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FINAL REPORT

"ADOBE BUILDINGS IN SEISMIC AREAS:
INNOVATIVE SCIENTIFIC RESEARCH"

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INTRODUCTION

1. BACKGROUND

Earthquakes have always caused large material damage and loss of life, especially in Third World countries where dwellings are made of soil, having generally very low strength.

Research work carried out on the strength of adobe constructions (a bibliographical collection of which is given in Ref.{ 1 }), analize only the characteristics of the adobe brick. However, from the standpoint of seismic behaviour of adobe dwellings, the weak zones of the adobe masonry have been found to be the joints, where adhesion between mortar and brick is a very important factor.

Several publications of studies carried out by the Pontificia Universidad Católica del Perú (PUCP) since 1973 { 2,3 } and by the Universidad Nacional Autónoma de México (UNAM) in 1978 { 4,5 } , have shown important differences in the strength of adobe masonry. A joint PUCP-UNAM research work has shown that, although adobe bricks from both countries had approximately the same compressive and flexural strength, the Mexican adobe masonry had a shear strength about 5 times larger than the Peruvian adobe masonry { 6 } .

Understanding the reasons why adobe masonry is strong or weak is important, since this will allow building adobe dwellings with a significant increase in their seismic resistance. Particularly, it is very important to understand why the Peruvian masonry strength is low, since this will help finding new building methods capable of offering adequate seismic strength level.

2. OBJECTIVES

The objectives of this research project are:

I.- To select a number of Peruvian soils, to obtain their complete physical, chemical and strength characteristics, and to determine their influence on the strength of the adobe masonry.

II.- To conduct laboratory tests aimed at improving the strength of the adobe masonry. It is expected that the results of this investigation will lead to practical recommendations.

III.- To develop strategies for spreading the information amongst people building with adobe.

Accordingly, this investigation has been divided into three parts.

PART 1

"INFLUENCE OF SOIL MATERIAL PROPERTIES OF THE STRENGTH OF ADOBE MASONRY"

1. SELECTION AND CHARACTERISTICS OF THE SOILS

Eigth zones of Peru where adobe construction is traditional were selected and enough samples of soil with different characteristics were collected for laboratory testing. For reference purposes, some Mexican adobe bricks (those used in the research of Ref. (6)) and bricks made in Illinois, USA, were also obtained. However, since it was not possible to analyze the original soil samples from which the Mexican and the Illinois bricks were made and since some Peruvian soils were capable of producing masonry with comparable strength, the Mexican and Illinois adobe bricks were dropped from the study.

After a selection of the different soils available, six soils were chosen for the rest of this investigation. These soils were obtained from the following regions of Peru shown in the map in Figure 1.1

1. Cajamarca
2. Cuzco
3. Huancayo
4. Huaraz
5. Pisco
6. Lima (PUCP)

The main laboratory tests performed are briefly presented in this section (see Appendix 1 for a detailed description).

The reaction of each soil to hydrochloric acid (HCl) and to hydrogen peroxide (H_2O_2) was used to detect the presence of carbonates and organic matter, respectively. Table 1.1 contains the results of these chemical tests and a brief description of the soils.

Chemical characteristics of the soils were determined by standard analysis procedures and results are presented in Table 1.2

The grain size distribution of the soils were determined through two different types of laboratory tests: by centrifuge procedures and by standard sifting. Tables 1.3 and 1.4 show the results of both tests.

Soil analyses were completed by investigating the presence of clay minerals by mineralogical analysis of the clay fraction in each soil by X-Ray diffraction (using CuK_α radiation).

The relative peak heights measured for the clay minerals in each soil is shown in Table 1.5

2. PHYSICAL PROPERTIES OF SOILS

2.1 Atterberg Limits

The Liquid Limit (LL), Plastic Limit (PL) and Shrinkage Limit (SL) of each soil were determined. The Plasticity Index was then computed as PI=LL-PL for all soils, as shown in Table 1.6
The Atterberg Limits were used to classify the soils, each of which was plotted in the Plasticity Chart as shown in Fig. 1.2

2.2 Standard Consistency

In order to control the workability of all mortars used in this research, a method for measuring the consistency of the soil mortars was devised. A steel ball was welded to the rod of a standard Vicat apparatus, used to measure the consistency in cement mortars. The modified Vicat equipment is shown in Fig. 1.3. The consistency of a mortar (k) was defined as the ball penetration (in mm) in the moisted mortar. After testing several soil mortars with different degrees of consistency, the value of 10 mm was adopted as a standard value throughout the investigation. This value corresponds to a workable, slightly dry soil mortar for all samples analysed.

The water content vs. consistency relationship was determined for each soil mortar prior to specimen fabrication. Figures 1.4 to 1.9 show these relationships for the selected soils. It can be seen that the water content vs. consistency relationship is nearly linear within the range of interest for all soils. The water content required for standard consistency (H) was selected as a parameter to characterize the different soils (see Table 1.7).

2.3 Strength of Soils

The strength of the dry soils was measured by means of compressive tests carried out on 1" cubes (performed at the University of California, Berkeley) and 10 cm cubes (performed at PUCP). Flexural tests on adobe bricks were also performed. Test results are summarized in Table 1.8

2.4 Effect of Additives and Treatment on Compressive Strength of Soils

A preliminary study aimed at determining the effect that the addition of small quantities of dispersive agents would have on the compressive strength of 1" cubes made of four types of soil was carried out at UCB. Test results are listed in Table 1.9. The effect of the additives on the water demand at casting is presented in Table 1.10.

The effect of adding sodium chloride (NaCl), calcium chloride (CaCl2), lime and cement to PUC soil was studied. The process known as "sleeping" by which the soil-water mixture is stored for a few days before the bricks are molded, was also investigated. Table 1.11 summarizes the compressive strength found for 1" cubes cast at a constant water-soil ration of 38%.

3. STRENGTH OF THE ADOBE MASONRY

3.1 Brick Manufacturing

The soil for manufacturing was "slept" for two days, following traditional practice in Peru. Afterwards, to guarantee uniformity in the manufacturing process, it was throughly blended using a soil mixer. The bricks were cast using 0.1 x 0.15 x 0.40 m wooden moulds. It was observed that environmental temperature and humidity influenced the drying shrinkage of the bricks. For this reason, the manufacture of bricks was carried out during the fresher hours of the day. Bricks were then dried in the shadow, as shown in Fig. 1.10

A month later, when the bricks were dry, the dimensions were checked in order to compute the volumetric drying shrinkage. It should be noted that this value would also reflect the drying shrinkage of mortar made from the same soil. Results are shown in Table 1.12

3.2 Mechanical Tests

a) Selection of Tests.-

Full scale shear tests on isolated masonry walls provide a good measure of the seismic strength of adobe buildings. However, these tests are generally very expensive and require a large amount of material for specimen manufacture. Therefore, it was decided to perform only a limited number of full scale tests on masonry walls at the end of the investigation, to corroborate the results obtained. Figure 1.11 shows the experimental set-up for the full scale masonry test chosen for this investigation.

Earlier work has shown that the diagonal compression test, performed using small (usually 60 by 60 cm) adobe masonry specimens, offers a good correlation with tests performed on full scale masonry walls, thus providing an adequate measure of the masonry strength [6,7]. For that reason, the diagonal compression test was selected as the basis for comparison in this investigation. A typical diagonal compression test experimental arrangement is shown in Figure 1.12

Two simpler tests, performed on specimens made of only two bricks joined by mortar, were selected to conduct preliminary studies, and for the cases when material was scarse: the direct tension (pull-out) and indirect tension (splitting) tests.

Figures 1.13 and 1.14 show the configuration of the samples and the testing equipment required. The correlation of results obtained from these tests with those obtained using the diagonal compression test will give an indication of the adequacy of these simple and unexpensive tests to evaluate the quality of adobe masonry.

b) Manufacture of Test Specimens.-

In general, each stage of specimen manufacture was carefully controlled and supervised, taking the following precautions:

- Bricks were carefully cleaned from excess sand used as mould release, in order to ensure good bond between mortar and brick.
- Prior to placement, brick surfaces were moistened to a saturated dry condition to minimize the amount of mortar water absorbed by the bricks, thus slowing down the rate of drying shrinkage.
- Horizontal and vertical joints thickness was kept at 15 mm. The consistency of the mortar was controlled at a standard value for all specimens.
- In order to avoid variations in the quality of workmanship, all specimens were manufactured by the same person.

c) Tests Results.-

The results from the diagonal compression, indirect tension and direct tension tests performed on adobe masonry specimens made of each of the selected soils is presented in Table 1.13. Table 1.14 indicates the average coefficient of variation of the results obtained for each type of test.

3.3 Drying Process of the Adobe Masonry

a) Study of the Process.-

The drying process of the soil mortar confined between adobe bricks was studied by preparing adobe masonry sandwiches (similar to those used for the indirect tension test), which were carefully opened at different ages. The following data were then recorded: average mortar water content, maximum crack width and number of cracks crossing two perpendicular 10 cm wires (see Figure 1.15). In order to determine the effect of initial consistency of the mortar on the drying process, specimens were prepared with dry, medium and wet mortars (consistency values of 4, 10 and 18 mm). The curves describing the variation of water content, number of cracks, and maximum crack width with time are shown in Figures 1.16, 1.17 and 1.18

The variation of water content with time during the drying of bricks was also studied. A comparison between the drying process of bricks and mortar is shown in Figure 1.19

b) Effect of Brick Wetting on Masonry Strength.-

The effect of prior wetting of the adobe bricks on masonry strength was investigated by performing indirect tension tests with sandwich specimens manufactured with bricks previously placed in a container with 1 cm of water for different periods of time, as shown in Figure 1.20

Four specimens were made for each wetting time, all of which were tested thirty days later. Results are presented in Figure 1.21

3.4 Effect of Age on Masonry Strength

Indirect tension tests were performed for all soils 30, 90 and 180 days after specimen manufacture, in order to evaluate the influence of age on the strength of the adobe masonry. Table 1.15 shows the test results obtained.

The variation of masonry strength during the first month of drying was studied by performing indirect tension test on specimens made of PUC soil, at different times after specimen manufacture. Figure 1.22 shows the variation of the indirect tension strength with time.

3.5 Preliminary Study of Effect of Additives on Masonry Strength

The effect of additives used for the soil mortar on the masonry strength was studied by performing indirect tension test on specimens made using PUC soil, tested after one month of drying. Lime, cement and manure were used as additives. Test results are summarized in Table 1.16.

4. DISCUSSION OF RESULTS

4.1 Selection of the Criterion for Evaluation of Soils

Before attemping to define the characteristics that a soil should have in order to obtain a good masonry built with bricks and mortar made of the same soil, it is essential to agree upon a criterion which would best reflect the strength of the adobe masonry. The strength of individual bricks cannot be used as a criterion for the strength of the masonry, because the latter is usually controlled by the strength of the joints, that is, by the strength of the

mortar-brick interface. Diagonal compression tests, however, have shown to provide an adequate measure of the full-size adobe wall strength and thus, of the adobe building strength.

The direct tension test is very difficult to perform due to the fragility of the specimens. A large scatter of the results is obtained and the correlation of the direct tension test results with those of the diagonal compression test is not very good, as shown in Figure 1.23. The indirect tension test shows a better correlation witn the diagonal compression test, but has also a large degree of scatter in the results. Figure 1.24 shows the relationship between the indirect tension and diagonal compression test results.

Because of the above mentioned reasons, it was decided to use the diagonal compression test as the criterion for evaluation of soil quality despite the problem that this test consumed more time and materials than the direct and indirect tension tests. Since indirect tension test results provide a rough estimate of the masonry strength, they were performed in this study to conduct preliminary investigations, or when a large number of tests with soils of which not enough sample was available were required.

According to the strength measured in the diagonal compression tests, soils which produced a better masonry where those from Huaraz and Cuzco (0.98 and 0.96 Kg/cm^2) followed by the soils from Pisco and Cajamarca (0.72 and 0.6 Kg/cm^2). The most inadequate soils from the point of view of strength were those from Huancayo Blanco (0.54 Kg/cm^2) and PUC (0.47 Kg/cm^2). See Figure 1.25

4.2 Chemical Characteristics of Soils

No correlation was found between the results of the chemical analyses, organic matter content or pH of the soils and the diagonal compressive strength of the adobe masonry.

4.3 Type and Amount of Clay Minerals in Soils

No direct relationship could be found between the type of clay minerals present in a soil and the diagonal compressive strength of the adobe masonry. The amount of clay minerals present in the soil, as indicated by the relative peak heights shown in the X-Ray diffraction analysis, seems to have some correlation with masonry strength. Huaraz and Cuzco soils, which produced the strongest masonry, showed significant presence of illite and smectite, respectively. Relatively strong peaks corresponding to smectite and kaolinite were observed in the case of the intermediate soils from Pisco and Cajamarca. Finally, soils which produced the weakest masonry, namely PUC and Huancayo Blanco, showed low presence of clay minerals.

4.4 Physical Characteristics

a) Soil Grain Size Distribution.-

The relationship between the grain size analysis of the soil (sand, silt and clay fractions) and strength of the adobe masonry is shown in Figures 1.26 to 1.28.

- Influence of Clay Content:

It can be observed that there is a tendency for strength to decrease with increasing clay content, probably because clay provides the adhesion and plasticity and controls the water demand and thus the

amount of drying shrinkage, the latter being related to the mortar cracking process.

The clay fraction ("clay fraction" refering to all material smaller than 2 microns, even if other materials are present) in the soil has some influence in the plasticity as reflected by the Plasticity Index. However, Cajamarca and Huancayo Blanco soils, having the same amount of "clay" material, have the largest and smallest Plasticity Indexes. Mineralogical analysis of both soils explains this difference in plasticity, revealing that a large amount of kaolinite is present in the Cajamarca soil and that the "clay fraction" of Huancayo Blanco soil is formed mainly by carbonates and organic matter, with only small quantities of illite and kaolinite.

- Influence of Silt Content:
  No defined tendency has been detected with relation to the masonry strength.

- Influence of Sand Content:
  The relationship between sand content and strength is not well defined.

Since it is believed that the coarse size fraction present in the mortar controls the microcracking due to drying shrinkage, it seems that the coarse sand fraction (# 4 mesh size > % sand > # 40 mesh size) would be more relevant to the strength than the total sand content. Figure 1.29 shows the correlation between masonry strength and coarse sand fraction content and it is possible to observe a better correlation than that shown in Figure 1.28 where the comparison parameter is the total sand content.

In summary, it seems that the adobe masonry strength increases with the coarse sand content, and decreases when the the clay fraction increases. The silt fraction content appears to be irrelevant.

b) Atterberg Limits.-

No direct relationship has been found between the Liquid, Plastic and Shrinkage Limits and the strength of the adobe masonry. Figure 1.30 shows the relationship between the Plasticity Index and the strength of the adobe masonry and no defined tendency can be observed between these two parameters.

It should be noted that the Plasticity Index not always indicates the actual plasticity of the soil used to make the mortar, since this index is determined using only the finer fraction of the soil (smaller than # 40 mesh) instead of the whole soil, which could contain an important percentage of coarse material.

c) Water required for a Standard Consistency.-

The amount of water required to obtain a standard consistency for mortars made with soils of low to moderate plasticity (Cuzco, Huancayo Blanco, Huaraz and Pisco) is similar, varying between 18.9 and 20%. For soils showing higher Plasticity (PUC and Cajamarca) about 25% water is required to reach standard consistency. The relationship between water required for standard consistency and the masonry strength is shown in Figure 1.31

It can be observed that the stronger masonry required less water than the weaker ones. However, this is not a clear tendency. For instance, the Huancayo Blanco soil which produces a weak masonry, also requires small quantities of water to reach the

standard consistency. This soil, however, has rather unusual characteristics: it has a very low plasticity (see Figure 1.2) and mortars made with this soil require a water content higher than the Liquid Limit in order to become workable (see Figure 1.6).

The water required for standard consistency explains therefore only part of the phenomenon. Water required by the mortar is a function of the plasticity of the soil, which is responsible for the bond between mortar and bricks, but the behaviour of the masonry as a whole is controlled also by the ability of the mixture to restrain the microcracking due to drying shrinkage, which depends on the amount of coarse material.

Tests devised for this investigation can be used to roughly estimate the plasticity characteristics of the soils. Soils with a large water demand would generally be too plastic and therefore lead to a weak masonry, unless something is done to arrest microcracking due to excessive drying shrinkage.

d) Drying Shrinkage.-

No correlation was found between the Shrinkage Limit of the soil and the strength of the adobe masonry. The shrinkage capacity of the soils can be evaluated directly by carefully measuring the dry adobe bricks. Figure 1.32 shows a good correlation between the volumetric shrinkage of the adobe bricks and the Plasticity Index of the corresponding soil. The relationship between the volumetric shrinkage of the brick and the strength of the masonry is ilustrated in Figure 1.33, in which a clear tendency can be noted: those soils showing no shrinkage problems, tend to produce a better quality masonry.

The cracking caused by the confined shrinkage of the mortar between bricks is therefore one of the most important factors controlling the strength of the masonry. Thus, in order to obtain a strong masonry, it is essential to restrain cracking due to drying shrinkage.

4.5 Drying Process of the Adobe Masonry

a) Drying Process.-

The variation of water content with time measured in the mortar of adobe sandwiches shows that drying of the mortar occurs in two stages: first, a very rapid loss of water which develops within the first ten hours and in which most of the cracking occurs, followed by a second stage of much slower drying, in which water is lost at an almost constant rate.

During the first stage, the loss of water from the mortar seems to be mostly due to absorption by the bricks. The gravitational effect on water loss was apparent in the adobe sandwiches, where the top interface showed consistently more cracking than the bottom interface.

Once a certain moisture equilibrium is reached (correspondig approximately to the Shrinkage Limit), water is lost outwards at a lower rate, due to evaporation. It has been found that following a one month drying period, the water content of the mortar is of the order of 3%.

The drying rate of the adobe brick made of PUC soil, was found to be much slower than that of the mortar made of the same soil.

The drying process for the bricks is basically through evaporation, whereas in the case of mortar, most of the water loss is due to absorption by the adjacent adobe bricks.

It has been observed that if the adobe bricks are dried resting on one of its narrow edges 2 or 3 days after bein manufactured, they are strong enough to be used for masonry construction in one week.

b) Effect of Wetting the Bricks.-

Integration between brick and mortar was significantly improved by wetting the adobe bricks prior to mortar application. Sandwiches made with bricks manufactured with PUC soil and placed in water for 10 minutes, were about 80% stronger (in indirect tension test) than sandwiches made with dry bricks. Wetting of the bricks seems to reduce the amount of water absorbed by the bricks thus decreasing the microcracking of the mortar.

c) Initial Consistency of the Mortar.-

The initial consistency of the mortar had an effect in both the number and size of cracks observed after the adobe sandwiches are opened. It could be observed that, during the first stage of the drying process, dryer mortars lost less water and at a slower rate than mortars with higher initial water content. It seems therefore advisable to make adobe walls using dry (but workable) mortars, since this would reduce both the amount and the rate of water lost by the mortar, thus reducing the number and size of cracks due to drying shrinkage.

4.6 Effect of Age on Strength

From the results of indirect tension tests performed on specimens manufactured with PUC soil, it was found that the masonry strength develops gradually during the first two weeks. Data on the indirect tension tests of specimens manufactured with the six selected soils does not show a significant increase in strength of the adobe masonry after further aging. Therefore, it seems reasonable to assume that adobe masonry under normal drying conditions, develops most of its strength in about two weeks.

4.7 Effect of Additives on Strength

Regarding the strength of adobe bricks, addition of small amounts of sodium carbonate (Na_2CO_3) was found to be effective in increaing the compressive strength of most soils (PUC soil turned out to be the exception). The reason for this increase in strength is possibly due to a better dispersion of clay caused by Na_2CO_3.

The addition of up to 20% lime to mortars made with PUC soil had a negative effect on the indirect tension strength of the masonry. When cement was added to the mortar in small proportions (5% or less) the indirect tension strength of the masonry was not effected. With the additon of 10% of cement, there is an increase in the indirect tension strength of about 60%.* Being cement an expensive material, it was decided to discontinue the study on its use for improving the strength of adobe masonry, considering the large proportion required to attain significant improvement in strength. The incorporation of small amounts of manure to the mortar provides an effective way of improving the strength of adobe masonry (up to 100% in indirect tension tests), probably due to the fact that its

* This increase of strength was obtained by simultaneouly adding coarse sand to PUC soil in 1:1 proportions.

fibers contribute to arrest the growth of the drying shrinkage cracks. The experimental tests have confirmed the adequacy of this traditional technology followed in Perú. It should be noted, however, that when large amounts of manure are incorporated to the soil, the strength is reduced, probably due to the large amount of organic matter or other constituents which may have an adverse effect on the bonding properties of a soil.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

a) The chemical and mineralogical characteristics of the soils do not seem to have any important influence on the strength of the adobe masonry. The content and type of clay present in a soil has an effect on plasticity and dry strength of soil, but there is no direct influence of these properties on the strength of the adobe masonry.

b) Although the presence of some clay is essential to provide plasticity and dry strength to the soil, an excessive amount of clay could be responsible for high drying shrinkage and microcracking of the mortar, which leads to a loss of strength in the masonry. The amount of coarse sand (larger than 0.5 mm) in the soil from which mortar is made is important from the standpoint of masonry strength. Sand in soil has a benefitial effect on the strength of the adobe masonry, since it helps to restrain the drying shrinkage and thus reduce microcracking of the mortar.

c) From the preceding observations, it follows that it should be possible to improve the strength of an adobe masonry reducing microcracking of the mortar, when low strength is caused by micro cracking.

d) The technology used for brick, mortar and masonry manufacturing, also plays an important role in determining the strength of the adobe masonry. Allowing the soil to get saturated with water (sleeping) for a few days before either molding the bricks or making the mortar, could increase the soil strength through proper dispersion of clay minerals. Wetting the bricks surfaces just before the application of mortar is also important, since it prevents rapid drying of the mortar (and subsequent microcracking). As a result of a stronger mortar and brick-mortar interface the components of the masonry are well integrated to form a high strength structure.

5.2 Recommendations

a) Since a large content of coarse sand generally leads to stronger adobe masonry due to reduction in microcracking, it seems reasonable to assume that in the case of soils containing small proportions of coarse sand, the strength of the mortar and thus of the masonry could be increased by adding coarse sand to the mortar. The effect of coarse sand addition to such soils should be investigated during the second stage of this research.

b) Addition of small amounts of manure was found to be effective in increasing the indirect tension strength of adobe masonry. The

ability of fibrous material to arrest the propagation of cracks in other materials in well known. Thus, incorporation of fibers in a soil mortars, either in the form of manure or chopped straw, could reduce microcracking of the mortar and increase the strength of the masonry. It is recommended to investigate the effect of manure or straw additions to mortar on the strength of adobe masonry.

PART II

"IMPROVEMENT OF ADOBE MASONRY CONSTRUCTION"

1. OBJECTIVES

The objectives of the second part of this investigation are:

(1) To conduct a laboratory investigation aiming to improve the strength of adobe masonry by controlling microcracking of the mortar through:

a. Restraining of drying shrinkage by addition of coarse sand to the soil.

b. Arresting the propagation and growth of cracks by addition of straw to the soil.

c. Reducing the rate of drying of the mortar by decreasing the difference in water content between mortar and brick.

(2) To develop practical recommendations for the improvement of adobe construction.

2. LABORATORY TESTING

The effect of addition of coarse sand or straw to PUC soil, used to manufacture adobe bricks and mortar, on the strength of the adobe brick and the adobe masonry was studied. Five full-scale adobe masonry walls were also tested, to corroborate the results obtained.

2.1 Addition of Coarse Sand

The coarse sand used as addition to PUC soil included particles with sizes comprised between 4.75 and 0.6 mm (# 4 and # 30 ASTM mesh sizes); the amount added varied between 30 and 300% of soil volume. The influence of addition of coarse sand to the mortar only, and to both the bricks and the mortar, was investigated. The experimental results obtained are summarized in Table 2.1. The relationship between the total amount of coarse sand present in the soil and the strength of the adobe brick is shown in Figure 2.1; the influence of coarse sand on the indirect tension and the diagonal compression strength of the adobe masonry is presented in Figures 2.2 and 2.3, respectively.

To complement the information obtained, diagonal compression tests were performed with specimens made of each of the five remaining soils, with different amounts of coarse sand added to the mortar only. The test results are shown in Table 2.2 and plotted in Figure 2.4

In order to evaluate the effect of addition of coarse sand on the drying process of the mortar and brick, a series of indirect tension tests, similar to those described in 3.3 and 3.4 of Part I were performed. Figure 2.5 shows the relationship between moisture content of the mortar and time, for samples with and without coarse sand addition. The influence of coarse sand addition on the number and width of cracks developed is presented in Figures 2.6 and 2.7. Figure 2.8 shows the variation of indirect tension strength with wetting time of bricks, prior to laying, using natural

PUC soil with coarse sand addition mortar. Finally, the increase in indirect tension strength of the masonry built with PUC soil with coarse sand addition, during the first month is presented in Figure 2.9

2.2 Addition of Straw

Two types of straw were studied: grass from PUC campus, and ichu straw, brougth from the Peruvian highlands. In both cases, dry straw was used. Ichu straw was chopped to about 10 cm length; grass leaves measured up to about 5 cm, they did not require chopping. The amounts of straw added to PUC soil varied between 0.5 and 4% in weigth. The indirect tension and diagonal compression strength shown by the specimens is recorded in Tables 2.3 and 2.4 respectively, and plotted in Figures 2.10 and 2.11

2.3 Full-Scale Wall Corroboration Tests

Five full-scale PUC adobe masonry walls were tested. Two of the walls were made with mortar and bricks fabricated with PUC soil with addition of ichu straw in a 100:2 weigth relationship. Two walls were made using bricks and mortar of PUC soil mixed with coarse sand in 1:1 volume proportions. The fifth wall was made of standard PUC soil, as a reference to evaluate the increase of strength obtained by the use of straw and sand additions. Figure 2.12 shows the lateral force vs. displacement relationships shown by the five walls. The most relevant data measured in the tests is given in Table 2.5

2.4 Strength of Monolithic Specimens

In order to estimate an upper limit for the strength of the adobe masonry under ideal conditions, diagonal compression tests were performed with monolithic specimens made of each of the selected soils (see Figure 2.13). This upper limit would be reached if a perfect integration between bricks and mortar is obtained. Table 2.6 presents the strength of the monolithic and the improved masonry specimens.

3. DISCUSSION OF THE RESULTS

3.1 Addition of Coarse Sand

As previously noted, the presence of coarse sand is very important from the standpoint of strength of the adobe masonry, since it helps restraining drying shrinkage and thus reduces microcracking which causes lack of bond between the mortar and the adobe bricks.

The effect of adding coarse sand to PUC soil in the indirect tension and diagonal compression strength of the adobe masonry can be observed in Figures 2.2 and 2.3 respectively. The increase of indirect tension strength is of 400% when sand is added to the mortar only (in 1:2.5 proportions) and of about 500% when sand is added to both the mortar and the brick (in 1:2 proportions). The improvements in the strength in diagonal compression are not so dramatic, being of about 100% and 150% when sand is added to the mortar only (1:1.5) and to mortar and brick (1:2), respectively.

It seems obvious that, after the peak, or optimum strength is reached, further addition of sand leads to a decrease in strength due to the lack of bond caused by the smaller percentage of clay in the mortar.

Addition of coarse sand to mortar made of the six selected soils shows also a tendency of the strength of the adobe masonry to increase within a certain range. In no case the addition of sand led to a decrease in masonry strength. The plastic soils, PUC and Cajamarca, showed a large potential to improve the strength of the adobe masonry made with these soils. Sandy or intermediately plastic soils, like Cuzco, Pisco and Huaraz do seem to improve their diagonal compression strength significantly. Huancayo Blanco is a case difficult to explain, since it is a very sandy soil with little plasticity. However, it had an important increment of diagonal compression strength due to addition of coarse sand to the mortar. In all cases, it could be observed that the largest strengths obtained were associated with the elimination of visible cracks in the mortar.

