITH SAWDUST AND/OR WOOD CHIPS

No experimental work was performed with a cement-lime mortar with sawdust and/or wood chips. It is perceived that the economics and the availability of such a mortar over a clay or lime-sand mortar would not be as beneficial since quantities of Portland cement and lime would still have to be purchased. The quantity of sawdust and/or wood chips that could be added to a cement-lime mortar, as an additive, also seems somewhat minimal [57, p. 21].

Chapter VII

RECOMMENDATIONS FOR FURTHER STUDY

7.1 CLAY MORTAR

1. Development of methods on how to improve the workability and to reduce the volumetric drying shrinkage of clay mortar would be beneficial; improvement of these two properties would also improve the property of bond.
2. Development of a method for reducing the effort and time required to prepare a clay mortar mix would be beneficial; the method should be of low-cost, low in technology and readily accessible.
3. Due to the high volumetric drying shrinkage which occurred with the clay mortars, if they are used in stackwall construction, they should at present be restricted to the wall portion only and prohibited in the corners; a mortar with relatively low drying shrinkage and which is compatible with the clay mortar should be used in the corners.

7.2 LIME-SAND MORTAR

1. Research work should be done so as to determine if a remixed mortar with a lime:sand ratio of 1:3 is or can be made compatible in a wall with its original counterpart.
2. Research work should be done so as to determine if the porous nature of lime-sand mortars provides a better insulated stackwall relative to one that is constructed with conventional mortar (see Definitions).

7.3 GENERAL

Using the suggested clay or lime-sand mortar (see Conclusions), wall panel tests of stackwall (see Reference 51 for construction details) should be performed in the laboratory. In such tests, the tensile bond strength, shear strength and compressive strength can be determined more accurately. Adequacy of the walls can also be measured in terms of the degree of shrinkage, behaviour under wetting and drying cycles and, if facilities exist, the behaviour under freezing and thawing cycles. To be more precise, construction of the walls should include the corners [51, pp. 39 to 41] with no artificial confinement. Drysdale and Suter [32, p. 3-8] state that a height-to-thickness ratio in the range of four to five is necessary in the testing of masonry prisms; this is necessary in order to eliminate the effects of the loading arrangement. It is recommended that this height-to-thickness ratio be applied to wall panel tests of stackwall. In terms of the length of wall required, perhaps a length-to-thickness ratio of four to five should also be used.

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