Addition of coarse sand to PUC soil mortar also helped reducing the amount of water required for standard consistency and the time for mortar drying. Furthermore, as evidenced in Figures 2.6 and 2.7 coarse sand addition was effective in reducing the average number and width of the visible cracks in the mortar, with respect to the natural PUC soil (curves shown were interpolated between results obtained for k = 4mm and 18mm as shown in Figures 1.17 and 1.18).

Brick wetting prior to specimen manufacturing improved the indirect tension strength of sandwiches made with PUC soil mortar with 100% coarse sand addition (Figure 2.8). For wetting times of 15 and 60 minutes the corresponding strength improvements were of 30% and 60%. (Similar results were obtained with natural PUC soil).

3.2 Addition of Straw

In many regions of Peru, it is a traditional practice to add straw to the soil used to fabricate adobe bricks. However, straw is either not added to the mortar, or the amount of straw added is very small. Data from the indirect tension and diagonal compression tests, indicate that the addition of straw to the mortar in larger quantities than those traditionally used is effective in improving the strength of the adobe masonry. The quality and size of the straw fibers used has some influence on the strength obtained. For instance, ichu straw chopped to about 10 cm, was more effective that grass leaves, which have a different shape, and measure about 5 cms.

The increase of strengths obtained were of up to 800% for the indirect tension test and up to 150% for the diagonal compression test. These values correspond to 4% and 3% straw added to the mortar. The workability of the mortar seems to limit the amount of straw which can be added to a soil, since for large amounts of straw it is more difficult to mix the mortars properly and in these

cases, the improvement in strength is not optimal (curves shown in Figure 2.11 are not linear and would eventually drop).

An attempt was made to add both sand and ichu straw to the PUC soil mortar. Incorporation of coarse sand to natural PUC soil (1:1) increased the indirect tension strength from 0.21 to 0.32 Kg/cm^2. Addition of both sand and straw (4%) to the mortar led to an increase of indirect tension strength to 1.19 Kg/cm^2, but the workability of the mortar was poorer than in the cases were only one additive was used. The strength obtained using straw only (4%) was significantly higher, 1.76 Kg/cm^2; therefore, the combination of sand and straw conducted to a lower strength masonry. It seems than when straw is added in the appropiate amount, microcracking is controlled, a good integration is obtained between adobe bricks and mortars due to the "sewing' of the interface caused by the ichu straw fibers; addition of sand in those conditions would therefore be at the expense of reducing the amount of clay in the mortar, which provides the strength.

3.3 Full-Scale Walls

These tests are more representative of the actual behaviour of adobe masonry buildings than diagonal compression tests.

The following results were obtained:

a) Addition of coarse sand in 1:1 volume proportions to PUC soil used to make both the adobe bricks and the mortar led to an improvement of shear strength of about 60% with respect to natural PUC soil adobe masonry. The elastic lateral stiffness and apparent

elastic limit were also significantly increased.

It is interesting to compare the cracking patterns observed in the walls (Figures 2.14 and 2.15). In those walls with addition of sand, the cracks tend to cross the adobe bricks, instead of following the joints. This indicates that,although the addition of sand controls microcracking, it weakens the bricks, thus preventing a further increase in the masonry strength. Brick weakening seems to be caused by the decrease in clay content.

b) The effect of adding ichu straw in 2% in weigth to both the PUC soil bricks and mortar produced an increase in the shear strength of the adobe masonry walls of more than 100%. The lateral stiffness and the apparent elastic limit were also significantly increased.

The wall failures occured basically following the joints between bricks (see Figure 2.16). This would mean that adding straw instead of sand is a better practice, since it controls microcracking of the mortar without weakening the bricks.

3.4 Comparison between Masonry and Monolithic Specimens Strength

Addition of sand or straw significantly improve the strength of adobe masonry, as could be proved by testing performed on PUC soil. The wetting technique had not been applied concurrently to those specimens, with which higher strengths could have been obtained.

It could be hoped that values shown in Table 2.6 for masonry could get closer to those for the monolithic specimens, assumed to be the upper limit.

Future research should be carried out regarding this problem. Addition of straw to other soils in higher amounts should also be investigated.

4. CONCLUSIONS

a) Presence of clay in bricks and mortar is fundamental to improve the strength of adobe masonry. Unfortunately, a large amount of clay also entails large microcracking due to drying shrinkage.

b) In order to obtain a better masonry strength with a given soil, microcracking, if it exists, must be controlled.

c) The best way to control microcracking, without decreasing the amount of clay, is to add straw to the soil from which adobe bricks and mortar are manufactured. The recommended quantity is the highest possible, allowing for adequate workability. Addition of straw improves the integration between adobe bricks and mortar by a "sewing" action in the brick-mortar interface. Furthermore, straw would help controlling eventual cracking due to seismic excitations or other external loading.

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d) Addition of coarse sand, especially to soils containing a significant amount of clay, is also benefitial. The optimum amount corresponds approximately to the elimination of most of the visible cracks in the mortar-brick interface.

e) An excessive amount of any of these additives has a negative effect in the strength of the adobe masonry.

f) Most of the increase on adobe masonry strength is due to the inclusion of these additives to the mortar. The amounts employed in the fabrication of adobe bricks can be smaller than those in the mortar (sufficient to prevent cracking due to drying shrinkage).

g) Wetting the adobe bricks prior to placing leads to a significant increase in the masonry strength.

5. REMARKS

a) This investigation was prompted by the difference in strength between adobe masonry made in Perú and Mexico. This difference could be explained now by the following three reasons:

- Addition of coarse sand to natural soil. This study has shown that addition of coarse sand to some soils, such as PUC, can lead to an increase in the masonry strength of up to 150%.

- Quality of workmanship. Improved workmanship could be responsible in some cases for an increase of the adobe masonry strength of up to 100%. (Table 2.7 shows the case of PUC soil).

- Diagonal compression test set up. Results from different laboratory test indicate that the dimensions of the metalic angular pieces used to apply the load have a significant influence on the measured strength of the specimen. Equipment with different characteristics were used in Peru and Mexico during the cooperative investigation.

b) The improvements on the strength of adobe masonry by the use of mortars made with cement and sand mixtures, with or without lime and gypsum are presented in Ref. {8,9}. They are of the order of about 100% to 150% with respect to the strength of masonry made with PUC soil. It is noteworthy to observe that the same order of magnitude of improvement has been attained during this investigation, by using cheaper, natural additives, such as straw or coarse sand.

6. FIELD PRACTICE

6.1 Field Tests

One of the main objectives of this project is to culminate in practical and simple recommendations, easy to understand for the people who build their own adobe houses, unskilled workers, etc.

a) Field Tests used for Soil Selection. -
During the soil recollection period a series of field tests were made to select the soils. These tests were extracted from the literature {10}. Appendix 2 contains a detailed explanation of each field test.

Table 2.8 shows the field test results obtained for the soils selected. These results were compared with performing the same tests in the laboratory, and with the soil properties determined by standard laboratory tests.

Most of the field tests performed are devised for evaluation of the plasticity of the material. They are performed with the soil fraction smaller than .425 mm (# 40 mesh). The brightness, dilatancy, adhesion to instruments and hand wash did not give consistent results. The ribbon test was inadequate, since it gave the same result (short ribbon) for all soils except the most plastic, Cajamarca. The adhesion to hands test gave erratic results for most soils. The toughness test provided very satisfactory results, showing a good correlation with the Plasticity Index, as shown in Figure 2.20

The granulometry of the soil was roughly estimated with the bottle test. This test is quite simple to perform, but only gives satisfactory results for soils without continuous gradation. There are cases in which is not possible to evaluate satisfactorily the amounts of the different particle sizes.

The dry strength of the soil was evaluated through simple compression of 10 cm cubes, obtained from adobe bricks. The results measured in the field were erratical, mainly because it was difficult to fabricate specimens with regular geometry (parallel faces, plane surfaces, etc.).

The presence of organic matter was detected by the odor and color of the soil.

It is possible to conclude that the only acceptable test in the toughness test; however, this test provides correct results only after gaining experience by performing the test many times with soils with known characteristics. A further inconvenience is that the material must be sifted through a # 40 mesh, available only in specialized laboratories.

b) Developed Tests.-

According to the conclusions of Part II of this investigation, two field tests were developed:

- Dry strength test: the test consists on manufacturing 3 or more little balls of soil, of approximately 1" (2.5 cm) diameter. They should dry for 24 hours. Once dry, each ball is crushed between the thumb and the index finger. If the balls are so strong that none can be broken, the soil has the sufficient presence of clay to be used for adobe construction, provided that micro-cracking due to drying shrinkage is appropiated taken care of by adequate additions. The stronger the ball the better the soil for adobe masonry construction.

  If all the balls are broken, the soil is inadequate, since it lacks enough clay.

  If one some of balls can be crushed, the test should be repeated. If the same result is obtained, the soil should be discarded.

This is a very simple and quite reliable test, as has been demonstrated by comparative laboratory tests. Table 2.9 shows the results obtained with the six soils selected for this study.

Test of cracking control: the test consists on fabricating 8 sandwiches (two bricks joined by mortar made on the soil to be studied) using existing adobe bricks. The mortar used in each sandwich is prepared by mixing the soil with coarse sand (0.5 to 5 mm approximately), in the following proportions:

Specimen #	Proportions Soil : Sand
1	1:0
2	1:0.25
3	1:0.5
4	1:1
5	1:1.5
6	1:2
7	1:2.5
8	1:3

After 48 hours of drying in the shadow, the sandwiches are carefully opened and the mortar is examined. The sandwich with least amount of sand without visible cracks indicates the most adequate soil: sand proportion for adobe masonry construction. This test has been corroborated with the six selected soils, by the evaluation of several observers.

6.2 Practical Field Recommendations

a) Selection and Amount of Additives.-

This study has shown that clay is the most important component of soil from the standpoint of strength of adobe masonry and the most efficient additive for improvement of the quality of the adobe masonry is straw.

Accordingly, the following procedure for selecting and improving a give soil is recommended.

- Perform the dry strength test.
- If the soil is found to be acceptable, add to the soil-water mixture, specially to that used for making mortar, the maximum amount of straw which allows for an acceptable workability. If straw is not available, coarse sand should be used as additive. The soil-sand proportions most adequate is determined by the cracking control test.

b) Construction Procedure.-

- It is recommended that adobe bricks should be wetted (at least the two horizontal faces) before laying the walls, by placing them on 1/2 to 1 cm of water for 10 to 15 minutes, or saturating them by another procedure.
- It is recommended to use the bricks after manufacturing as soon as they have acquired sufficient strength to be properly handled. (They would have a higher water content, thus reducing the amount of water absorbed from the mortar).

- Other recommendations for the construction of adobe masonry are: elimination of foreign objects from the soil, uniform mixing, drying the adobe bricks in the shadow, cleaning the bricks before laying, uniform joints, vertical walls.

PART III

"STRATEGIES FOR THE DISSEMINATION OF ADOBE TECHNOLOGY"

1. PRELIMINARY CONSIDERATIONS

In order to establish a realistic strategy for the dissemination of techniques for improved construction with adobe, a team of Anthropologists and Sociologists from PUC carried out a field survey in representative regions of Peru. The following zones were visited to obtain local information and to study the most appropiate communication channels, according to the social organization.

Urban zones : Lima, Arequipa and Piura
Rural zones : Cuzco, Junín, Puno and Ayacucho

The location of these regions is shown in the map of Peru (Fig. 3.1).

The 1980 National Population and Housing Census showed the existence of about 3'300,000 houses for a Peruvian population of 17 million. Only 44% of the dwellings could be described as adequate. 1'576,000 were adobe houses, 767,000 located in urban areas and 809,000 in rural areas.

The number of houses increased during the inter-census period 1972 - 1981 with an average annual rate of 2%. This is a slow rate, compared to the 3.8% rate measured during the 1961 - 1972 period. This fact indicates a direct relationship between income and quality of housing.

Income, which depends on the working conditions of each head of family, has dropped in almost 50% during the last 10 years. As a consequence, there is a decrease in the buying capacity of the families, and thus a lower tendency to save for the construction of a dwelling.

Table 3.1 describes the distribution of adobe housing in the regions surveyed during the study. The Puno, Cuzco, Junín and Ayacucho regions, located in the andean highlands, have the largest percentage of adobe houses in both the urban and rural areas. In Arequipa, located also in the highlands, the most popular building material is "sillar", a soft volcanic rock, abundant in the area. Most of the population of Lima and Piura are concentrated in the coastal region.

2. DISSEMINATION OF TECHNOLOGY IN PREDOMINANTLY LITERATE COMMUNITIES

The most representative indicator for literate areas within an urban zone is the Metropolitan Lima region and its surrounding shanty towns. In this area, there are 294 "Pueblos Jóvenes" (shanty towns). Of these, only 119 have a complete basic infrastructure necessary for the construction of housing.

Although most of the inhabitants of these shanty towns have scarce economic resources, the large expansion of their urbanization process can be explained through the nature of their social organization, which promote communal activities. The establishment of most of the shanty towns around Lima and the main cities of Perú occured basically in the following stages:

- Organization of groups of people for invasion of unoccupied land.
- Struggle with local authorities to obtain legal property of the land and installation of the basic utilities (water, sewage, electricity).
- Organization for the defense of other communal interests.

In summary, the "Pueblos Jóvenes" constitute a socially organized population, formed mainly by immigrants. Physically, they present a progressive, relatively slow urban development, lasting in average about 10 years. Economically, the population generally corresponds to the lowest income levels.

The information gathered in the survey showed that there is a significant resistance of the dwellers of the "Pueblos Jóvenes" around the principal cities of Peru to accept the idea of building with adobe. They prefer to make important economic sacrifices, and build with materials such as masonry and reinforced concrete, which would also involve a sign of prestige among the community. This situation does not seem to appear in smaller urban areas ("caseríos o anexos") in which adobe construction, being the most important alternative, is accepted.

The following alternatives seem feasible from the standpoint of dissemination of technology among these communities, taking into consideration the available information channels:

- To embark upon a large-scale dissemination task among the adobe masons or "adoberos".
- To make use of traditional, permanent institutions such as the "Asociaciones Vecinales" (Neighborhood Associations).
- To provide training courses, similar to those offered by SENCICO, an Institution related to the building industry, which promotes and finances courses for semi-qualified personal.
- To use the facilities provided by the educational entities operating in the selected areas, such as the ESEPS (Professional Education High Schools).

- To develop support programs to persons desiring to build their houses, in coordination with the "Banco de Materiales" (Materials Bank). This is a Government Agency which gives loans in building materials to head of families of scarce resources, living mainly in the marginal zones or "Pueblos Jóvenes".
- To design radio "micro programs" (lasting 1 to 2 minutes) to be broadcasted in the stations which usually transmit folkloric music. The purpose of these programs would be mainly to inform the listeners about the availability of information for better construction with local materials.
- To make contact with the Regional Associations, which represent the migrating Peruvian population.
- To work in coordination with all the institutions which would be currently working in the shanty towns, such as public or private institutions, Universities (through their social service programs) and others.

3. DISSEMINATION OF TECHNOLOGY IN PREDOMINANTLY ILLITERATE AREAS

The problem of dissemination of building technology in rural areas of Peru is related to the characteristics of the agricultural hamlets or towns. There are three basic types of settlements in the rural areas of Peru:

- Nuclear: Concentration of dwellings around a central plaza or square. The cultivated fields ("chacras") are located in the periphery, the dwellings being located centrally, on small lots.

- Disperse Nuclear: Concentration of a part of the population around a central plaza; the rest being scattered around the whole of communal grounds, with houses in the chacras.
- Disperse: Dwellings are scattered in both, the communal grounds and the "chacras".

Most of the rural settlements in Peru can be basically described as nuclear or disperse nuclear. The first one is most favourable from the point of view of performing dissemination and mobilization activities.

The rural dwellers are generally organized according to democratic principles of participation, education, integration and planification. The participation of the population in communal and other activities can be categorized in two basic fields:

- "Traditional Activities": These are exclusively communal activities performed using the most typical ways of organization: the "cargos", "asambleas" and communal work such as "minka", "faena", etc. Fig. 3.2 shows an example of "minka": members of a community of Puno engaged in preparing the soil for adobe brick fabrication.
- "Modern Activities": These are derived from the penetration of the so called "national culture" in the environment of the communities. They are, for example, the participation on Agricultural Associations or Organizations and the attendance to training courses.

The analysis of the information obtained has identified the following alternatives for the dissemination of adobe construction technology in the rural regions of Peru.

- To take advantage of the communities network already established through the Agricultural Associations (Asociaciones Agrarias), responsible for the organization of the agricultural production and commercialization, which are the most important activities in the rural areas.

- To teach the people through the Schools and other Educational Centers operating within the rural environment.

- To develop audio-visual methods for teaching in the native language. To design broadcasting programs, in native languages, including interviews to technically skilled local people.

- To distribute dissemination booklets and complementary material among the literate members of the communities.

- To take advantage of the facilities existing on the Municipalities.

- To encourage the creation and development of communal workshops on adobe construction.

- To make contact with the religious groups which are currently developing programs on Integral Rural Development.

- To coordinate the work of dissemination with the most prestigious Communal Organizations.

4. CASE OF AN EMERGENCY ZONE: PIURA

As it is already known (October 1983), the situation of the physical and social structures of the city of Piura have been seriously affected, due to heavy rains and floods, which occured in the period comprised between November 1982 and June 1983. This situation has deteriorated due to the

lack of coordination within the different institutions which operate in the area.

The research team planned a field observation trip to that zone, which allowed the recollection of first-hand information and data. Their main observation were:

- As of the 1st. of July 1983, according to the statistics of the Piura Commission for Population and Health of the Concejo Provincial de Piura, out of a total of 9,249 families, 92.97% lost their dwellings and 7.03% suffered relatively minor damage.
- 90.3% of the families which lost their houses belong to urban marginal settlements; most of them in the "Pueblos Jóvenes' of Nueva Esperanza, San Martín, Los Algarrobos and Micaela Bastidas.
- As of April 1983, it was estimated that about 15,000 houses were partially or totally destroyed by the rains and the resulting floods. There is no statistical information referred to May and June of this year, during which the rains continued.
- Most of the houses destroyed were made of adobe.
- As a result of this situation, the general consensus of the population of Piura now, is to mistrust adobe houses, due to their failure during the rain period. It is therefore urgent to rebuild the trust in an improved adobe construction, to recover the possibility of building suitable dwellings at a reasonable cost, in accordance to their income levels.

The best way to disseminate improved adobe technology in the emergency zone seems to be to work in coordination with the agencies and organizations already operating in the zone towards ressettling of communities or reconstruction of buildings. The research team has already established a number of contacts, the most important of which are:

- INADE : National Institute for Development.
- CORPIURA : The Government Agency in charge of the reconstruction of Northern Peru.
- SENCICO : State Agency for construction personnel training, through the local Piura Office.
- INCOOP : The National Institute of Cooperative Associations (Cooperativas).
- Banco de Materiales : Official Bank with soft loans in materials.
- ININVI : National Institute for Research in Housing.
- CARE : Institution for Community service, with experience in emergency situations.
- Cooperación Popular : Political government institution, established to organize and promote communal work.

Considering that some of the severely affected areas of Bajo Piura such as La Arena, Unión, etc. have a deeply rooted tradition of adobe construction, we consider them to be suitable areas for developing and disseminating and reconstruction project.

5. CONCLUSIONS

The field work developed was efficient in reformulating ideas about dissemination of adobe construction technology in rural and urban zones.

The available possibilities for dissemination are extremely varied, they seem to complement each other and depend on each particular situation or case. There does not seem to be a "unique solution". The recommended action must be multiple.

Within the urban context, methodology is more uniform and is geared mainly towards a literate user. The most appropiate methods are:

- Radio and television programs, complemented with a correspondence service (consultation by mail).
- Development of training courses for masons (adoberos). Institutionalization of some kind of diploma of recognition or official certificate of achievement. Specialized booklet.
- Community courses in adult schools, technical schools, neighborhood associations, housing associations, savings associations, etc. Popular booklet.

Since in urban zones the use of adoberos or masons is more generalized, the programs directed to the community must have as its main objective the improvement of the acceptance of adobe construction, based on an improved adobe technology. This last one should be very simple, avoiding too many specialized details to allow as many people as possible to understand it.

Within the rural context, the methodology would be much more varied, depending on the traditions of the communities:

- Courses for adobe masons and general public, through the agrarian associations or cooperative associations. Courses within the existent agricultural education programs and distribution of technical booklets.

- Radio programs.
- Distribution of "popular" booklets, through the goverment institutions, such as CORDES, religious institutions, etc.

The most effective dissemination should be made in places where there would be a larger potential for construction at the moment. Therefore, it seems especially convenient to develop accelerated educational programs in the zones of rehabilitation of natural disasters.

FINAL CONCLUSIONS

In accordance to the objectives of this study, the research program was divided in three parts. A number of significant conclusions were obtained at each stage of the study; they are presented at the end of each part of this report. In order to present an overall view of what has been learned during this project, the most relevant findings and conclusions obtained are summarized next.

1. It has been confirmed that the seismic strength of adobe masonry is primarily controlled by the adhesion between mortar and bricks, i.e. by the strength of the joints. It must be recognized, however, that in the cases in which there is a good bond between mortar and bricks, the strength of the masonry could be controlled by the strength of the adobe bricks.

2. The chemical and mineralogical properties of soil used for adobe masonry construction do not have a significative influence on the strength of the adobe masonry.

3. The presence of clay in soil is fundamental, since it provides plasticity to the soil-water mixture used to manufacture bricks and mortar, and strength to the dry material. However, a large amount of clay in the soil also leads to significant amounts of drying shrinkage.

4. Microcracking of the mortar due to drying shrinkage generally leads to lack of bond between mortar and bricks, and thus to a poor strength of the adobe masonry. In order to build strong adobe masonry, it is therefore essential to reduce microcracking of the mortar due to drying shrinkage.

5. The most efficient way to control microcracking due to drying shrinkage is to add straw to the soil-water mixture. The optimal amount of straw to be added is the largest that allows for reasonable workability.

6. The presence of coarse sand in the soil has been found to help restraining drying shrinkage. Strength of adobe masonry made with soils containing small amounts of coarse sand can be improved (although not as much as with addition of straw) by proper addition of coarse sand. The optimal amount to be added is associated with the elimination of visible cracks in samples in which the brick-mortar interface can be observed.

7. Strength of adobe masonry can be significantly increased by an adequate construction technology. For instance, storing the soil-water mixture for a few days before adobe brick or mortar manufacturing ("sleeping"), wetting the adobe bricks before laying, and careful workmanship have shown to be effective in improving the strength of the adobe masonry.

8. It is possible to devise simple field tests for selection of soils adequate for adobe masonry construction and for determination of the required amount of straw or sand for control of microcracking of the mortar due to drying shrinkage. Two of these tests are recommended in this study. They do not require instrumentation or a great deal of previous experience to be succesfully performed. Hence, they appear to be easily transmitted to the adobe builders.

9. A number of strategies for the dissemination of adobe technology have been explored. It has been detected that clearly distinct approaches have to be taken for rural and urban communities. Accordingly, general recommendations have been made for dissemination of adobe technology for each of these cases. It is clear, however, that application of these recommendations has to be done taking into account the social reality for each particular zone. It is apparent that disaster areas undergoing the rehabilitation stages offer an opportunity for the introduction of new, improved technologies for adobe construction.

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TABLE 1.1

SOIL DESCRIPTION

SOIL NAME	IDENTIFICATION CODE	COLOR	Reaction with Hc1	H202	REMARKS
Cajamarca	C	Reddish	Strong	Slight	Very plastic
Cuzco	CO	Reddish-brown	Medium	Slight	Silty sand with clay
Huancayo Blanco	HB	Pale,whitish grey	Strong	Strong	Not plastic
Huaraz	HZ	Greenish-grey brown	None	Moderate	With straw, from adobe
Pisco	PO	Brownish	Strong	None	Sandy, from adobe
PUC	P	Greyish brown	None	Moderate	Loose, modules

TABLE 1.2

CHEMICAL COMPOSITION OF THE SOILS

SOIL	SiO_2	%			
		Fe_2O_3	Al_2O_3	CaO	MgO
Cajamarca	57.81	1.27	4.78	traces	6.19
Cuzco	63.34	3.50	6.20	9.29	1.17
Huancayo B.	58.35	5.45	7.13	10.19	5.48
Huaraz	60.10	2.80	10.0	1.15	1.55
Pisco	53.55	3.65	10.18	7.65	1.35
PUC	54.72	4.90	11.96	4.18	2.00

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(continued) TABLE 1.2

SOIL	PPM		%		
	SO_4^{-2}	Cl^-	Soluble salts	Organic matter	Ph
CAJAMARCA	traces	5	88	12.36	6.70
CUZCO	47	10	195	7.05	7.85
HUANCAYO B.	167	338	1510	8.77	7.95
HUARAZ	41	9	232	6.81	7.7
PISCO	135	139	516	8.67	6.8
PUC	74	10	383	6.20	6.5

TABLE 1.3

SIZE FRACTION ANALYSIS (%)

SOIL	Total sand	Total Silt	Total Clay	Coarse Sand
CAJAMARCA	39	33	28	8
CUZCO	41	50	9	20
HUANCAYO	52	20	28	15
HUARAZ	53	25	22	30
PISCO	59	29	12	11
PUC	35	20	45	11

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TABLE 1.4

PARTICLE SIZE DISTRIBUTION BY SIEVE ANALYSIS

SOIL	Accumulated Retained %							
	Sieve (mm) 4 (4.75)	8 (2.36)	16 (1.18)	30 (0.50)	50 (0.30)	100 (0.15)	140 (0.106)	200 (0.075)
Cajamarca	0.0	1.9	3.5	5.5	10.9	24.6	32.4	39.0
Cuzco	2.9	9.8	15.1	18.6	23.9	29.8	33.9	40.8
Huancayo B.	0.6	2.1	4.2	9.4	21.9	36.5	43.5	52.1
Huaraz	1.1	9.1	17.6	26.6	34.1	42.6	46.9	53.3
Pisco	0.0	0.0	0.7	10.0	15.3	26.5	48.4	59.0
PUC	0.7	2.4	4.5	6.9	15.9	25.6	30.3	34.6

TABLE 1.5

RELATIVE PEAK HEIGHTS OF CLAY MINERALS PRESENT BY X-RAY DIFRACTION

SOIL	SMECTITE	ILLITE	KAOLINITE
Cajamarca	None	Weak	Strong
Cuzco	Very Strong	Medium	Medium
Huancayo B.	None	Weak	Weak
Huaraz	Weak	Very Strong	Strong
Pisco	Strong	Weak	Weak
PUC	Medium	Medium	Weak

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TABLE 1.6

ATTERBERG LIMITS AND SOIL CLASSIFICATION

SOIL	LL	PL	PI	SL	CLASSIFICATION
CAJAMARCA	28	11	17	9	CL
CUZCO	19	15	4	16	CL-ML
HUANCAYO B.	16	14	2	15	ML
HUARAZ	27	18	9	14	CL
PISCO	21	13	8	14	CL
PUC	27	15	12	14	CL

TABLE 1.7

WATER REQUIRED FOR STANDARD CONSISTENCY

SOIL	H %
CAJAMARCA	26.0
CUZCO	18.9
HUANCAYO B.	19.6
HUARAZ	19.8
PISCO	20.0
PUC	25.1

TABLE 1.8

DRY SOIL STRENGTH (Kg/cm^2)

SOIL	Compressive Strength (1" cubes)	Compressive Strength (10cm.cubes)	Flexural Strength
Cajamarca	39.6	37.2	7.4
Cuzco	31.3	20.4	6.1
Huancayo B.	8.7	18.5	5.6
Huaraz	34.2	18.8	7.0
Pisco	20.5	19.9	9.4
PUC	29.6	22.5	8.2

TABLE 1.9

EFFECT OF ADDITIONS ON COMPRESSIVE STRENGTH (Kg/cm^2)

SOIL	100% Soil	5% Cement	5% CaO	0.1% Na_2CO_3
Cuzco	31.3	10.7	11.5	37.3
Huancayo B.	8.7	10.3	5.3	12.9
Huaraz	34.2	11.1	9.2	36.6
PUC	29.6	11.3	6.1	25.3

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TABLE 1.10

WATER CONTENT AT CASTING (%)

SOIL	100% Soil	5% Cement	5% CaO	0.1% Na_2CO_3
CUZCO	25.1	30.3	31.6	23.1
HUANCAYO B.	23.3	25.3	27.3	23.3
HUARAZ	30.1	37.3	37.0	30.8
PUC	38.0	38.9	38.9	38.0

TABLE 1.11

EFFECT OF ADMIXTURE/TREATMENT ON COMPRESSIVE STRENGTH OF PUC SOIL

SAMPLE	STRENGTH
100 %	29.6
5 %	11.3
5 %	6.1
0.1 %	25.3
0.1 %	26.5
0.1 %	28.6
"Sleeping"	32.5

TABLE 1.12

VOLUMETRIC DRYING SHRINKAGE OF ADOBE BRICKS

Initial Dimensions: 10 x 15 x 40 cm
Initial Volume : 6000 cm^3

SOIL	Final Dimensions (cm)			Final	%
	Length	Thick	Heigth	Vol.(cm^3)	Shrinkage
CAJAMARCA	37.3	13.0	9.0	4637	22.7
CUZCO	39.2	14.7	9.4	5437	9.4
HUANCAYO	*	*	*	*	*
HUARAZ	38.7	14.5	9.3	5187	13.5
PISCO	38.5	14.6	9.4	5287	11.9
PUC	38.1	14.3	9.1	4959	17.4

* Due to shortage of this soil, no bricks were fabricated.

TABLE 1.13

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STRENGTH OF ADOBE MASONRY

SOIL	Sigma d (Kg/cm^2)	Sigma i (Kg/cm^2)	Sigma m (Kg/cm^2)
CAJAMARCA	0.26	0.51	0.60
CUZCO	0.76	0.81	0.96
HUANCAYO	*	0.54**	0.54**
HUARAZ	0.46	0.52	0.98
PISCO	0.27	0.42	0.72
PUC	0.12	0.21	0.47

* Test not performed.

** Specimen made using a mixture of two Huancayo Soils, for the bricks and Huancayo Blanco for the Mortar.

TABLE 1.14

COEFFICIENT OF VARIATION TESTS ON ADOBE MASONRY

Test	Coefficient of Variation (%)
Diagonal Compression	9.0
Indirect Tension	19.4
Direct Tension	29.9

TABLE 1.15

EFFECT OF AGE ON STRENGTH OF ADOBE MASONRY

SOIL	Direct Tension			Indirect Tension		
	30	90	180	30	90	180
CAJAMARCA	0.26	0.16	***	0.51	0.35	***
CUZCO	0.76	0.83	0.54	0.81	0.80	0.73
HUANCAYO	*	*	*	0.54**	0.41**	0.51**
HUARAZ	0.46	0.46	0.47	0.52	0.66	0.72
PISCO	0.27	0.26	0.20	0.42	0.42	0.33
PUC	0.12	0.09	0.11	0.21	0.26	0.23

* No test were performed, due to fragility of samples made of HB.

** Specimen made using a mixture of two Huancayo soils for the bricks, and Huancayo Blanco for the mortar.

*** Test not performed.

TABLE 1.16

EFFECT OF ADDITION OF LIME AND MANURE TO PUC SOIL

% Lime (in weight)	Sigma i (Kg/cm^2)	% Manure (in weight)	Sigma i (Kg/cm^2)
0%	0.21	0%	0.21
5%	0.15	2%	0.40
10%	0.14	5%	0.36
20%	0.13	10%	0.31

(continued) TABLE 1.16

EFFECT OF ADDITION OF COARSE SAND TO PUC SOIL

PUC SOIL		PUC SOIL-COARSE SAND 1:1	
% Cement (in weight)	σ_i (Kg/cm^2)	% Cement (in weight)	σ_i (Kg/cm^2)
0	0.21	0	0.32
2.5	0.17	2.5	0.22
5	0.20	5	0.34
10	0.22	10	0.50

TABLE 2.1

EFFECT OF ADDITION OF COARSE SAND TO PUC SOIL

		Brick	Mortar				Brick and Mortar	
Soil: Coarse Sand Proportions	% > Sieve # 40	σ_c (Kg/cm^2)	σ_i (Kg/cm^2)	σ_m (Kg/cm^2)	Visible cracking	Max.crack width (mm)	σ_i (Kg/cm^2)	σ_m (Kg/cm^2)
1:0	11	22.5	0.21	0.47	very cracked	1.5	0.21	0.47
1:0.3	31.5	*	0.23	0.57	very cracked	1.4	*	*
1:0.5	40.7	22.6	0.30	0.77	cracked	0.8	0.72	1.08
1:1.0	55.5	17.9	0.32	1.01	few cracks	0.4	0.87	1.17
1:1.5	64.4	14.7	0.67	1.08	very few cracks	0.3	1.24	1.09
1:2.0	70.3	12.8	0.72	1.03	none	---	1.38	1.28
1:2.5	74.6	11.4	1.06	1.01	none	---	0.85	1.07
1:3.0	77.8	*	0.96	0.95	none	---	*	*

* Test not performed.

TABLE 2.2

EFFECT OF ADDITION OF COARSE SAND TO MORTARS MADE WITH DIFFERENT SOILS

CAJAMARCA					CUZCO					HUANCAYO BLANCO				
arse opor	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)	Propor tion	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)	Propor tion	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)
	8	0.50	very cracked	4.0	1:0	20	0.96	cracked	0.5	1:0	15	0.54	few	0.3
	54	1.31	very cracked	1.5	1:0.2	33.3	0.98	cracked	0.3	1:0.5	43.3	0.96	very few	0.1
	59.3	1.29	cracked	0.8	1:0.5	46.7	0.90	few cracks	0.3	1:1	57.5	1.11	none	---
	77.0	1.07	few cracks	0.1	1:1.33	65.7	0.97	none	---					

(CONTINUED) TABLE 2.2

EFFECT OF ADDITION OF COARSE SAND TO MORTARS MADE WITH DIFFERENT SOILS

	HUARAZ				PISCO					PUC				
arse por	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)	Proportion	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)	Proportion	% > # 40	σ_m (Kg/cm^2)	Visible cracking	Max.Crack Width (mm)
	30	0.98	cracked	1.6	1:0	11	0.72	very cracked	1.4	1:0	11	0.47	very cracked	1.5
2	41.7	1.02	cracked	0.5	1:0.5	40.7	0.72	cracked	0.4	1:0.3	31.5	0.57	very cracked	1.4
5	56.3	1:14	cracked	0.5	1:1	55.5	0.79	few cracks	0.1	1:0.5	40.7	0.77	cracked	0.8
					1:2	70.3	0.66	none	---	1:1	55.5	1.01	few cracks	0.4
										1:15	64.4	1.08	very few cracks	0.3
										1:2	70.3	1.03	none	---
										1:2.5	74.6	1.01	none	---
										1:3	77.8	0.95	none	---

TABLE 2.3

EFFECT OF ADDITION OF STRAW TO PUC SOIL MORTARS

	PUC + Ichu		PUC + Grass	
Soil:Straw Proportions	σi (Kg/cm^2)	σm (Kg/cm^2)	σi (Kg/cm^2)	σm (Kg/cm^2)
100:0	0.21	0.47	0.21	0.47
100:0.5	0.74	0.93	0.51	0.81
100:1	1.02	1.09	0.83	0.83
100:2	1.76	1.21	0.86	1.18
100:3	1.58	1.32	1.12	1.23
100:4	1.76	*	1.31	*

* Test not performed.

TABLE 2.4

EFFECT OF ADDITION OF STRAW TO PUC SOIL BRICK AND MORTAR

	PUC + Ichu		PUC + Grass	
Soil:Straw Proportions	σ_i (Kg/cm^2)	σ_m (Kg/cm^2)	σ_i (Kg/cm^2)	σ_m (Kg/cm^2)
100:0	0.21	0.47	0.21	0.47
100:4	1.58	1.54	1.39	1.12
100:8	0.52	1.30	1.34	1.02

TABLE 2.5

DIAGONAL COMPRESSION TESTS ON FULL-SCALE WALLS

MATERIALS FOR BRICK AND MORTAR	PUC	PUC-Ichu 100:2		PUC-Coarse Sand 1:1	
Wall	#1	#1	#2	#1	#2
Age (days)	33	26	31	16	31
Maximum Diagonal Load (Kg)	2949	6178	6225	4570	4975
Deformation of Diagonal in Compression at Maximum Load (mm)	3.27	1.87	2.85	1.67	1.28
Deformation of Diagonal in Tension at Maximum Load (mm)	1.28	1.04	1.28	1.28	0.71
Maximum Lateral Load (Kg)	2085	4368	4402	3231	3518
Lateral Displacement at Maximum Load (mm) Height from base					
- 194.5 cm.	8.86	5.39	5.15	4.10	5.14
- 121.0 cm.	5.15	3.66	3.61	3.09	3.50
- 47.5 cm.	0.79	1.04	0.91	0.76	1.73
Shear Modulus (Kg/cm^2)	1091	1608	1330	2398	2191

TABLE 2.6

DIAGONAL COMPRESSION STRENGTH OF IMPROVED MASONRY AND MONOLITHIC SPECIMENS

SOIL	Natural Soil	Addition of Coarse:Sand	Addition of Straw	Monolithic Specimens
C	0.60	1.68 (1:2.5)	0.79* (0.8%)	5.46
CO	0.96	0.98 (1:0.2)	**	3.09
HB	0.54	1.11 (1:1)	**	**
HZ	0.98	1.14 (1:0.6)	**	2.61
PO	0.72	0.79 (1:1)	**	2.36
P	0.47	1.28 (1:2)	1.54 (4%)	2.29

* Only a very small amount of straw was employed.

** Test not performed.

TABLE 2.7

POSSIBLE EXPLANATION FOR THE DIFFERENCE OF STRENGTH OBSERVED FOR PERUVIAN AND MEXICAN MASONRY.

Description	Diagonal Compression Strength (Kg/cm^2)
Traditional adobe masonry, PUC soil, no additives.	0.23*
Adobe masonry fabricated under laboratory conditions** PUC soil, no additives	0.47
Adobe masonry fabricated under laboratory conditions, PUC soil + coarse sand (1:2 proportions).	1.28
Adobe masonry fabricated under laboratory conditions**, mixture of Mexican soils with coarse sand.	1.4

* Average from tests performed in the Perú-Mexico Cooperative Research Program.

** Peruvian quality of workmanship (during this study) was better than Mexican.

TABLE 2.8

FIELD TESTS (1st. STAGE)

Color	Odor Organic Matter	Brightness	Hand Washing	Dilatancy	Toughness	Ribbon	Adhesion to hands	Adhesion to instruments	Granulometry
Greyish brown	No	Opaque	sandy	weak	medium	short	medium	medium	52%
Greyish brown	No	Opaque	silty	none	none	very short	weak	weak	70%
Brown	No	Opaque	sandy	none	weak	short	weak	medium	47%
Greyish brown	Yes	Opaque	sandy	medium	medium	short	weak	medium	69%
Ochre	No	shiny	clayish	medium	strong	medium	weak	medium	72%
Grey	No	shiny	clayish	weak	weak	short	medium	medium	50%

TABLE 2.9

DRY STRENGTH TEST

SOIL	Observation
HB	Easily broken.
PO	Not broken, small deformation.
CO	Not broken, small deformation.
HZ	Not broken, small deformation.
P	Not broken, hard ball.
CA	Not broken, very hard ball.

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TABLE 3.1

Housing Distribution in Surveyed Areas

Departamento	Houses in Urban Area Total	Houses in Urban Area Adobe	Houses in Rural Area Total	Houses in Rural Area Adobe
Lima	828,804	146,945	43,751	25,722
Piura	121,646	35,134	79,913	40,688
Arequipa	115,603	10,379	27,357	7,119
Puno	57,847	45,413	153,343	117,349
Cuzco	70,328	61,522	107,573	82,195
Junín	99,439	70,332	75,500	45,272
Ayacucho	41,636	31,973	74,530	43,611

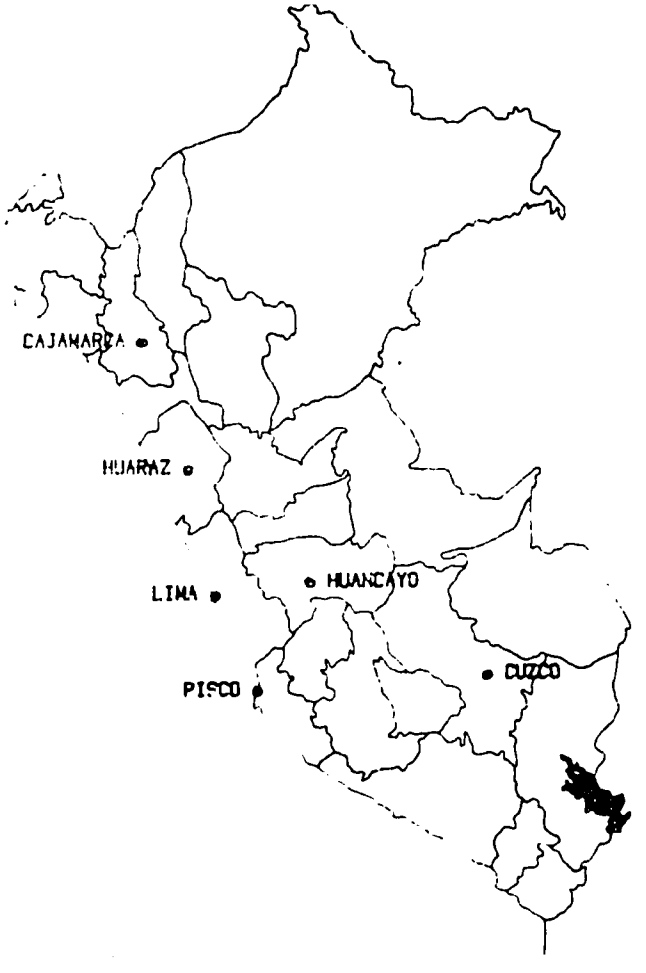

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Fig. 1.1 AREAS OF TECHNICAL STUDY

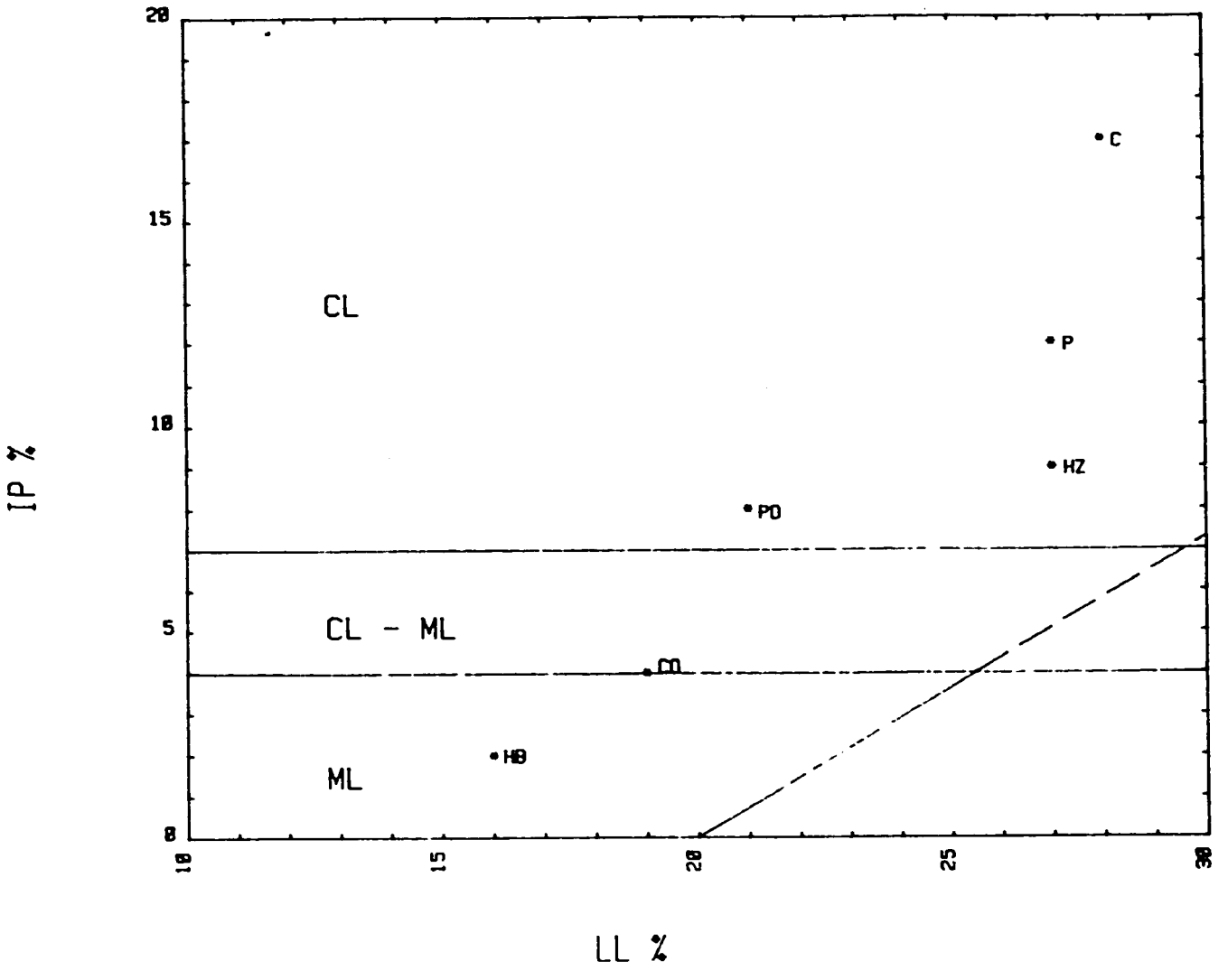

Fig. 1.2 PLASTICITY CHART OF SELECTED SOILS

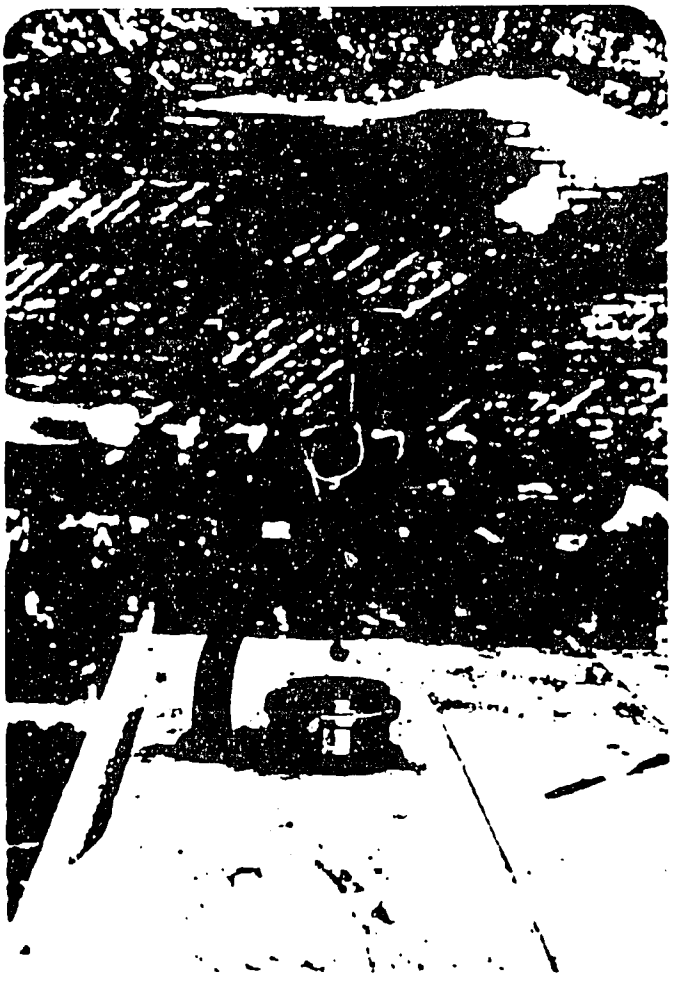

Fig. 1.3 Modified Vicat Apparatus

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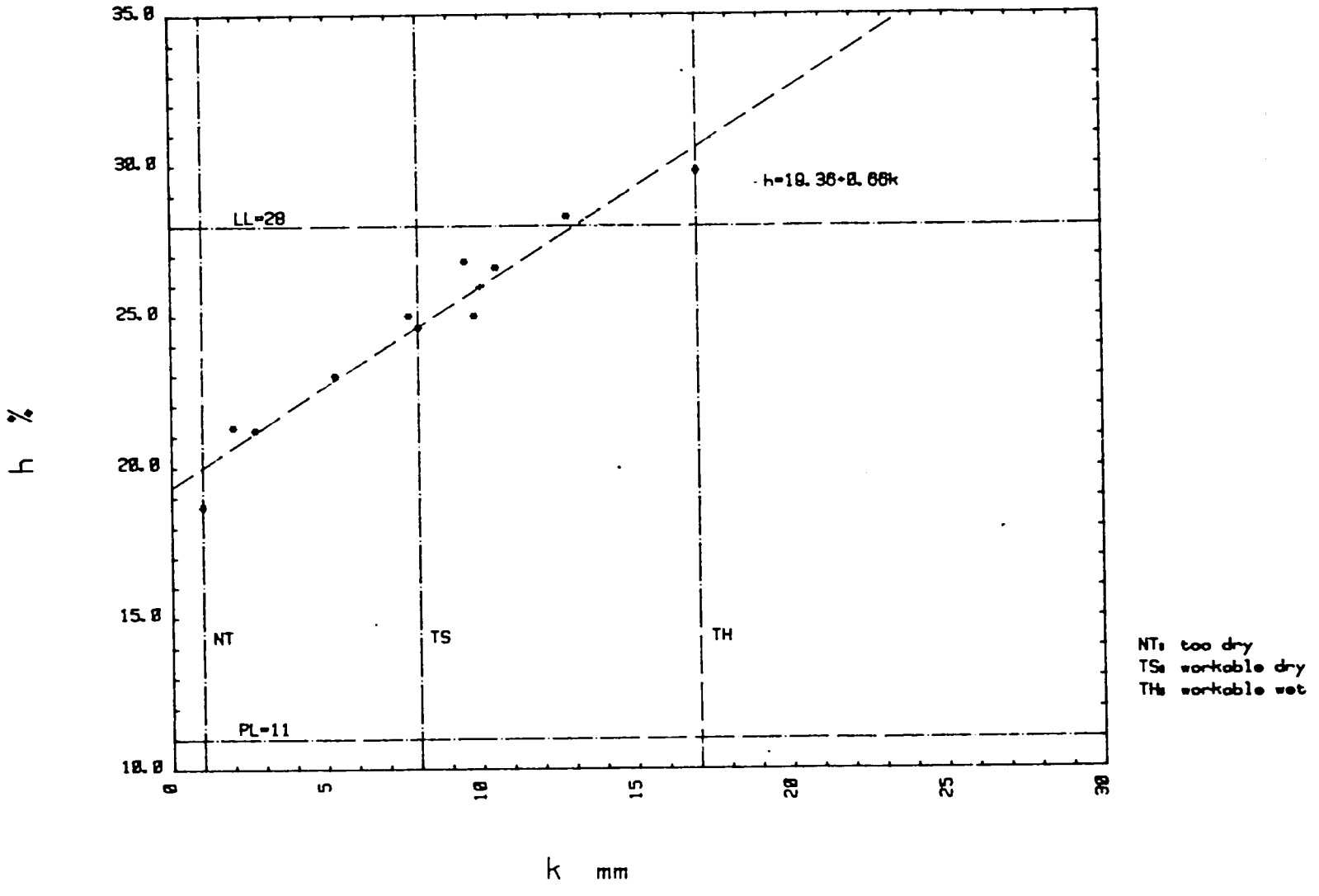

Fig. 1.4 WATER CONTENT vs CONSISTENCY OF MORTAR

Cajamarca (C)

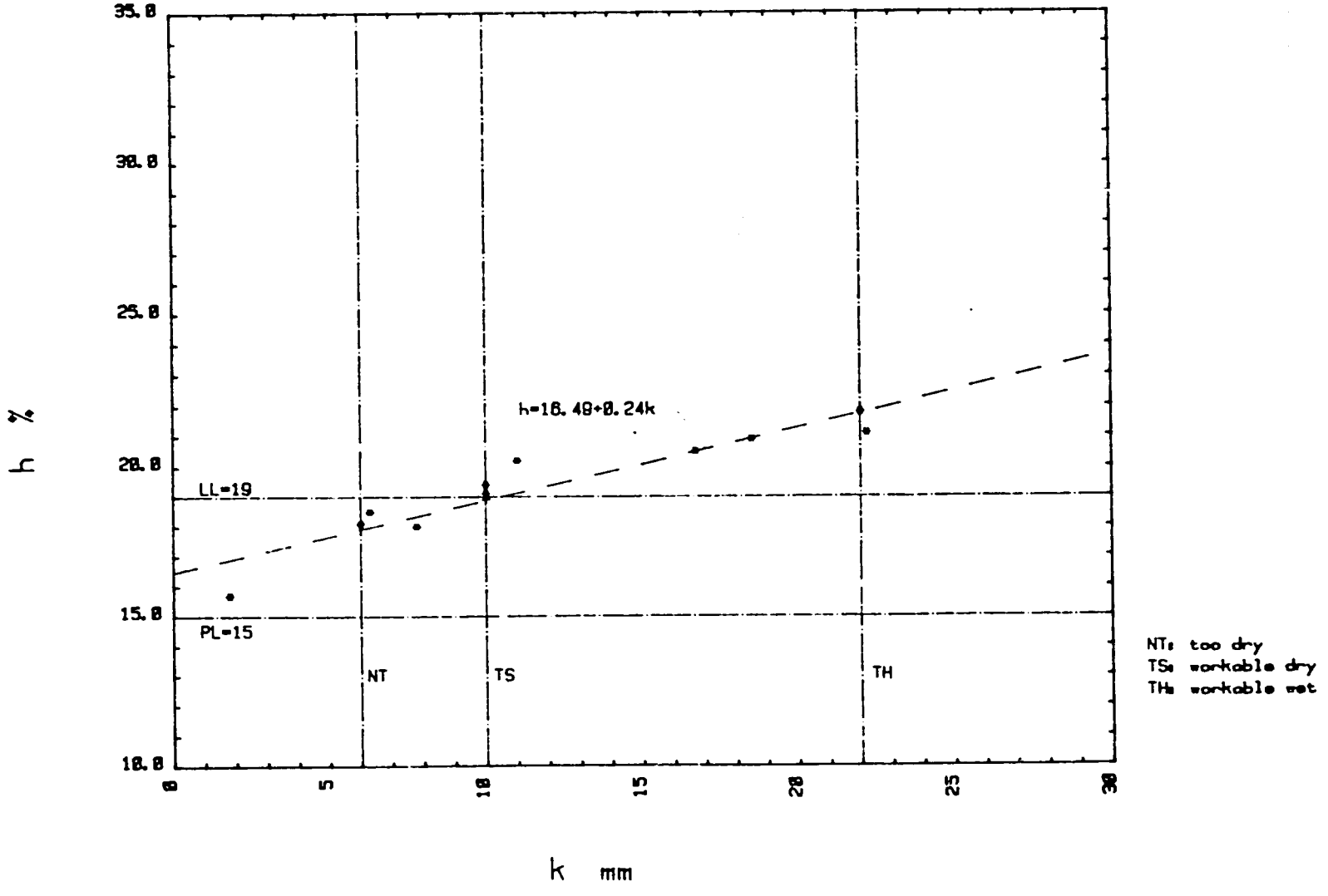

Fig. 1.5 WATER CONTENT vs CONSISTENCY OF MORTAR

Cuzco (CO)

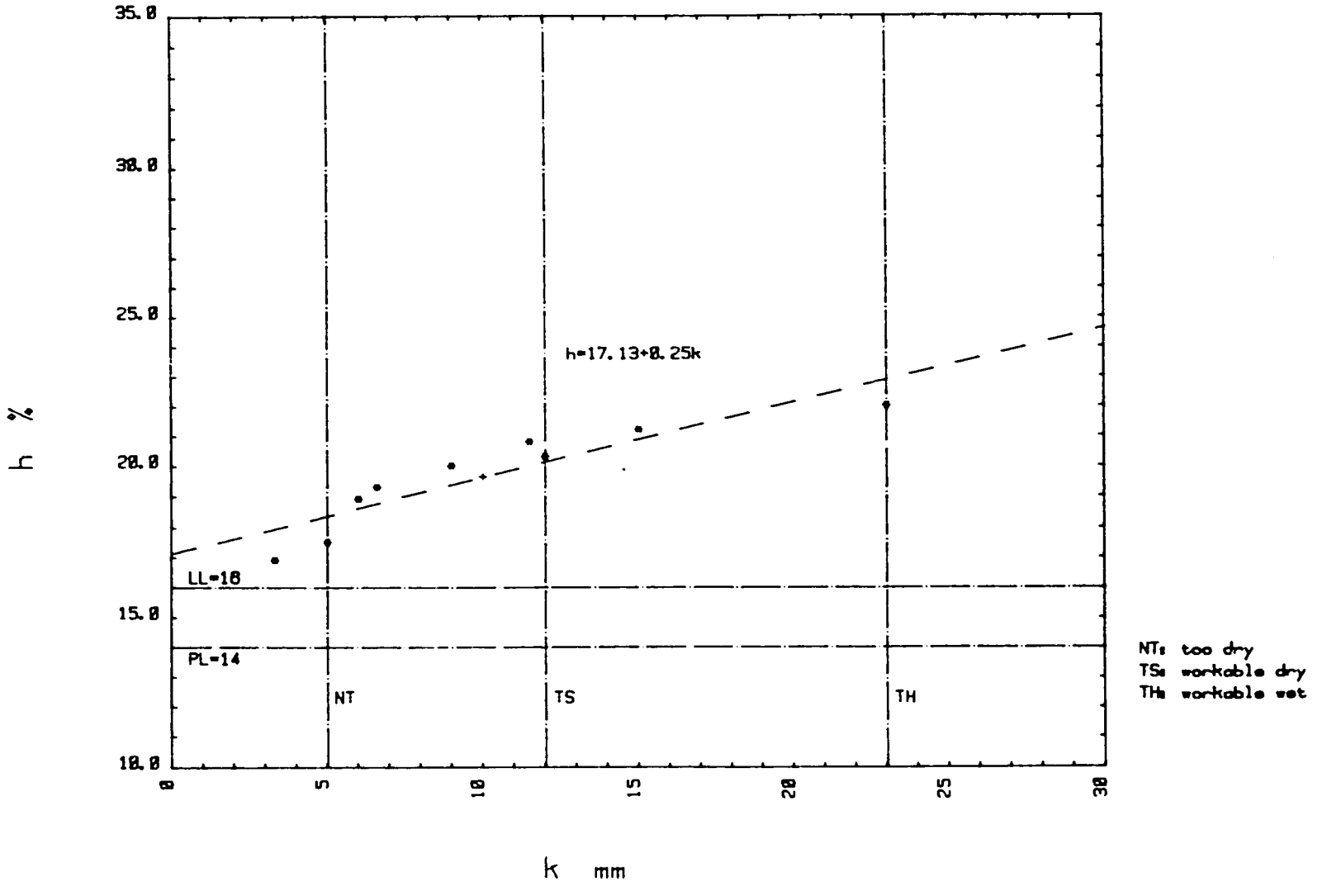

Fig. 1.6 WATER CONTENT vs CONSISTENCY OF MORTAR

Huancayo Blanco (HB)

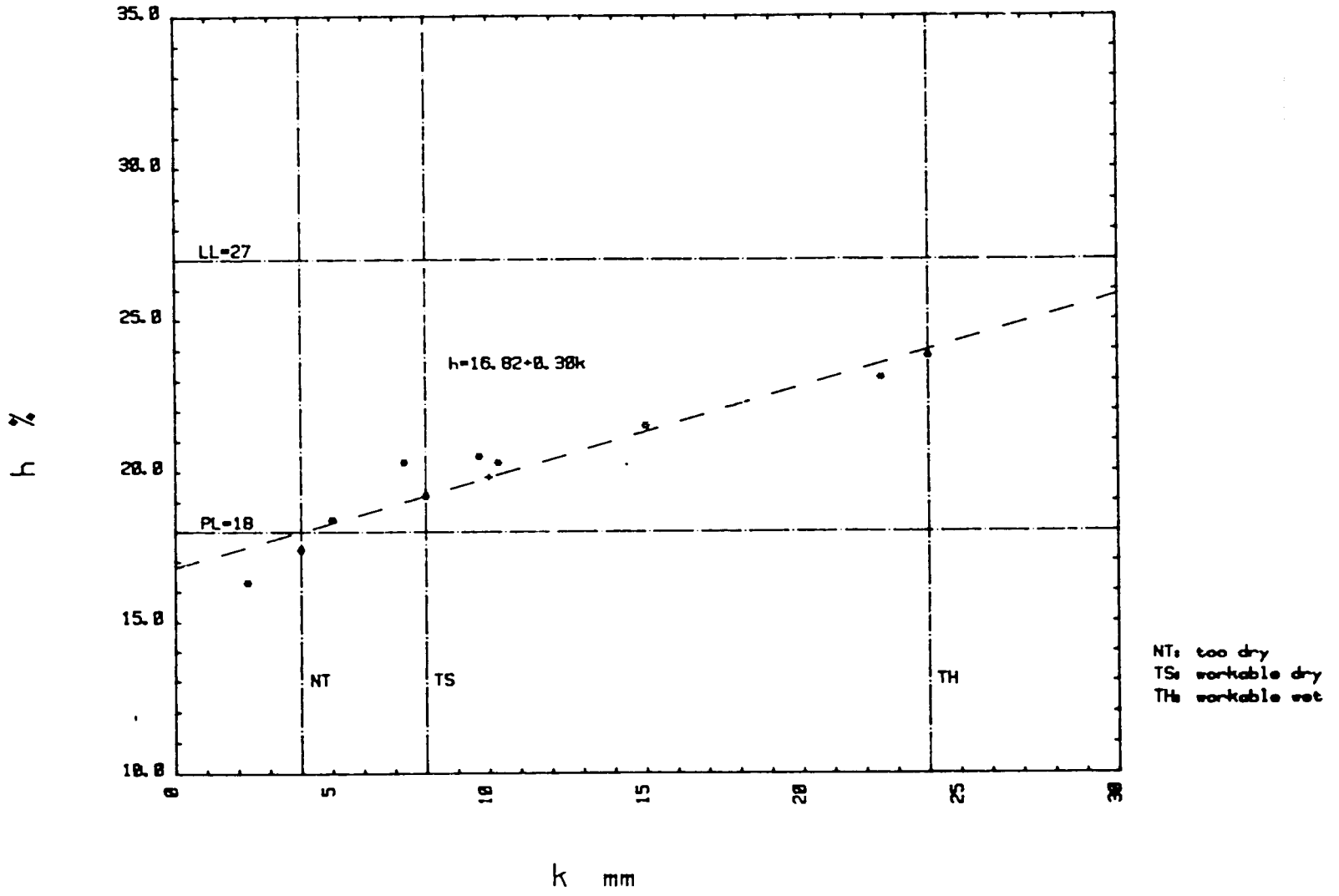

Fig. 1.7 WATER CONTENT vs CONSISTENCY OF MORTAR

Huaraz (HZ)

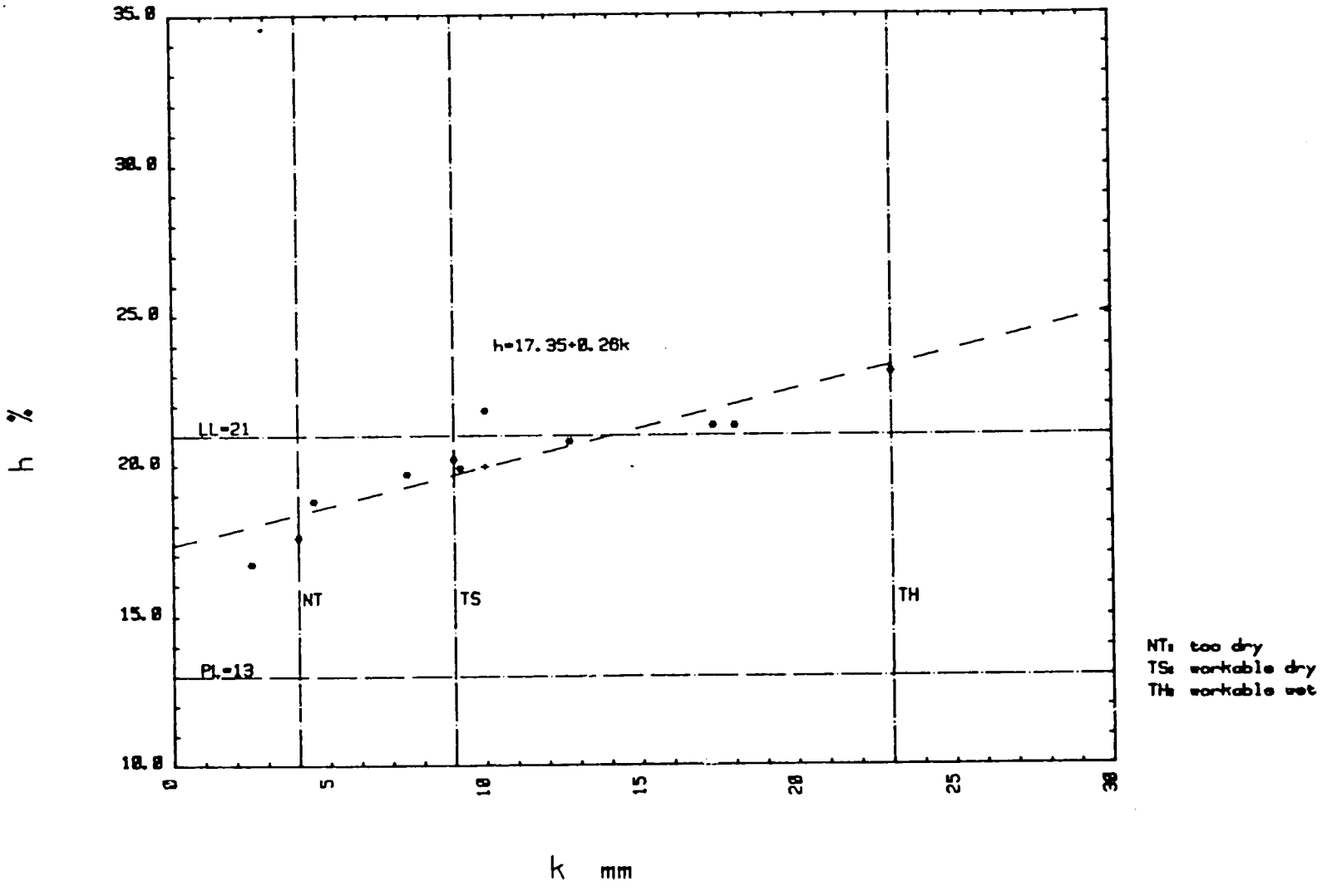

Fig. 1.8 WATER CONTENT vs CONSISTENCY OF MORTAR

Pisco (PO)

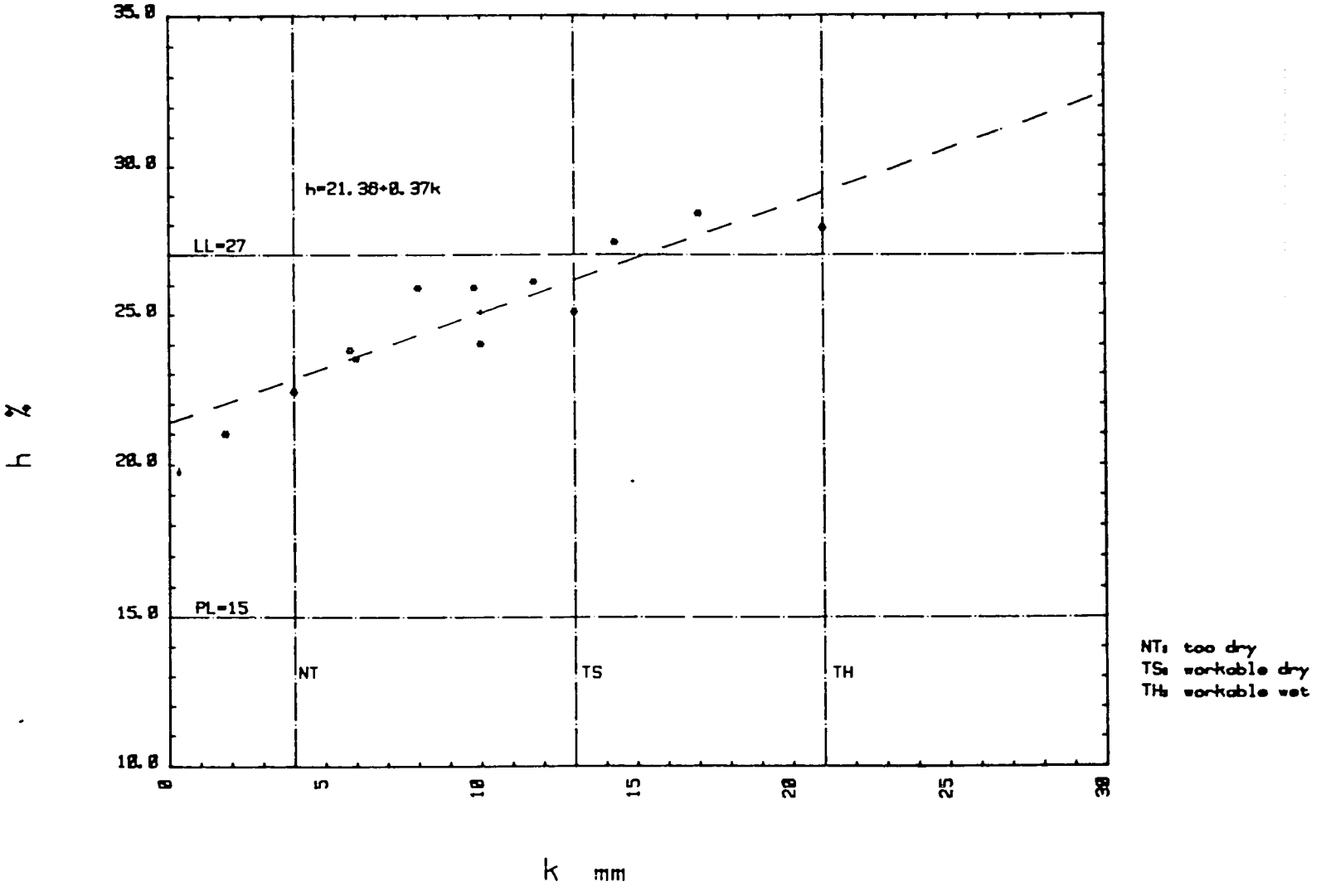

Fig. 1.9 WATER CONTENT vs CONSISTENCY OF MORTAR

PUC (P)

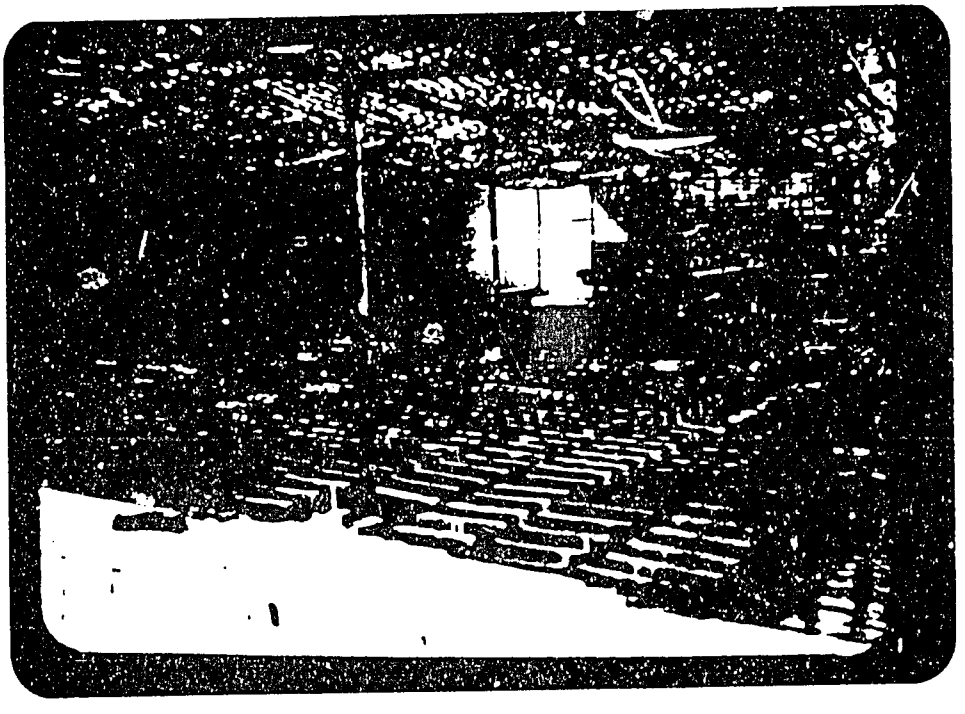

Fig. 1.10 Adobe Bricks Drying in the Shadow

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Fig. 1.11 Full-Scale Adobe Wall Test

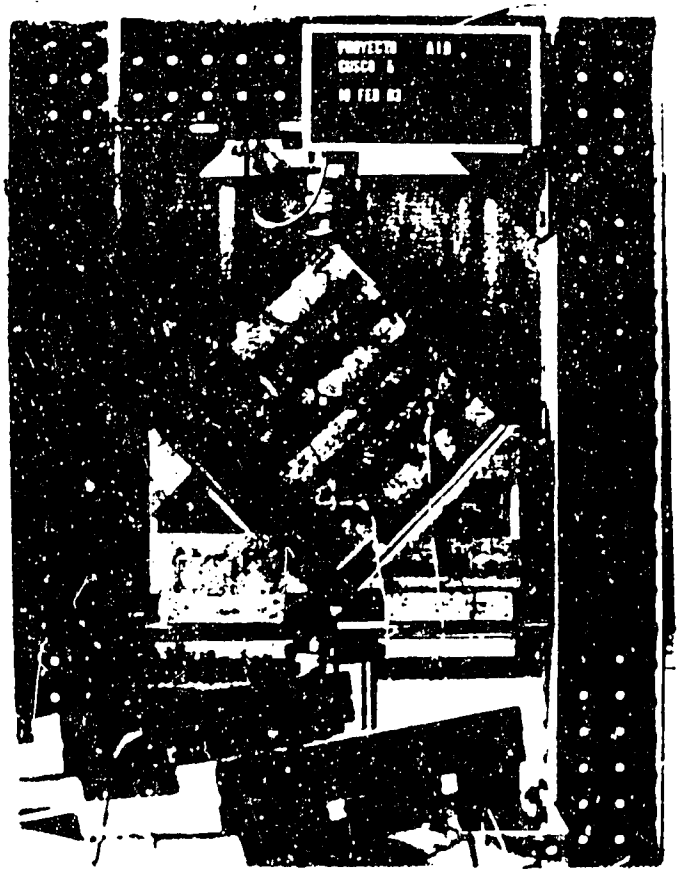

Fig. 1.12 Diagonal Compression Test

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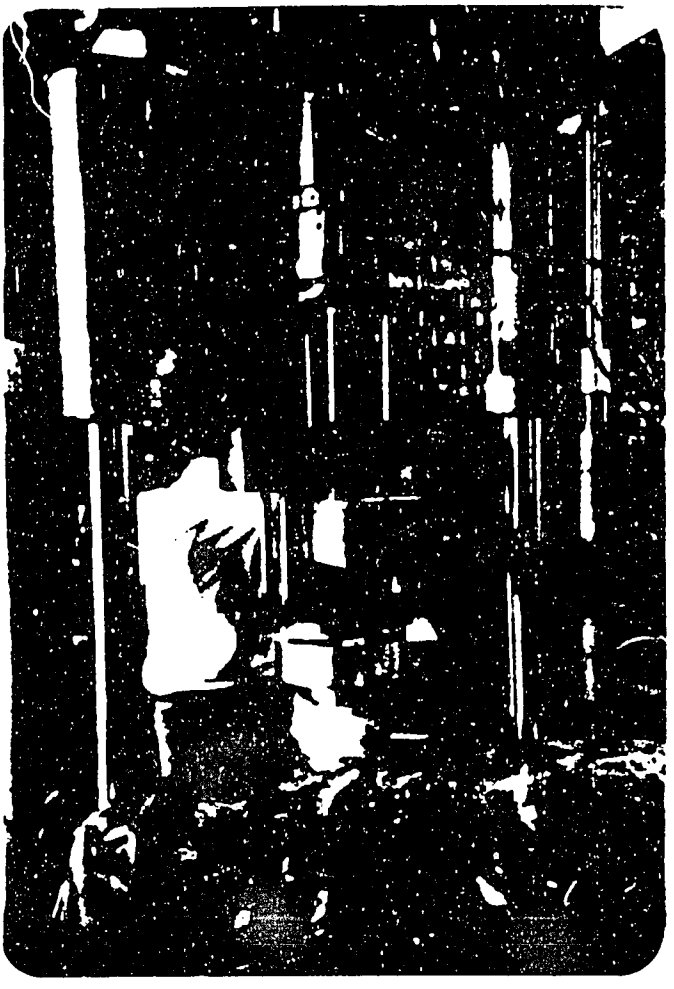

Fig. 1.13 Direct Tension Test

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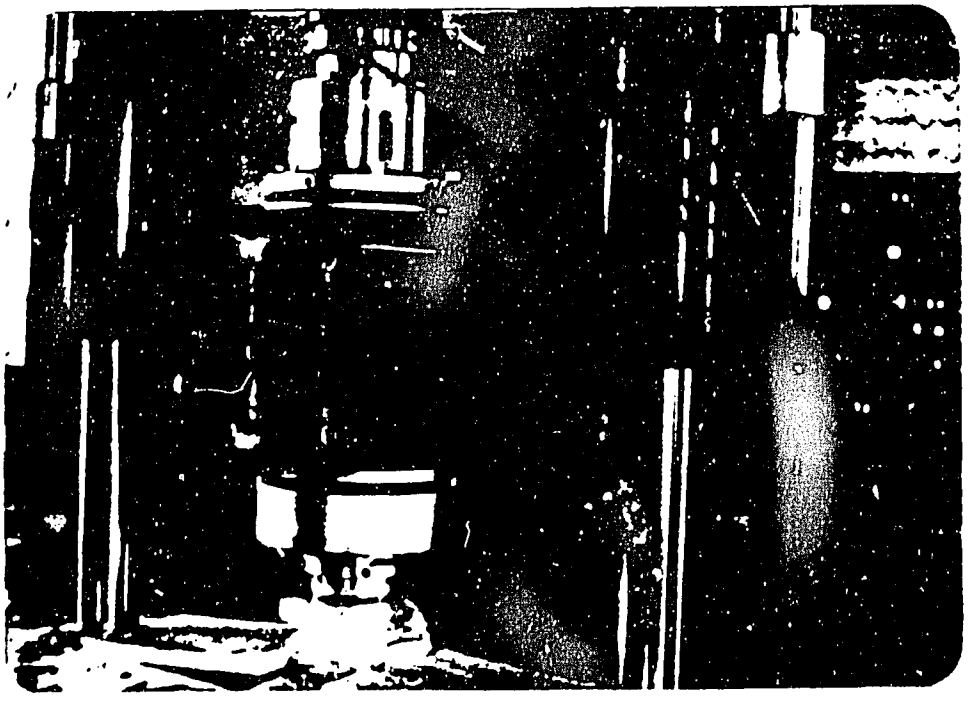

Fig. 1.14 Indirect Tension Test

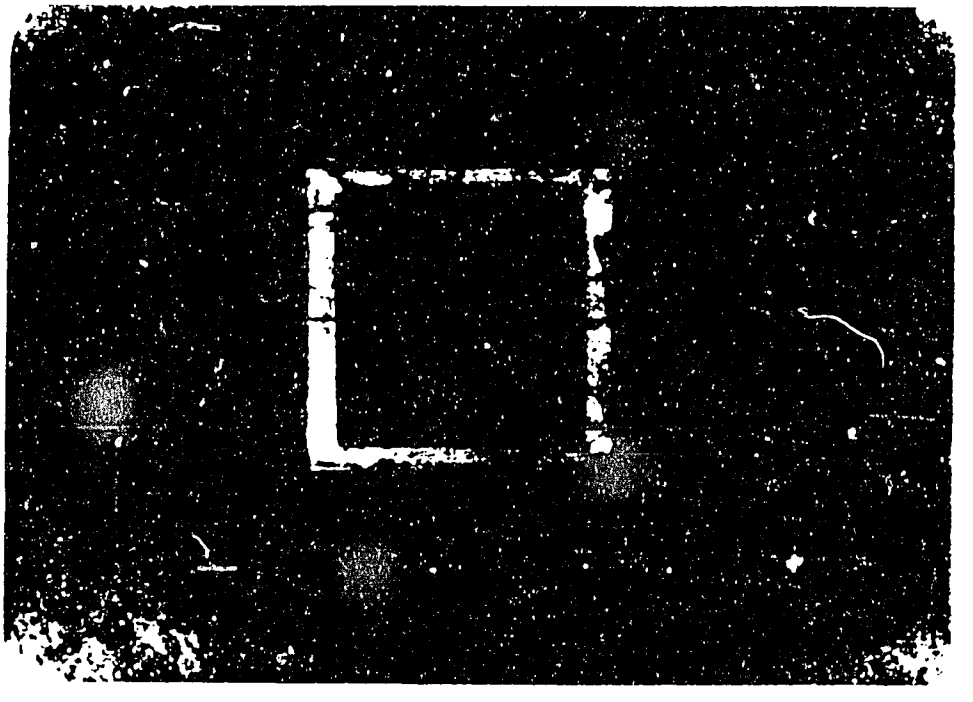

Fig. 1.15 Measure of Visible Cracks of Mortar

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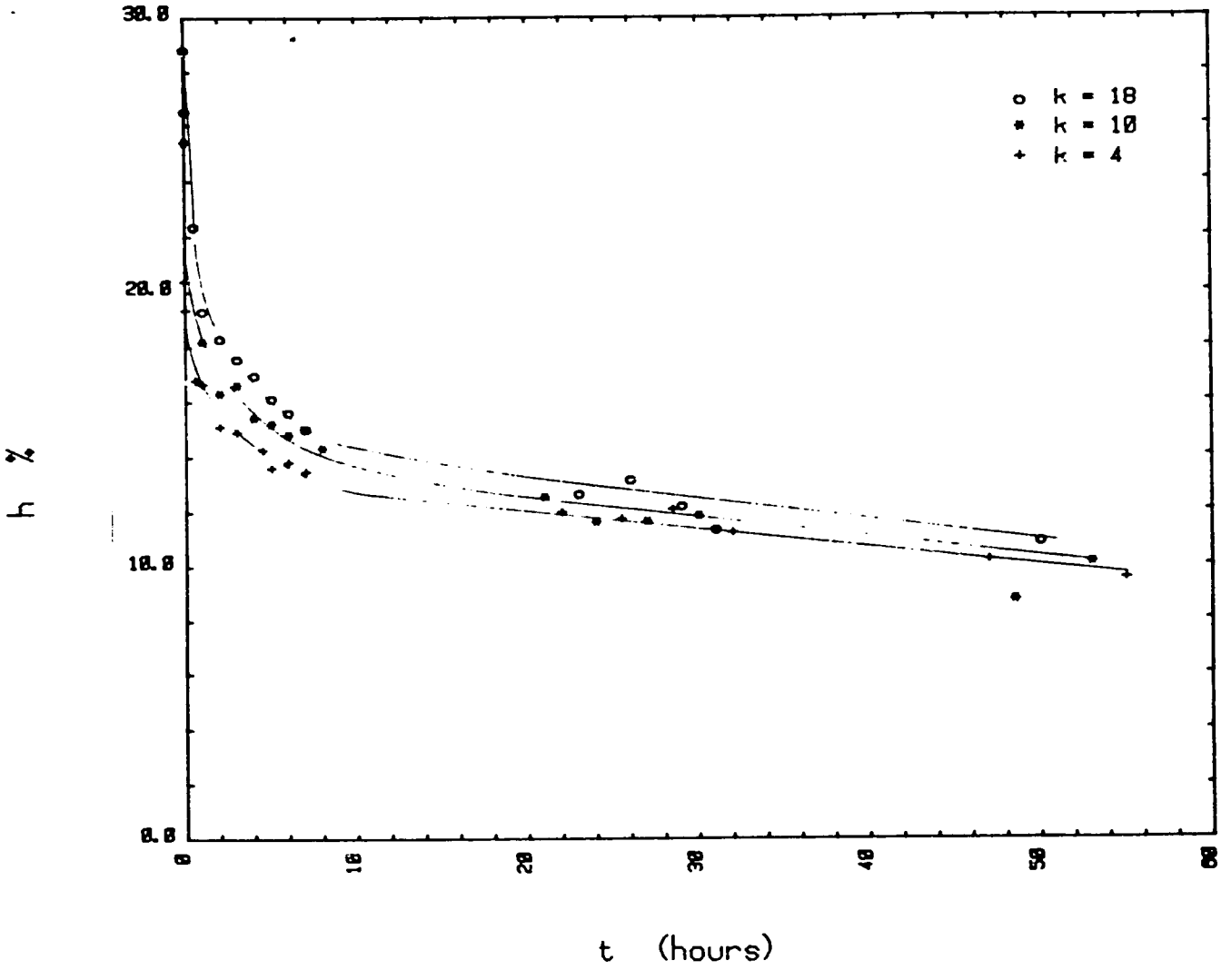

Fig. 1.16 % WATER CONTENT vs TIME IN MORTARS

Effect of inicial consistency

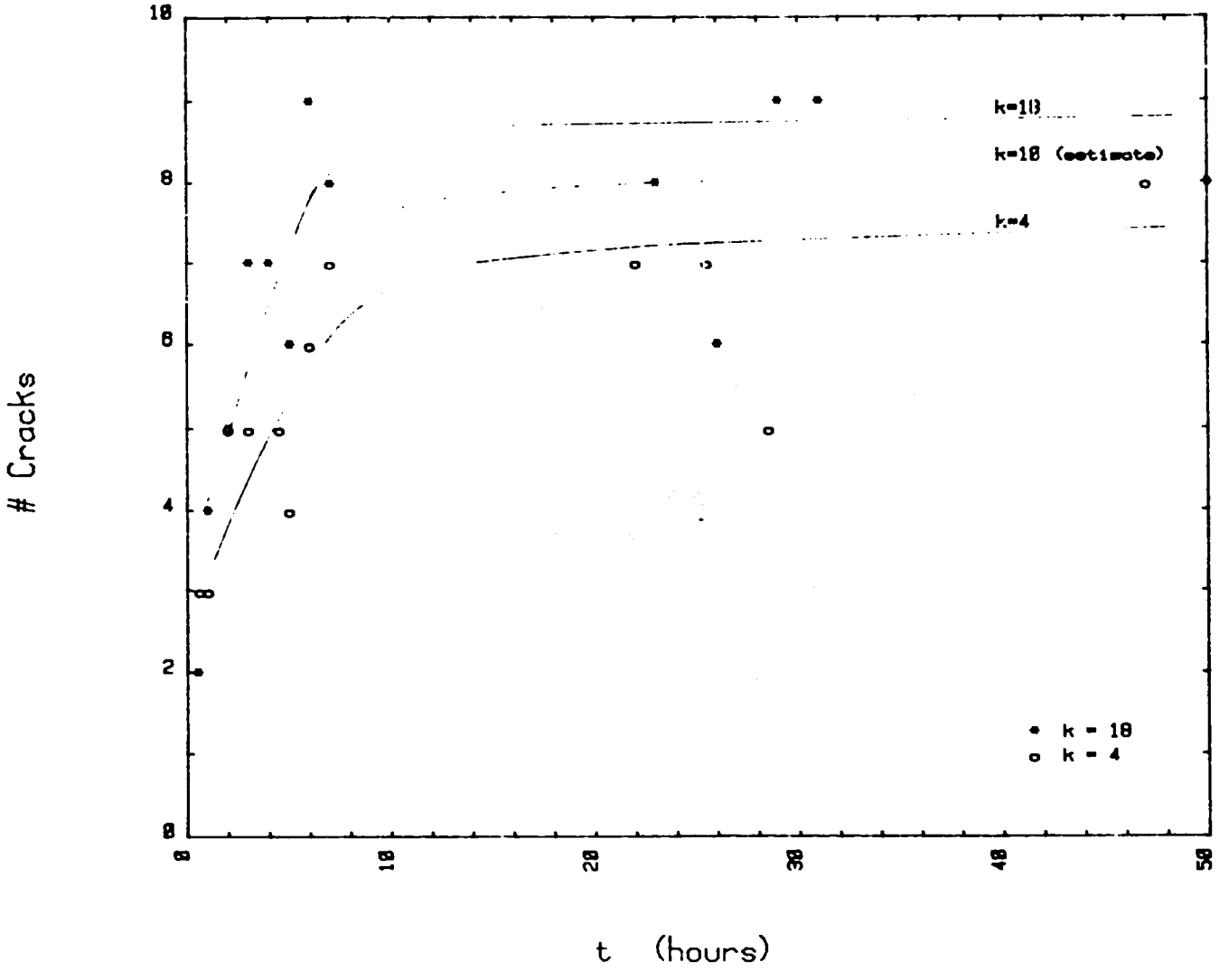

Fig. 1.17 NUMBER OF CRACKS vs TIME

Effect of inicial consistency

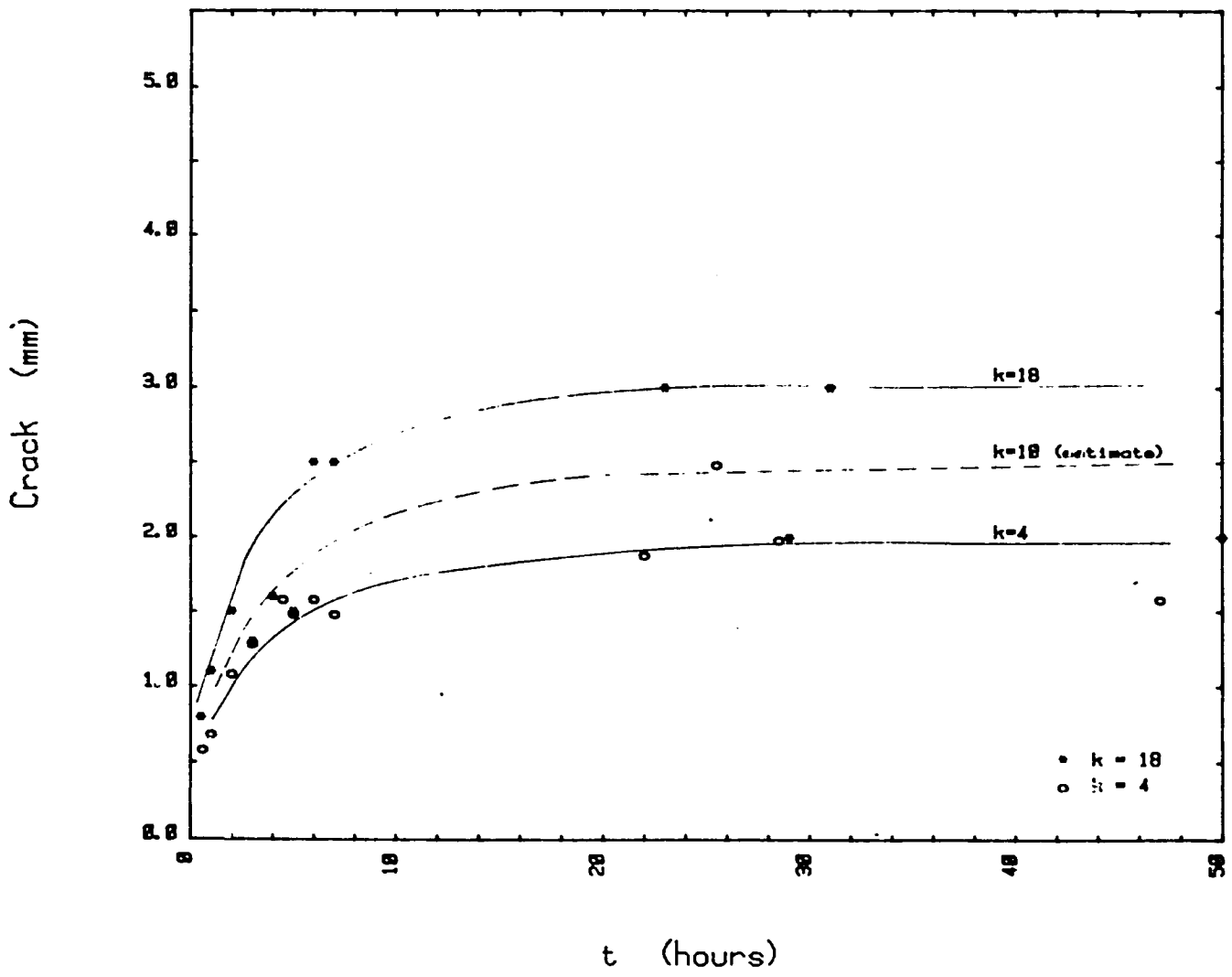

Fig. 1.18 MAXIMUM CRACK WIDTH vs TIME

Effect of inicial consistency

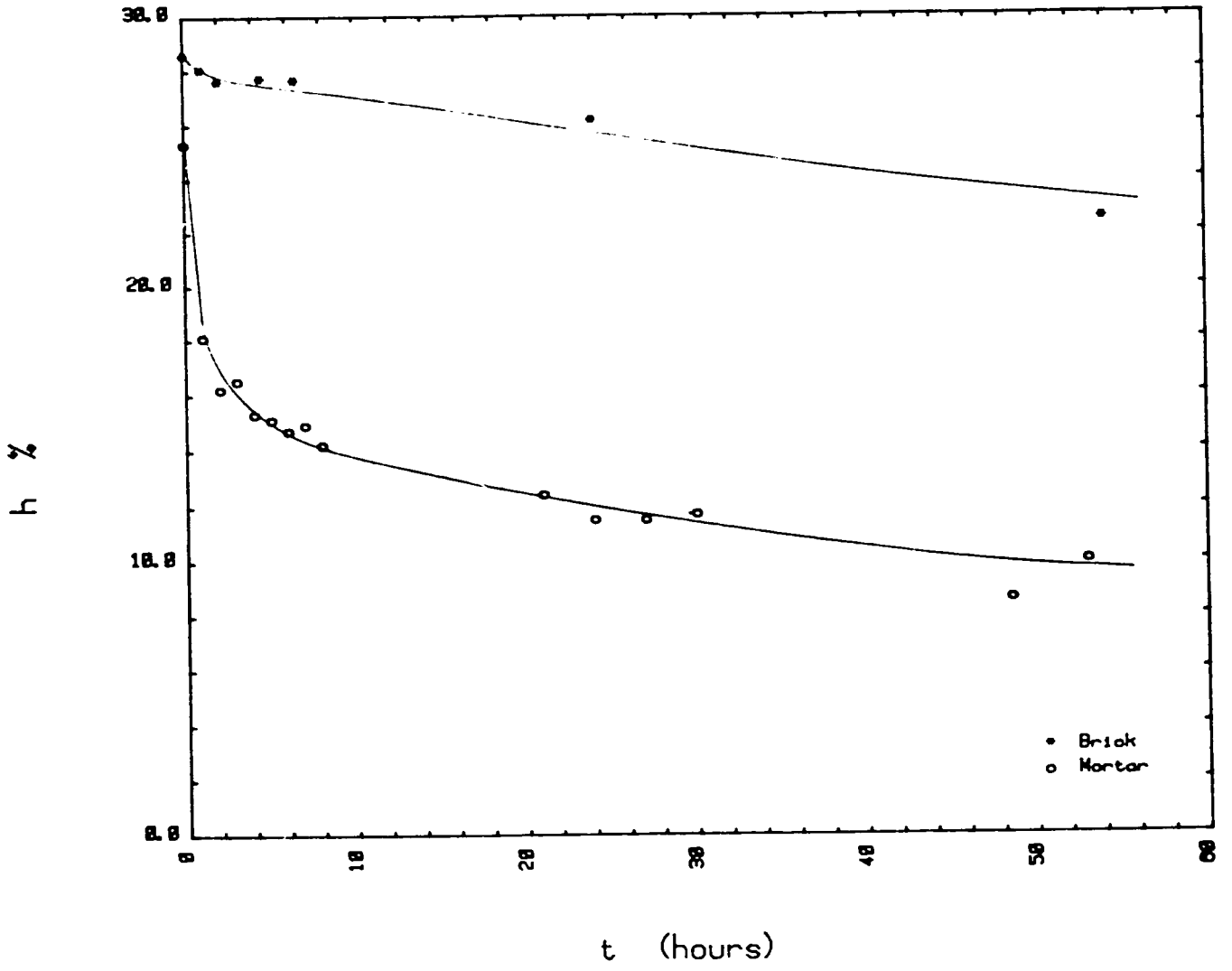

Fig. 1.19 WATER CONTENT vs TIME

Mortar and Brick

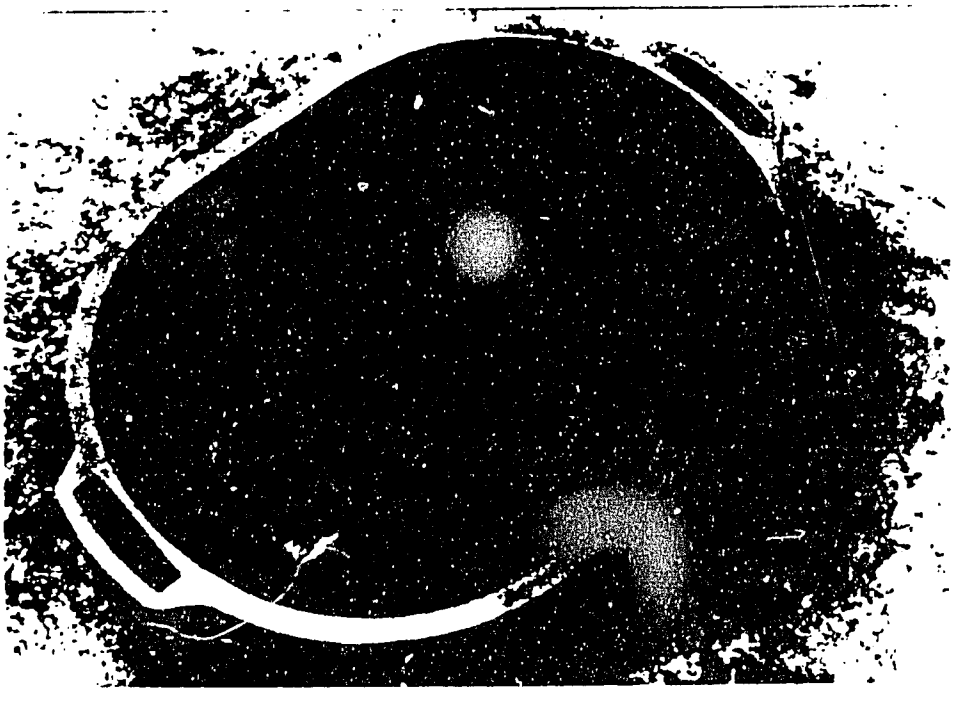

Fig. 1.20 Wetting of Adobe Bricks

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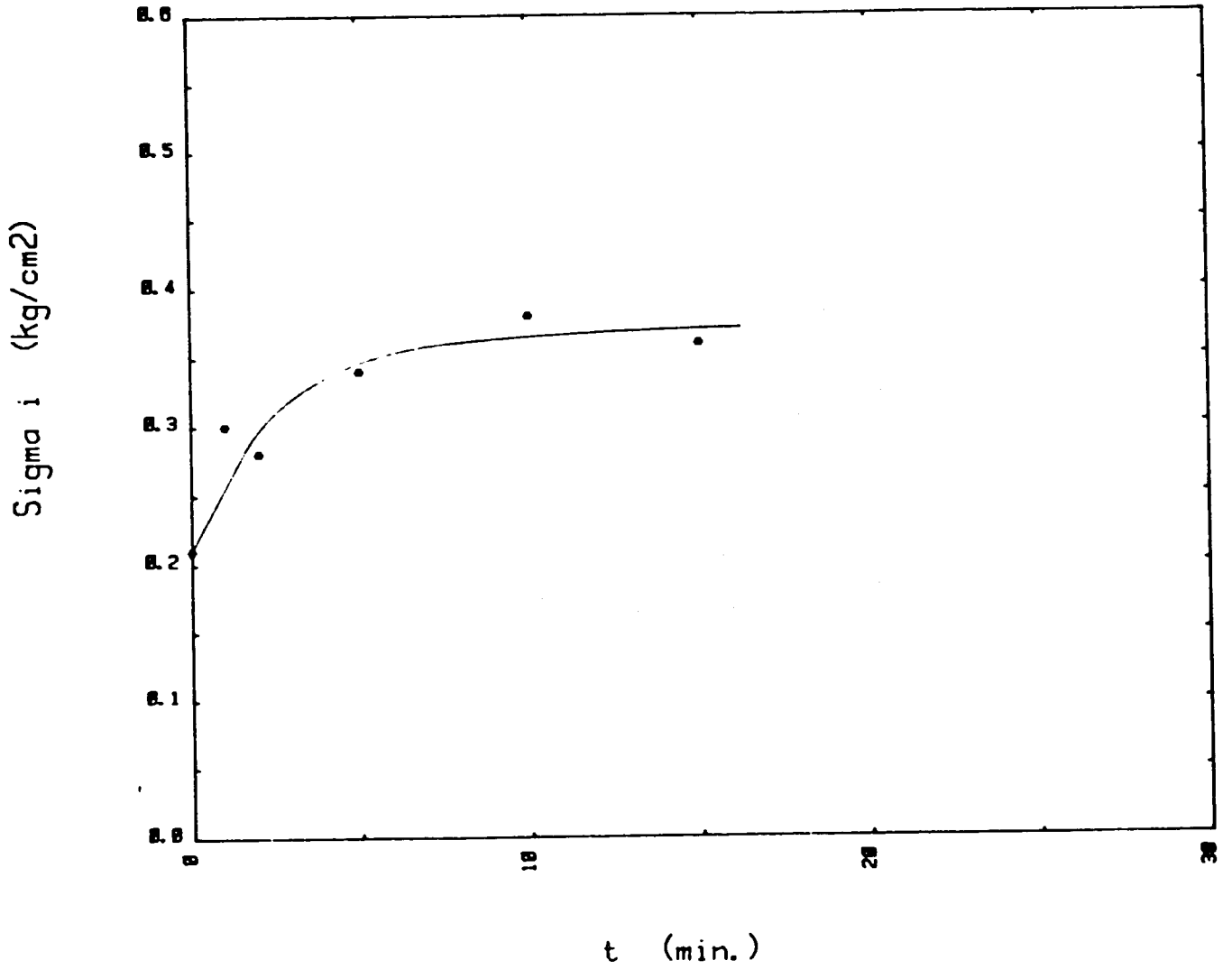

Fig. 1.21 EFFECT OF BRICK WETTING

PUC soil

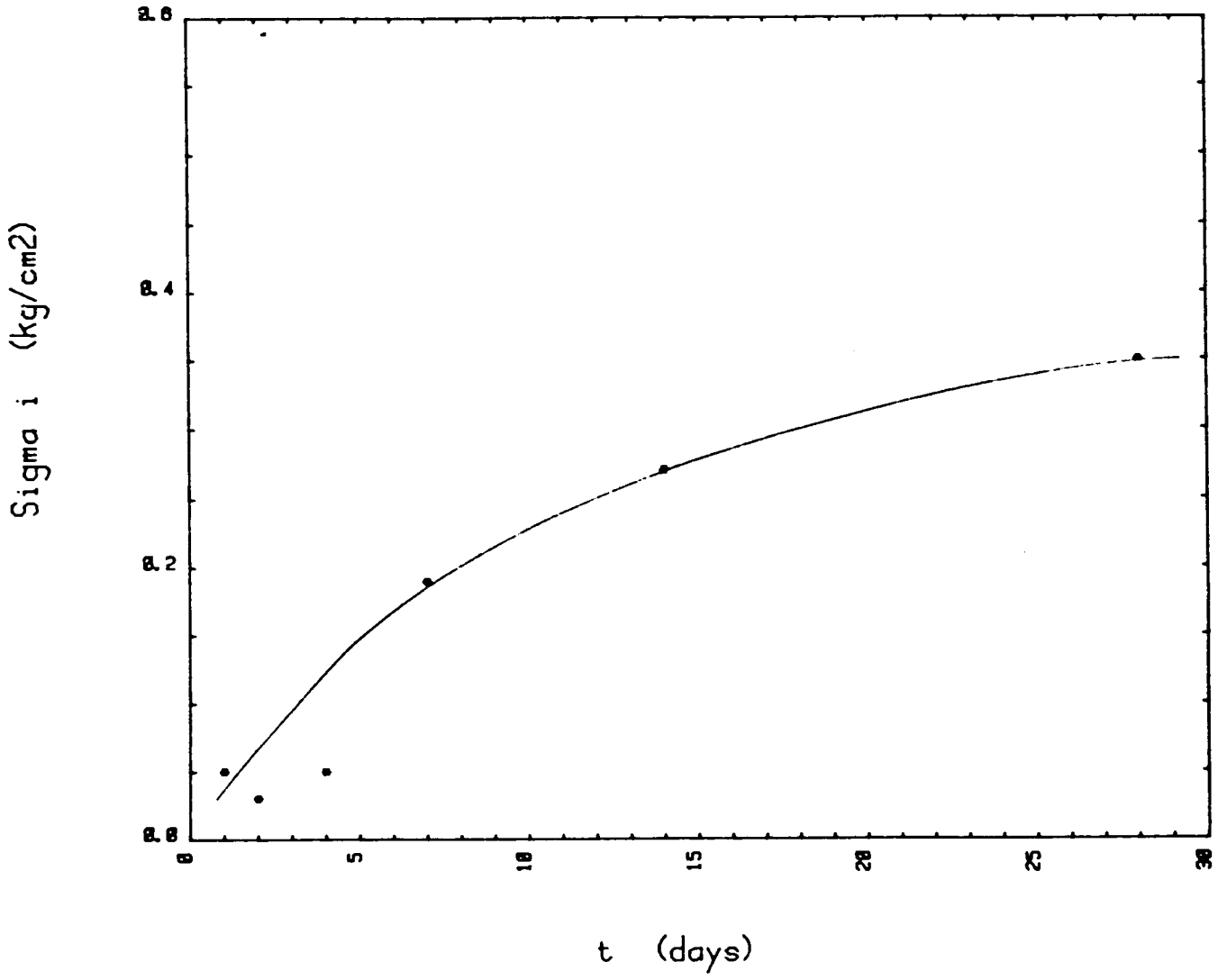

Fig. 1.22 INDIRECT TENSION STRENGHT vs TIME

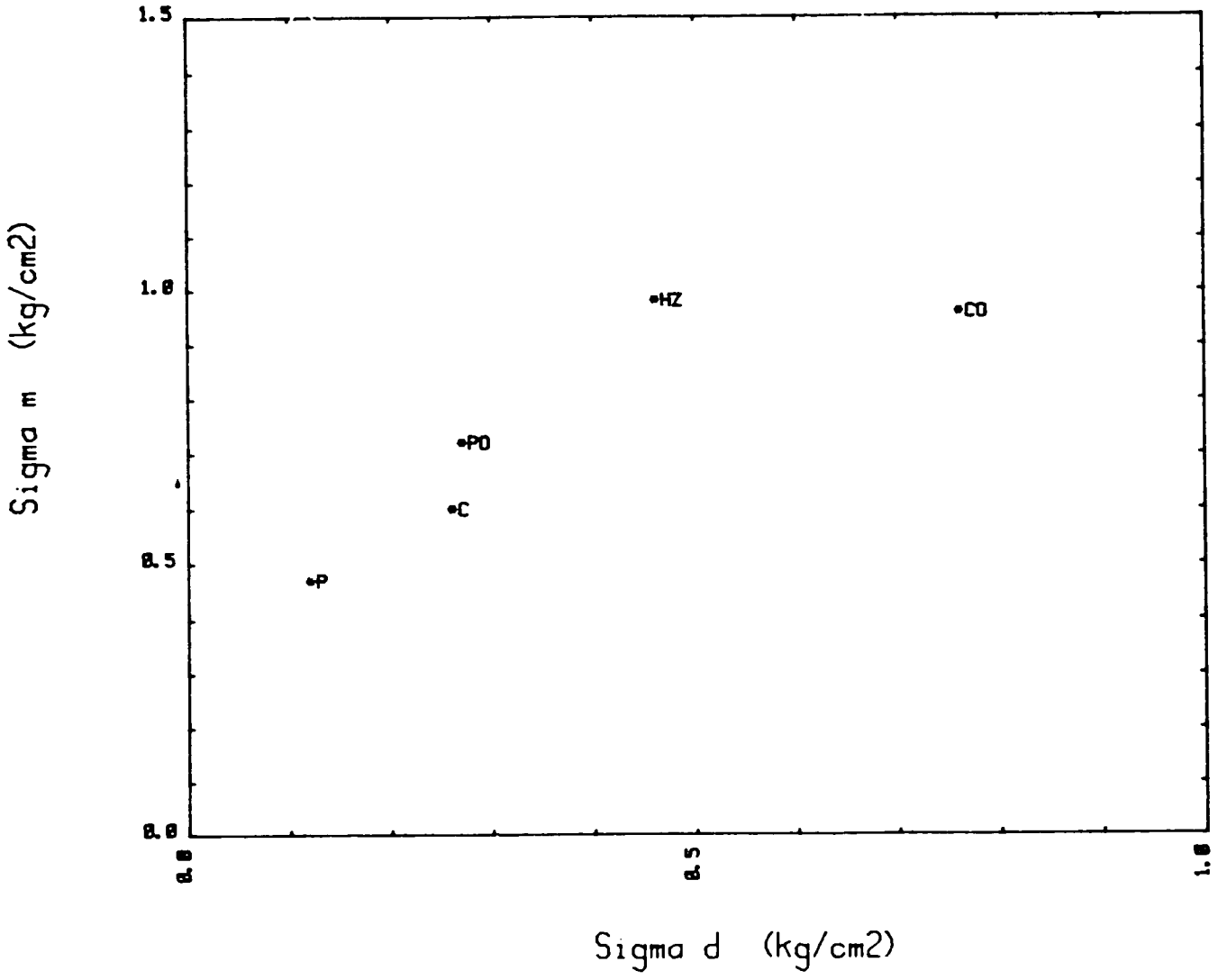

Fig. 1.23 DIAGONAL COMPRESSION vs DIRECT TENSION

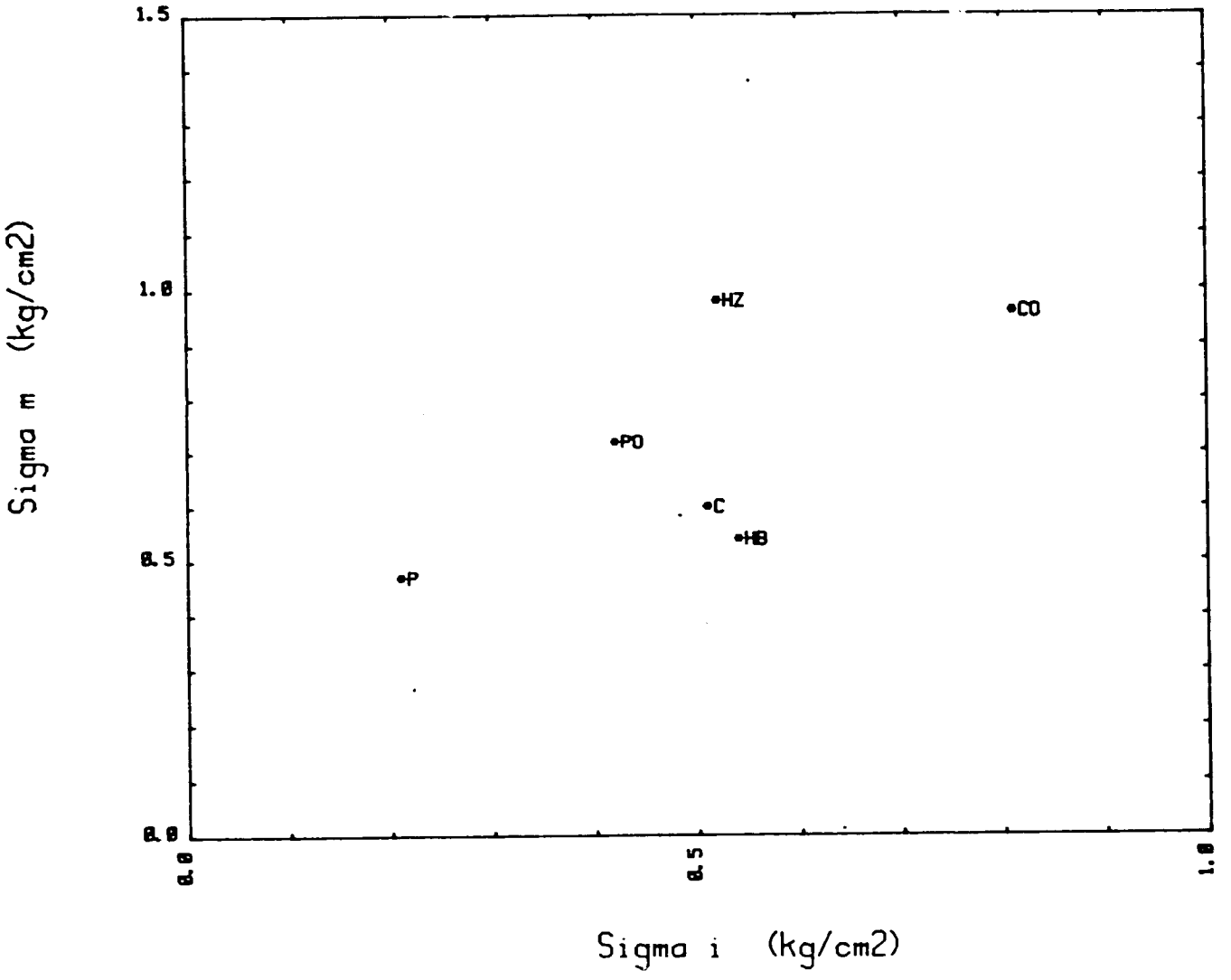

Fig. 1.24 DIAGONAL COMPRESSION vs INDIRECT TENSION

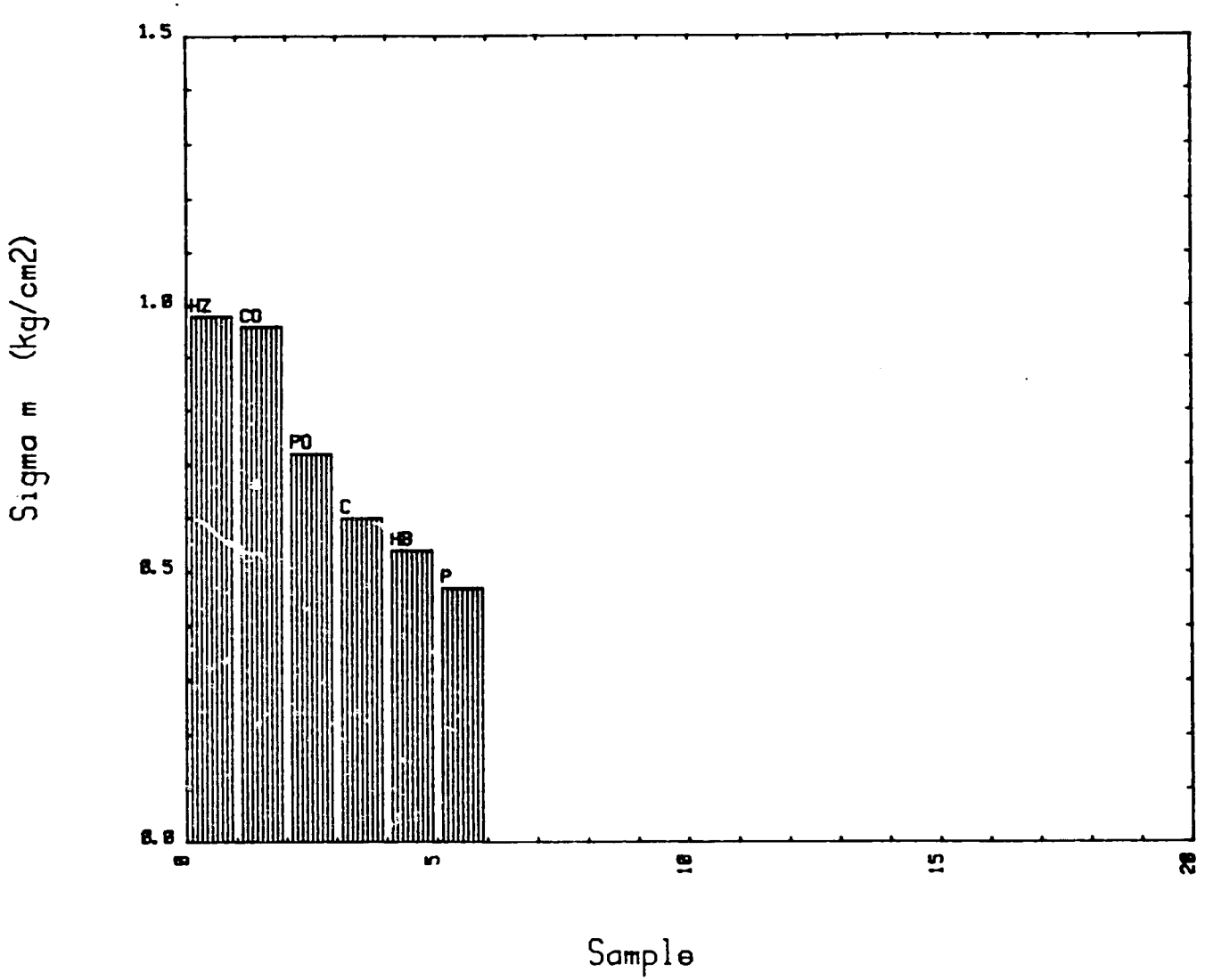

Fig. 1.25 DIAGONAL COMPRESSION TEST RESULTS

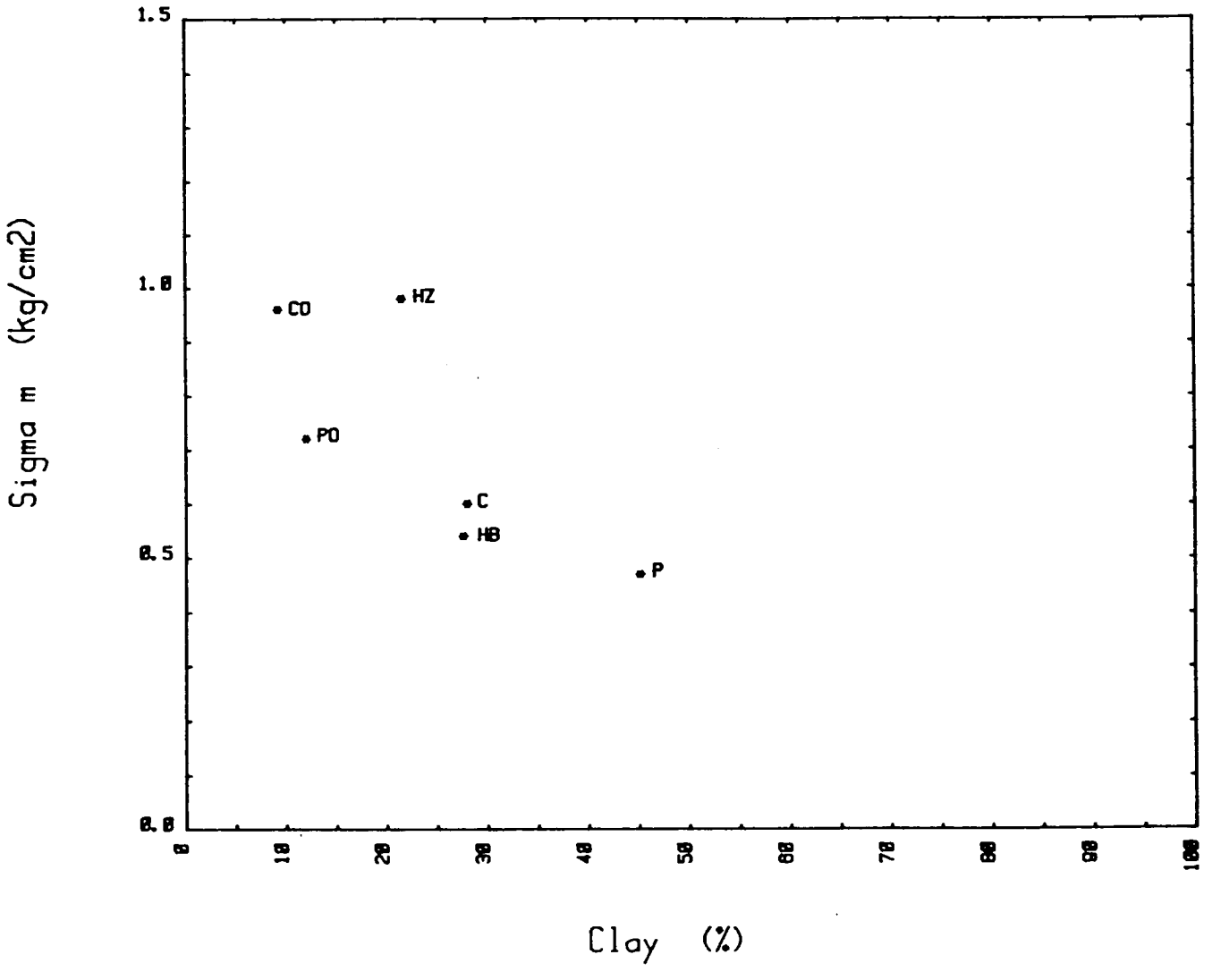

Fig. 1.26 DIAGONAL COMPRESSION vs CLAY CONTENT

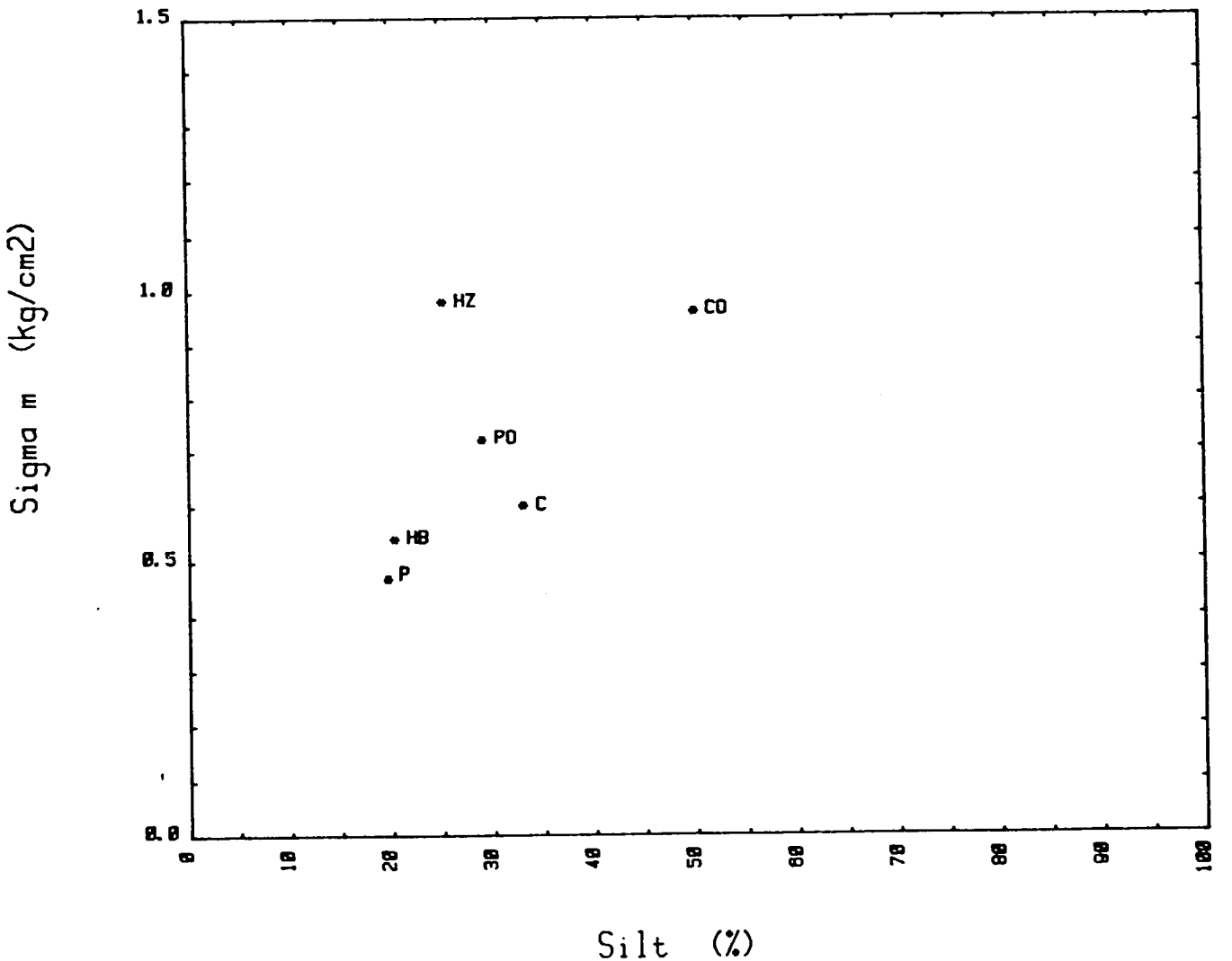

Fig. 1.27 DIAGONAL COMPRESSION vs SILT CONTENT

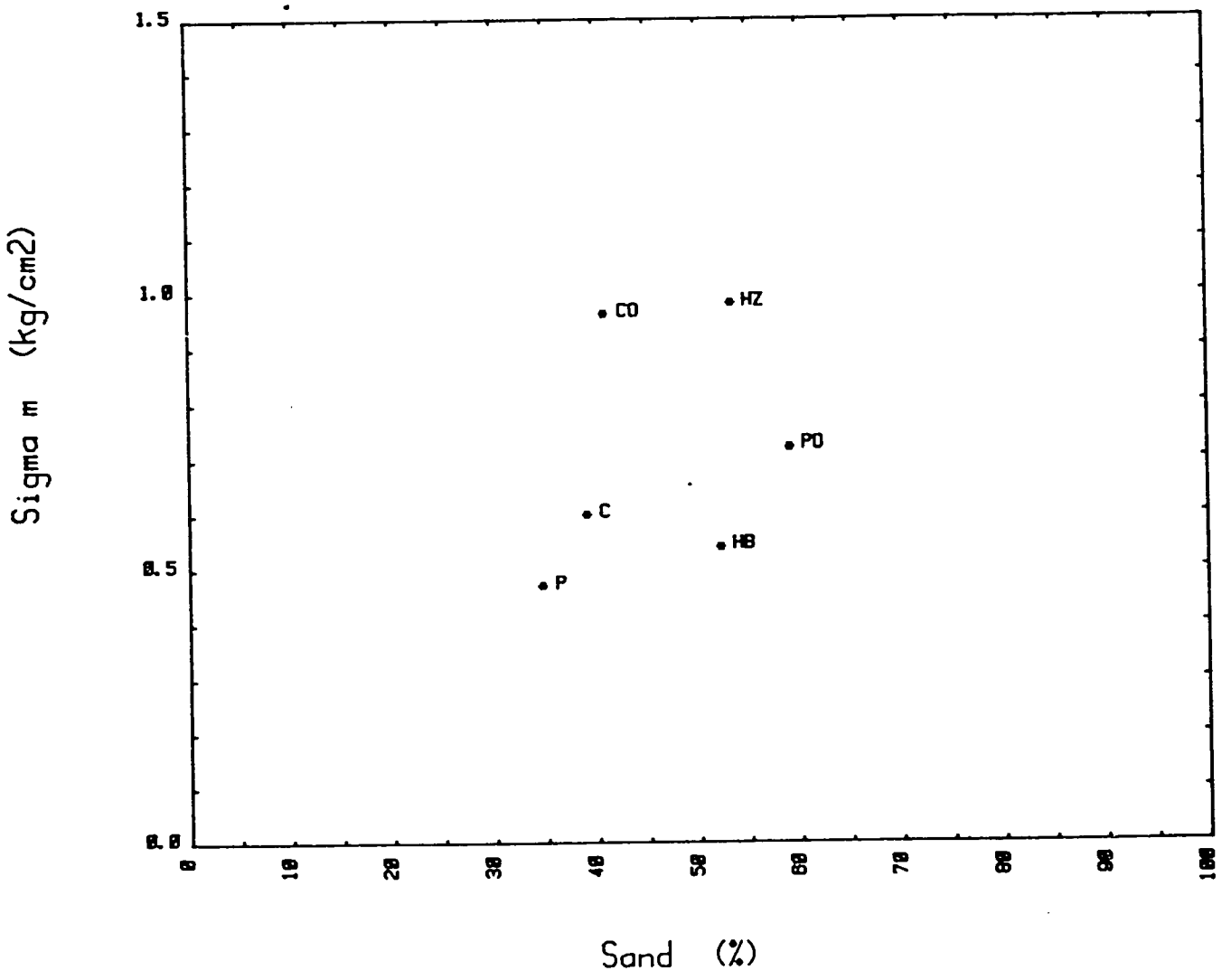

Fig. 1.28 DIAGONAL COMPRESSION vs SAND CONTENT

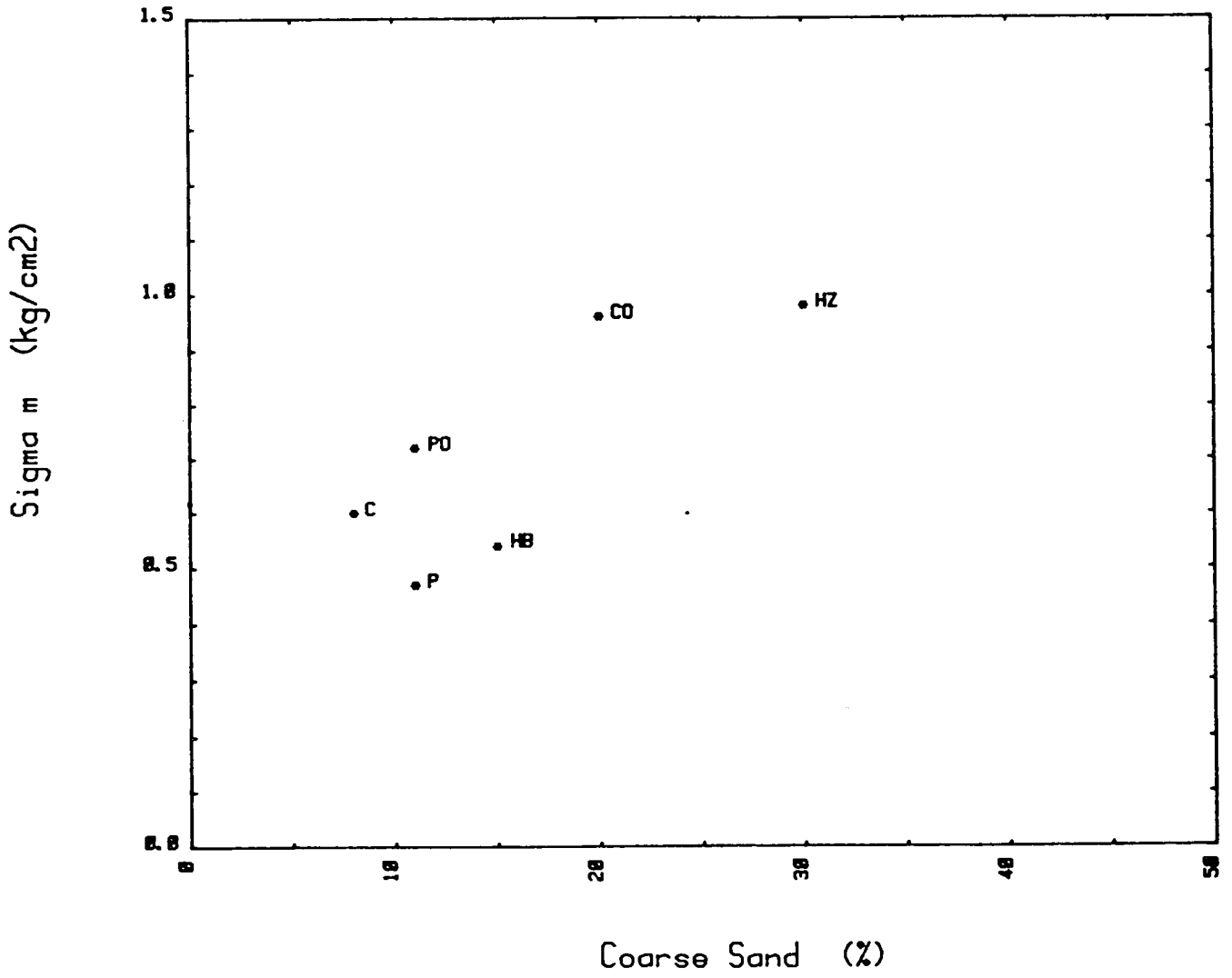

Fig. 1.29 DIAGONAL COMPRESSION vs COARSE SAND CONTENT

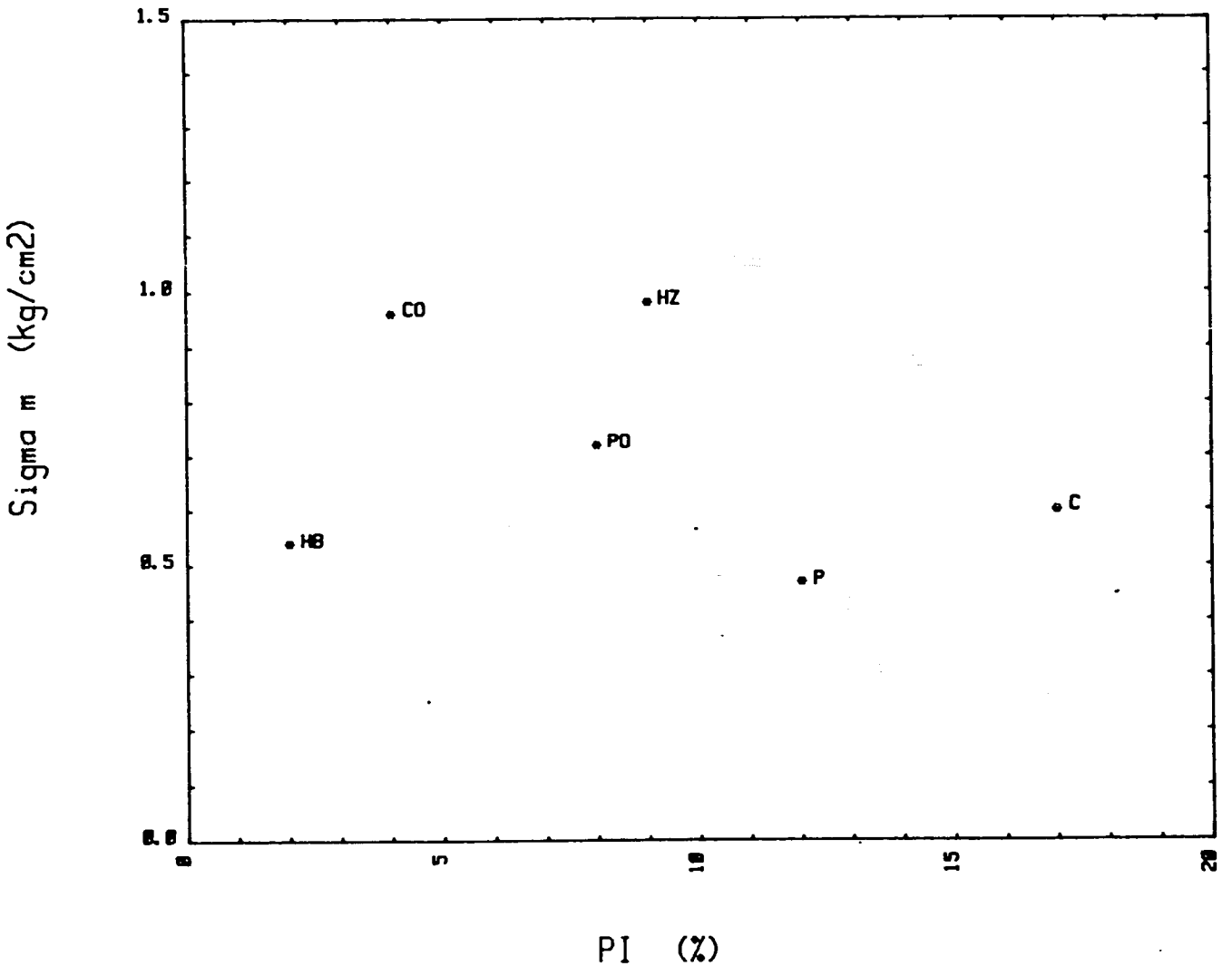

Fig. 1.30 DIAGONAL COMPRESSION vs PLASTICITY INDEX

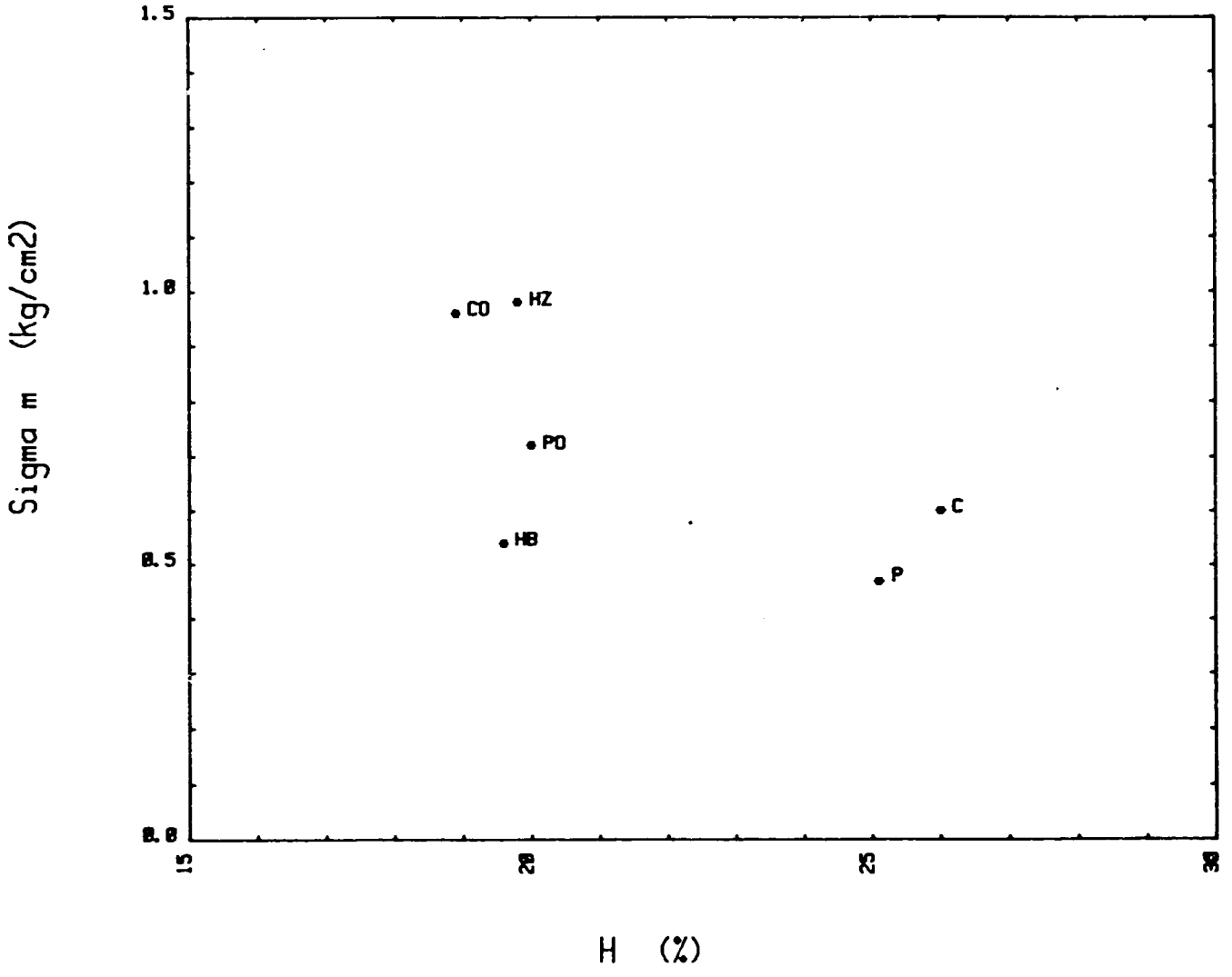

Fig. 1.31 DIAGONAL COMPRESSION vs WATER REQUIRED FOR STANDARD CONSISTENCY

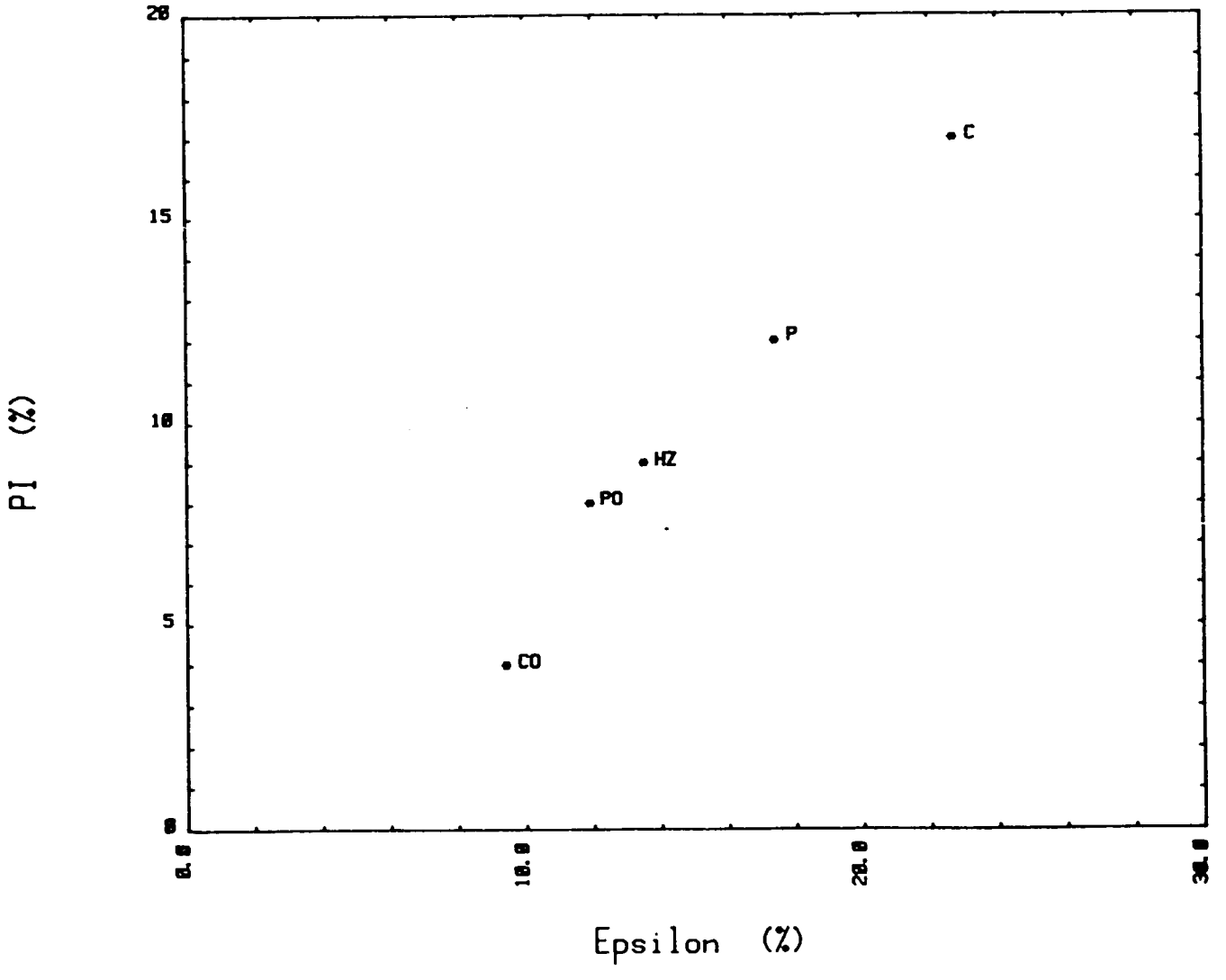

Fig. 1.32 PLASTICITY INDEX OF SOILS vs VOLUMETRIC DRYING SHRINKAGE OF ADOBE BRICK

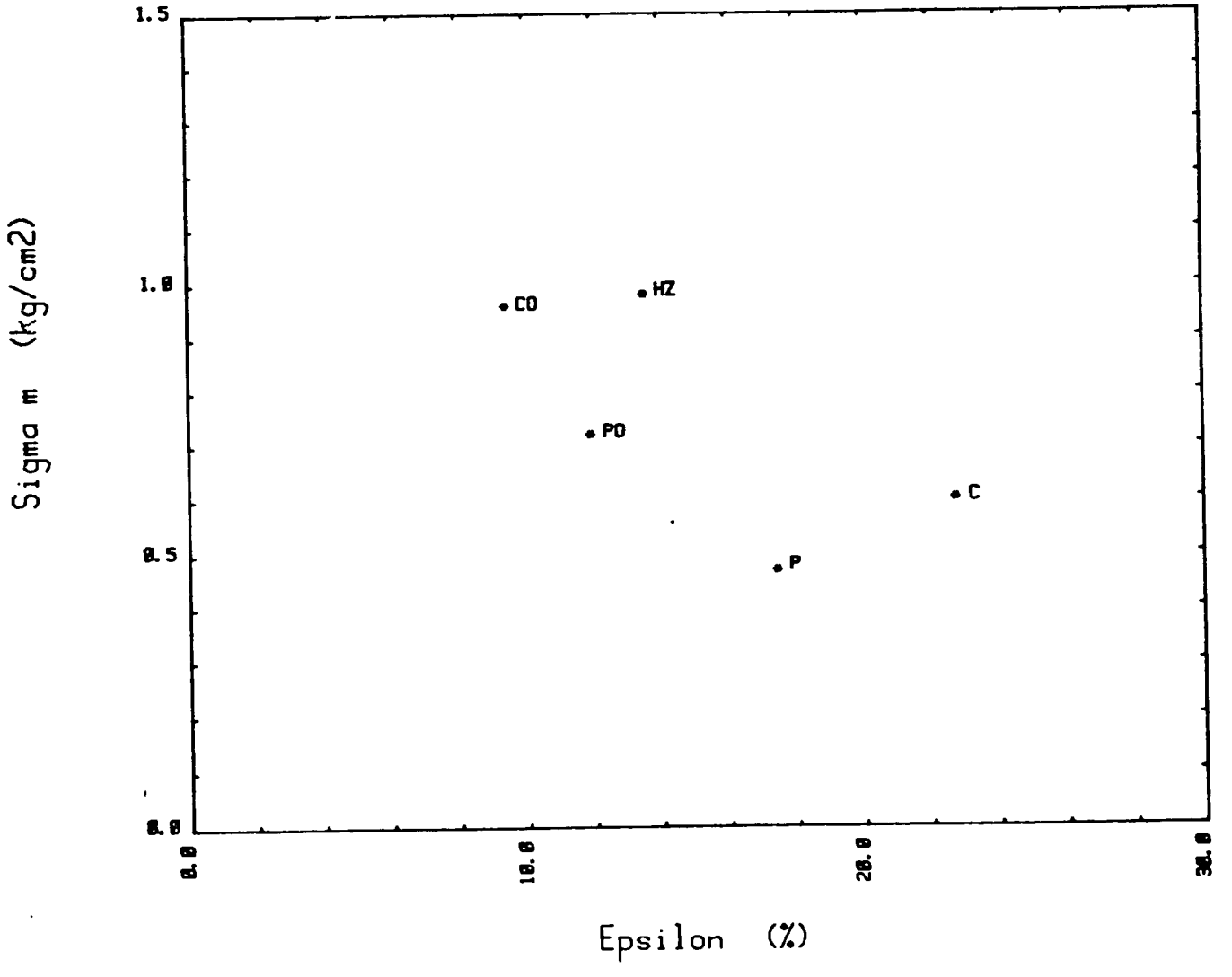

Fig. 1.33 DIAGONAL COMPRESSION vs VOLUMETRIC DRYING SHRINKAGE OF ADOBE BRICK

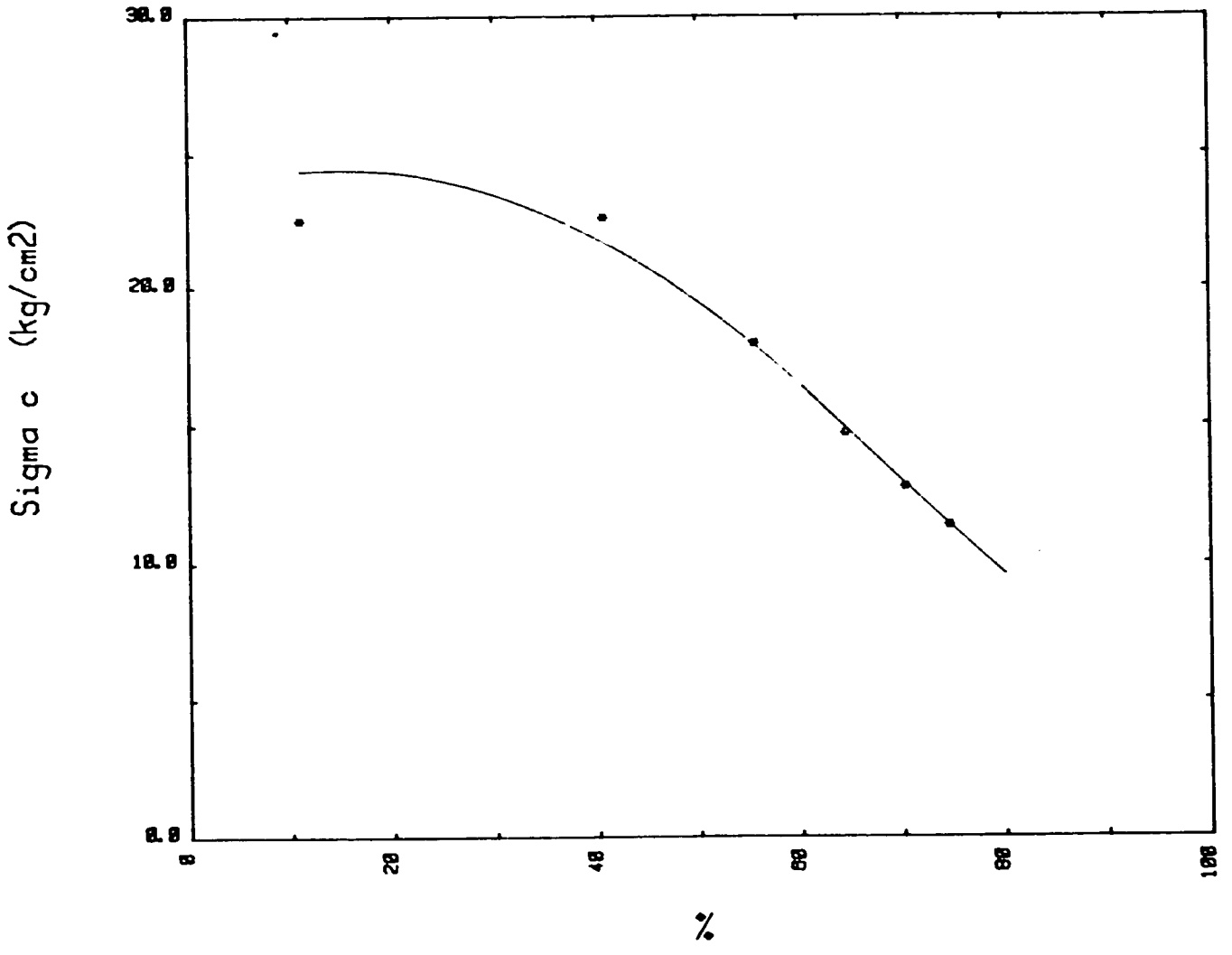

Fig. 2.1 EFFECT OF ADDITION OF COARSE SAND ON COMPRESSIVE STRENGTH OF ADOBE BRICK

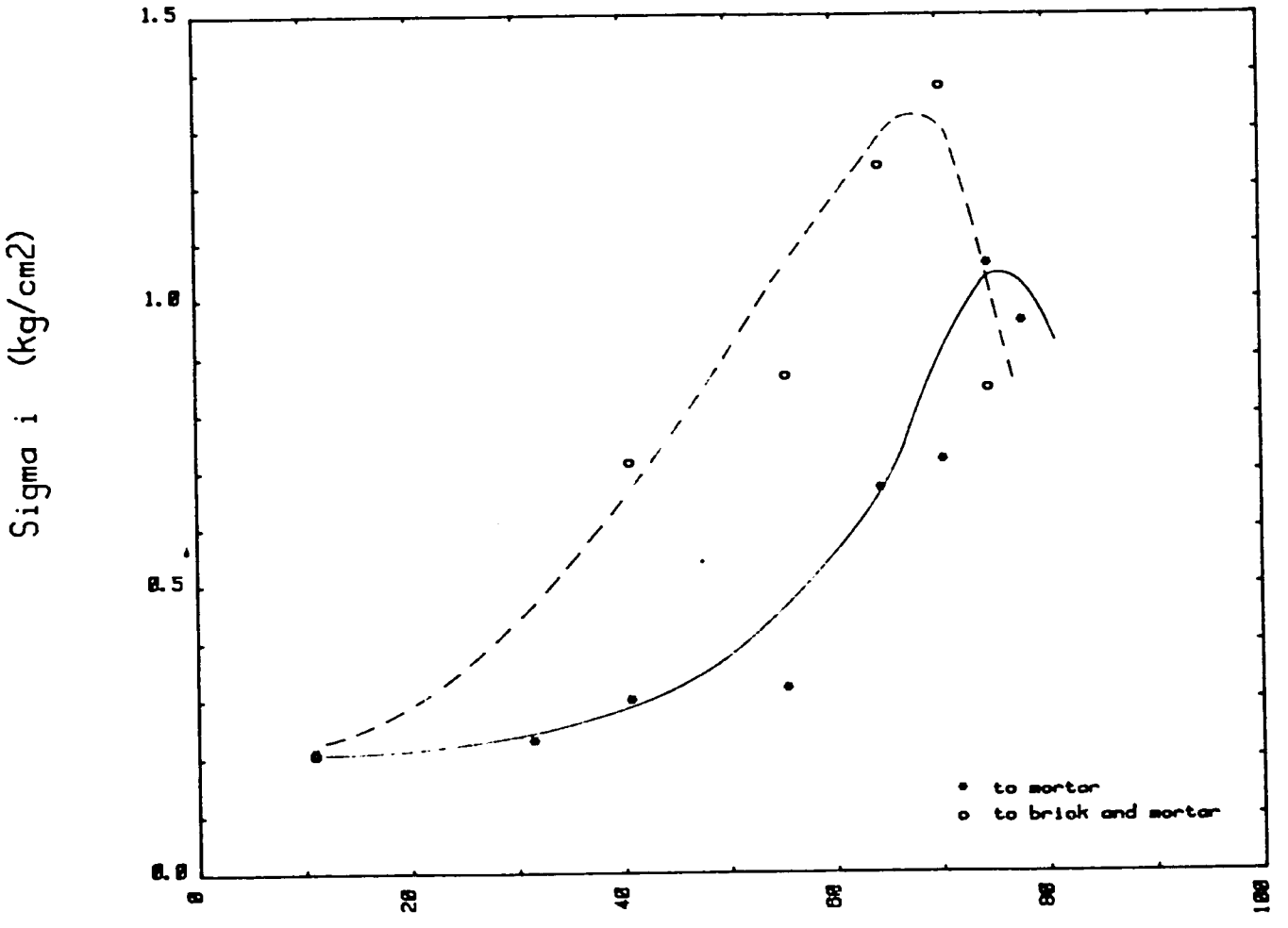

Fig. 2.2 EFFECT OF ADDITION OF COARSE SAND TO PUC SOIL - INDIRECT TENSION TEST

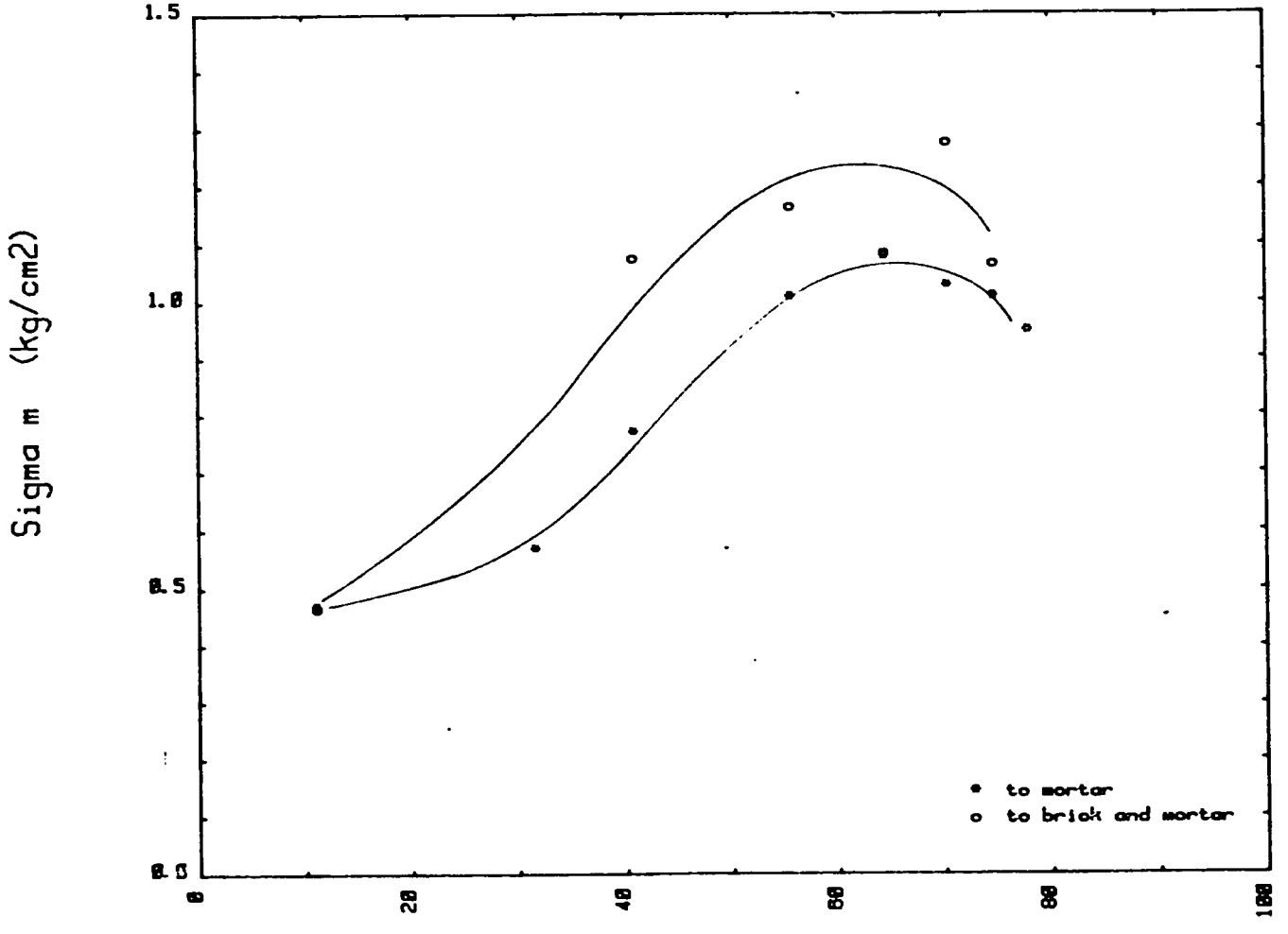

Fig. 2.3 EFFECT OF ADDITION OF COARSE SAND TO PUC SOIL - DIAGONAL COMPRESSION TEST

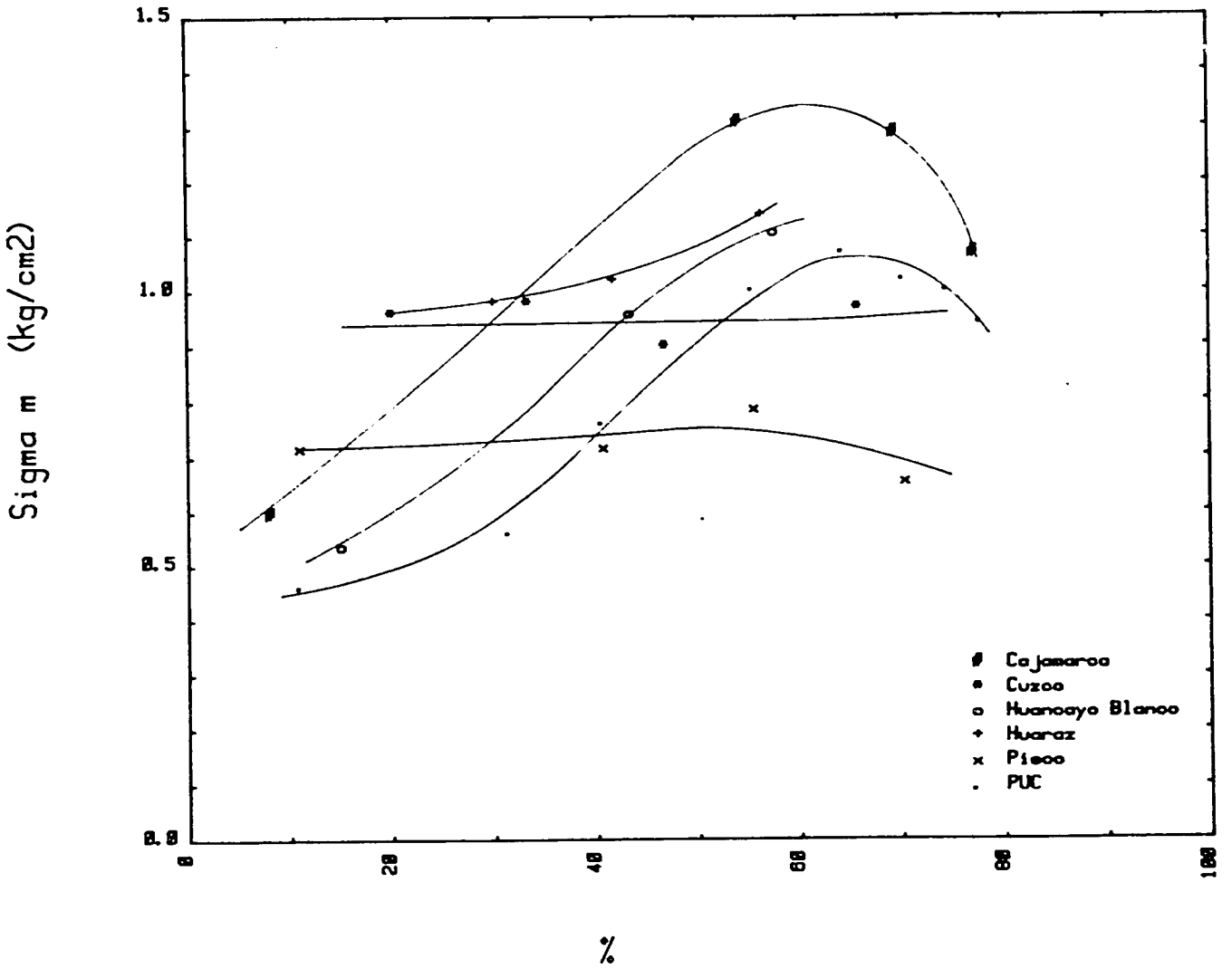

Fig. 2.4 EFFECT OF ADDITION OF COARSE SAND TO DIFFERENT SOILS - DIAG. COMPRES. TEST

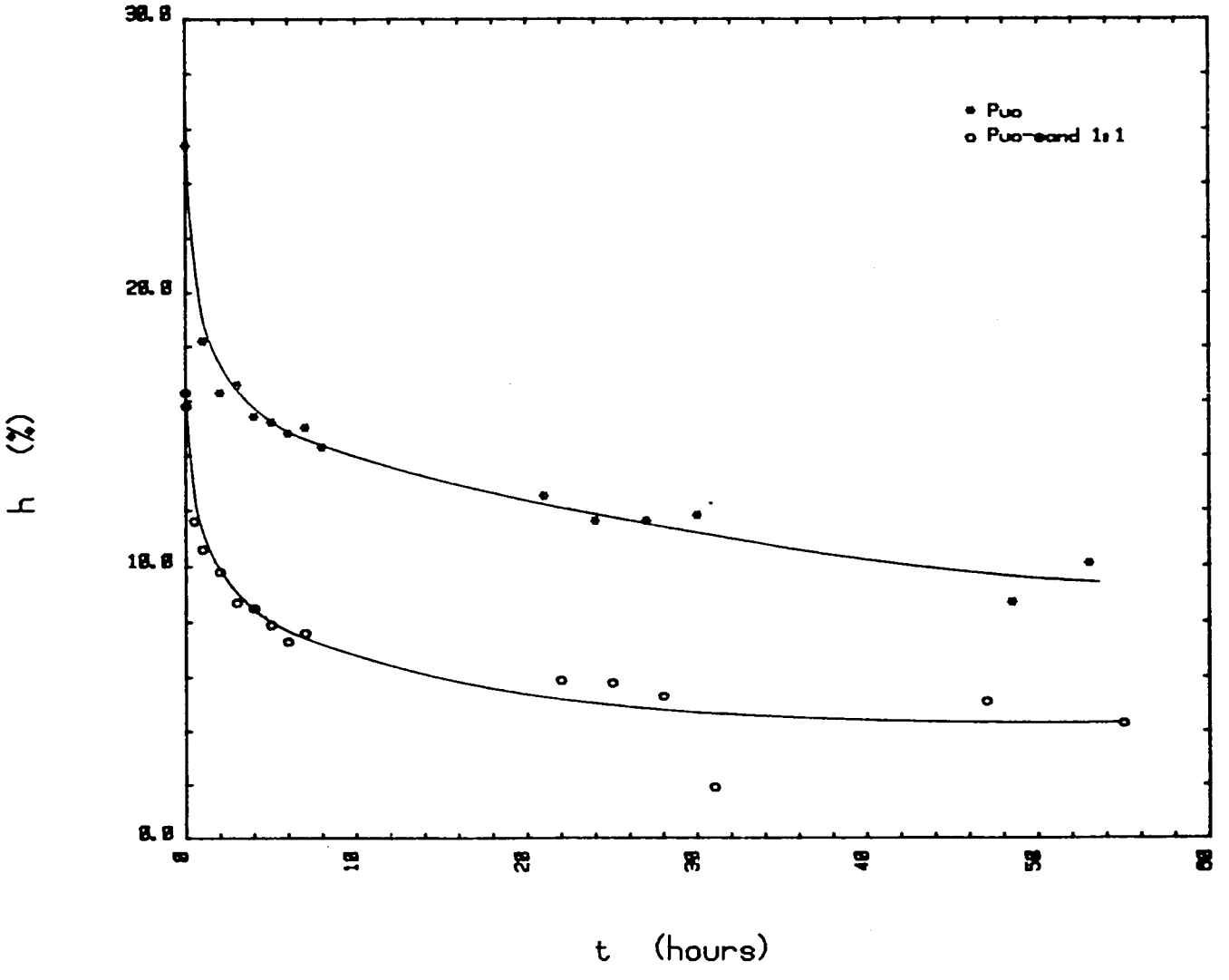

Fig. 2.5 WATER CONTENT vs TIME IN MORTARS

Effect of Addition of Coarse Sand

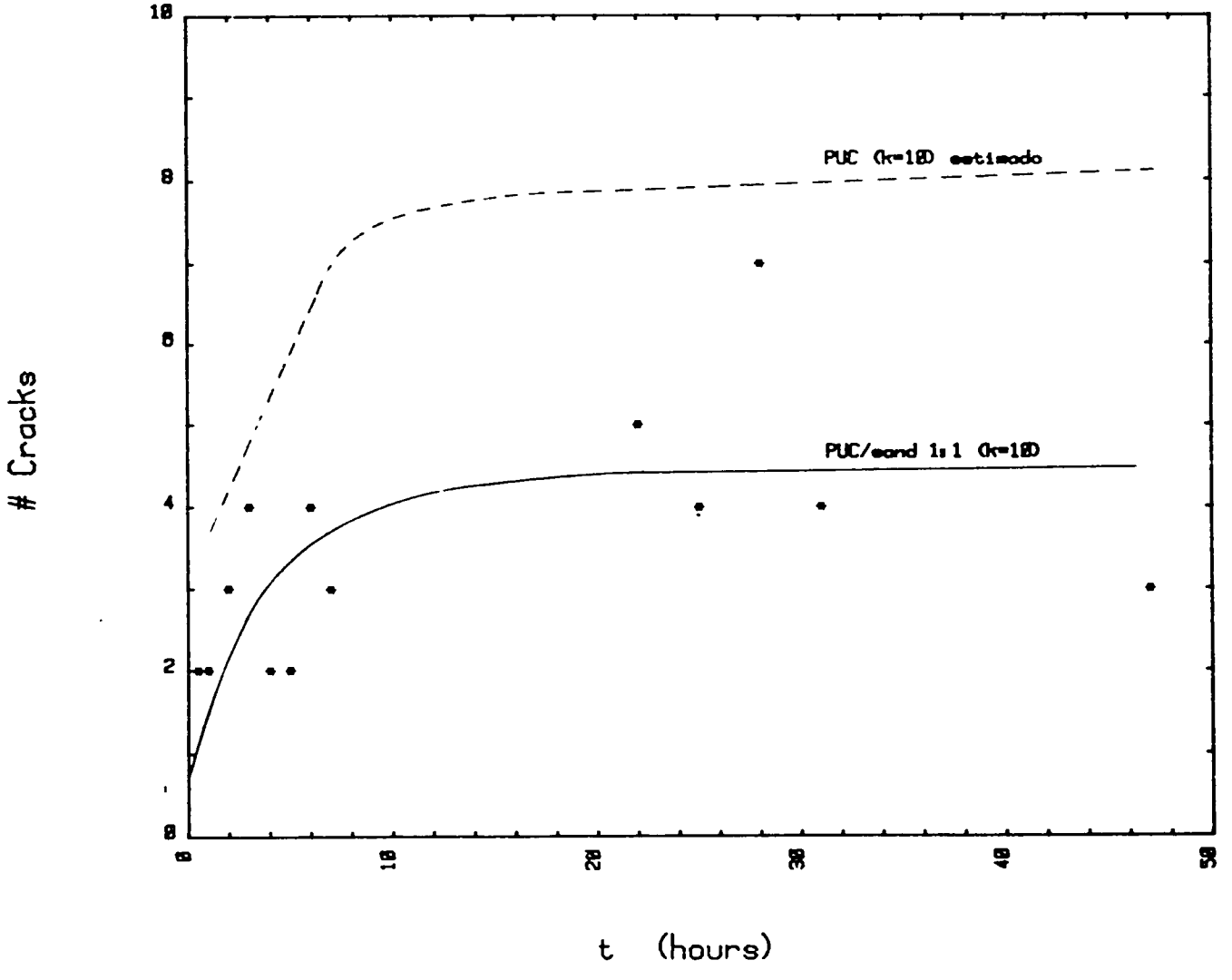

Fig. 2.6 NUMBER OF CRACKS vs TIME

Effect of Addition of Coarse Sand

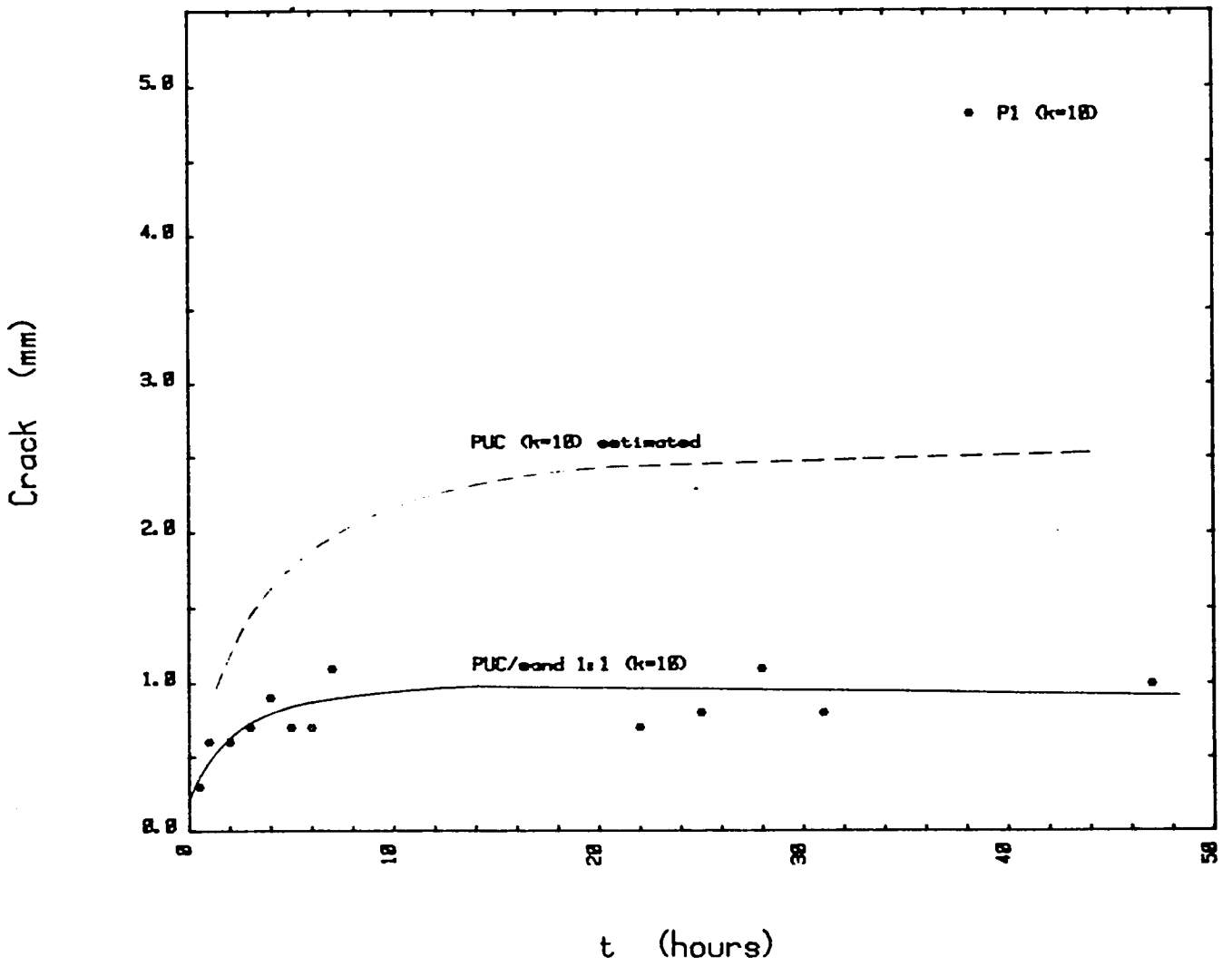

Fig. 2.7 MAXIMUM CRACK WIDTH vs TIME

Effect of Addition of Coarse Sand

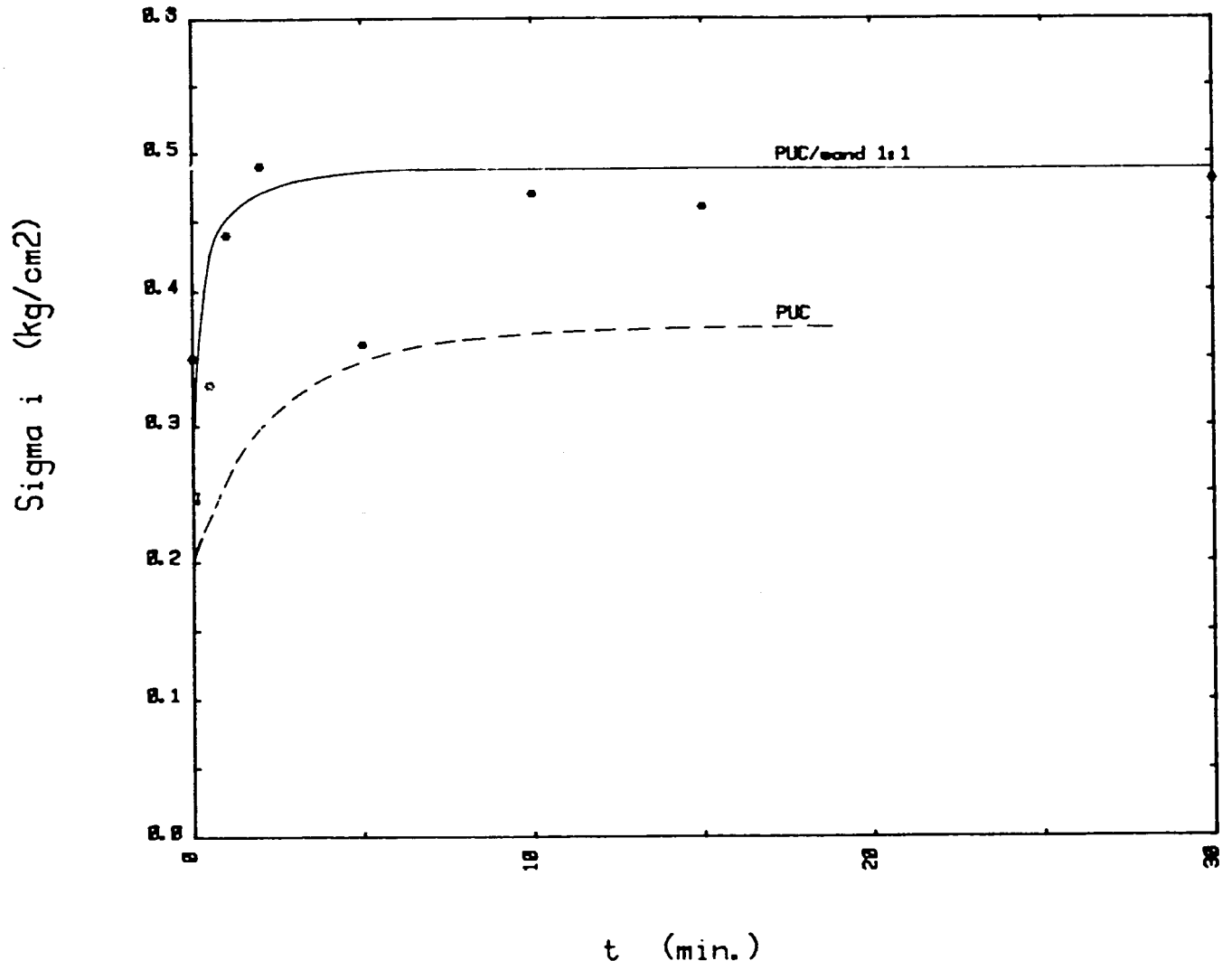

Fig. 2.8 INDIRECT TENSION STRENGTH vs WETTING TIME

MORTAR : PUC + COARSE SAND 1:1

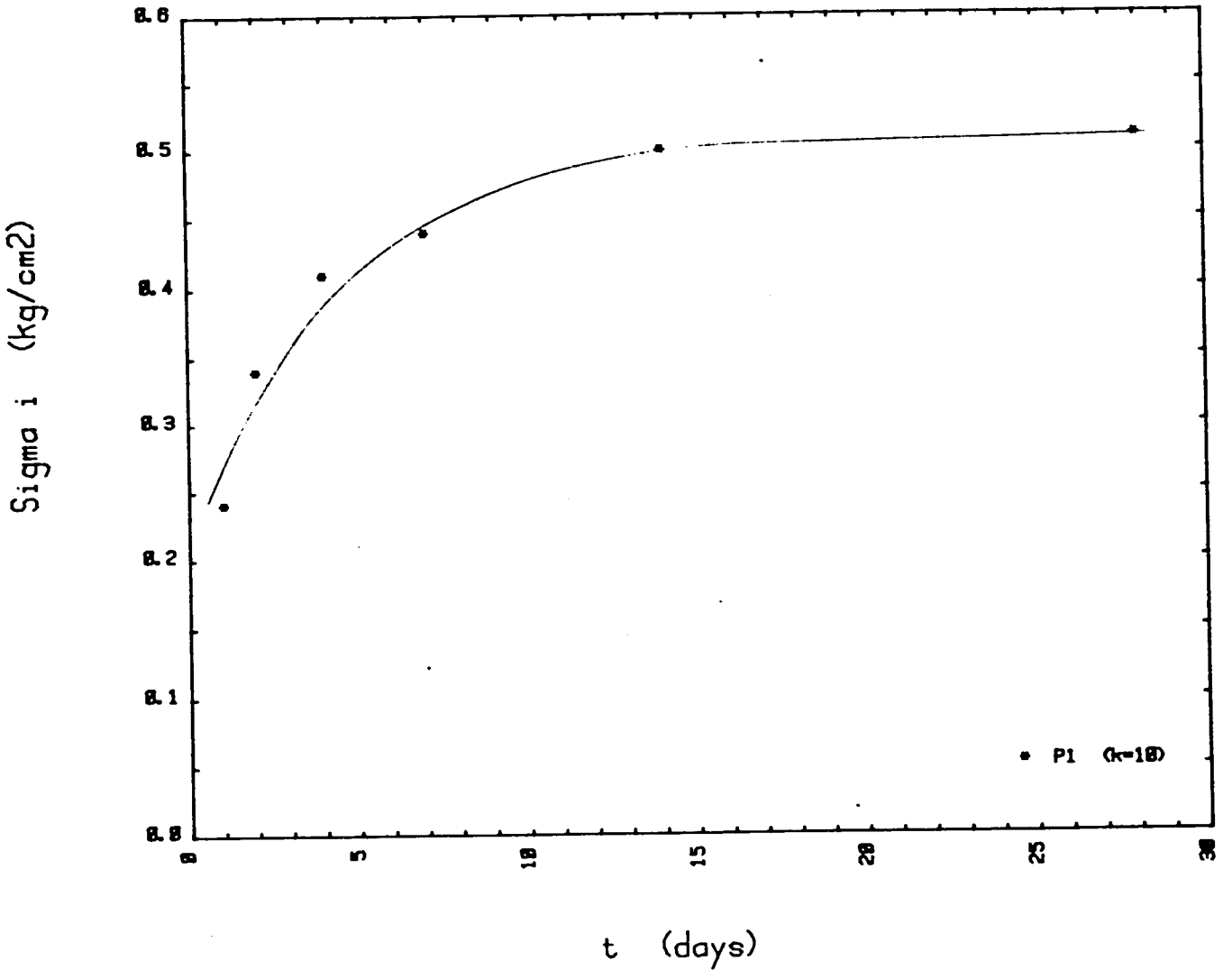

Fig. 2.9 INDIRECT TENSION STRENGHT vs TIME

Effect of Addition of Coarse Sand to Mortar

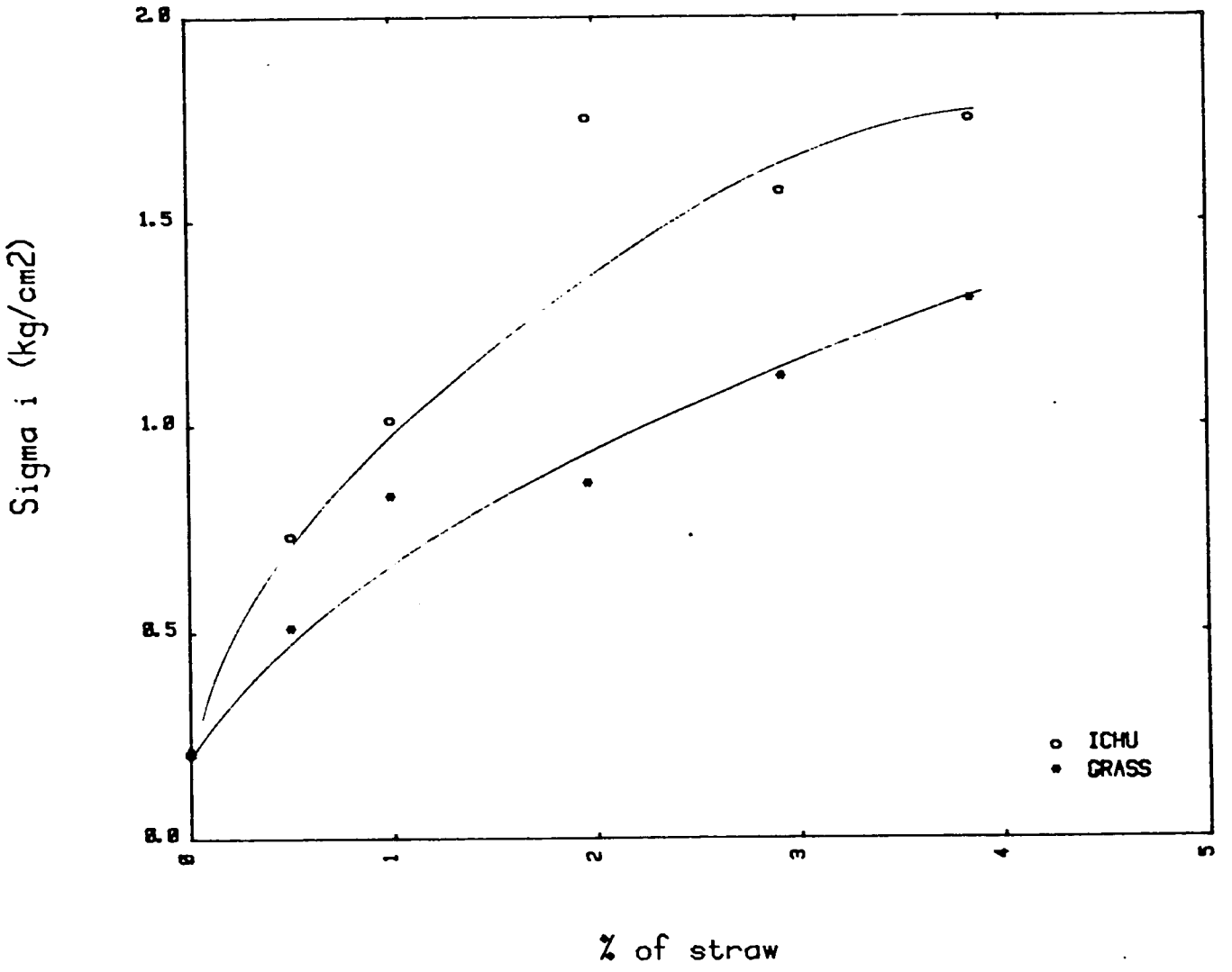

Fig. 2.10 EFFECT OF ADDITION OF ICHU OR GRASS TO PUC MORTAR - INDIRECT TENSION TEST

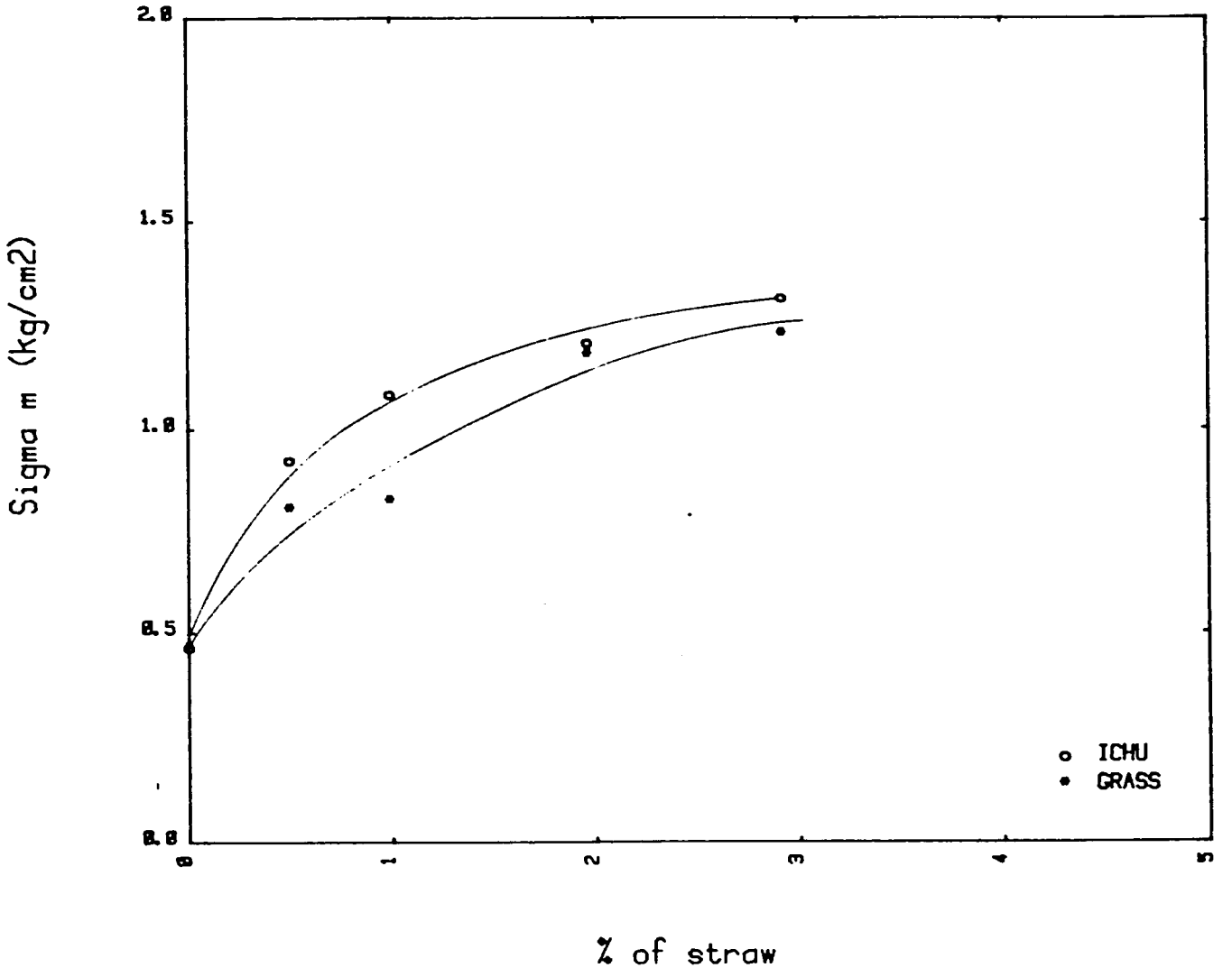

Fig. 2.11 EFFECT OF ADDITION OF ICHU OR GRASS TO PUC MORTAR - DIAGONAL COMPRESSION TEST

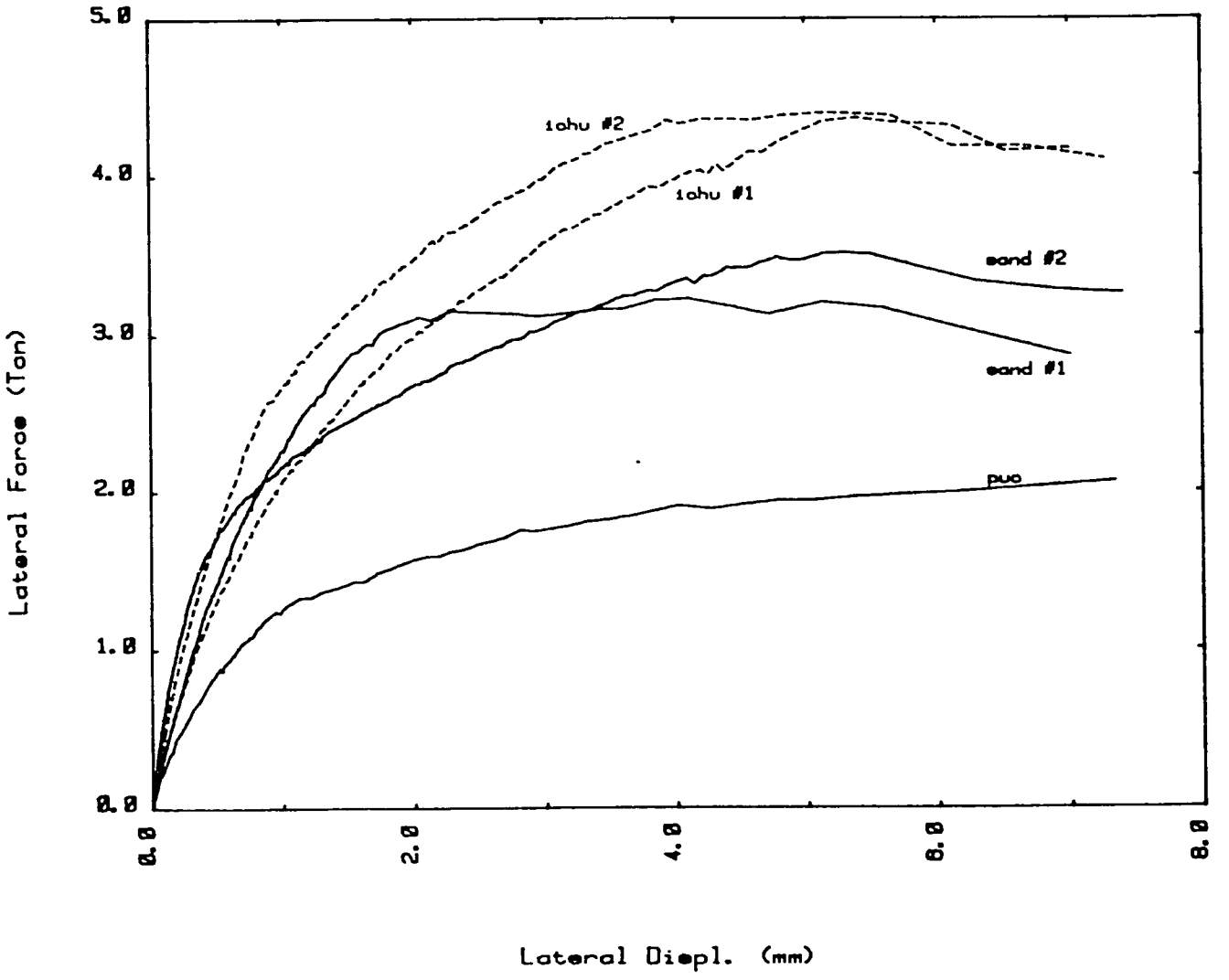

Fig. 2.12 FULL SCALE WALLS

Fig. 2.13 PUC Soil Monolithic Specimen

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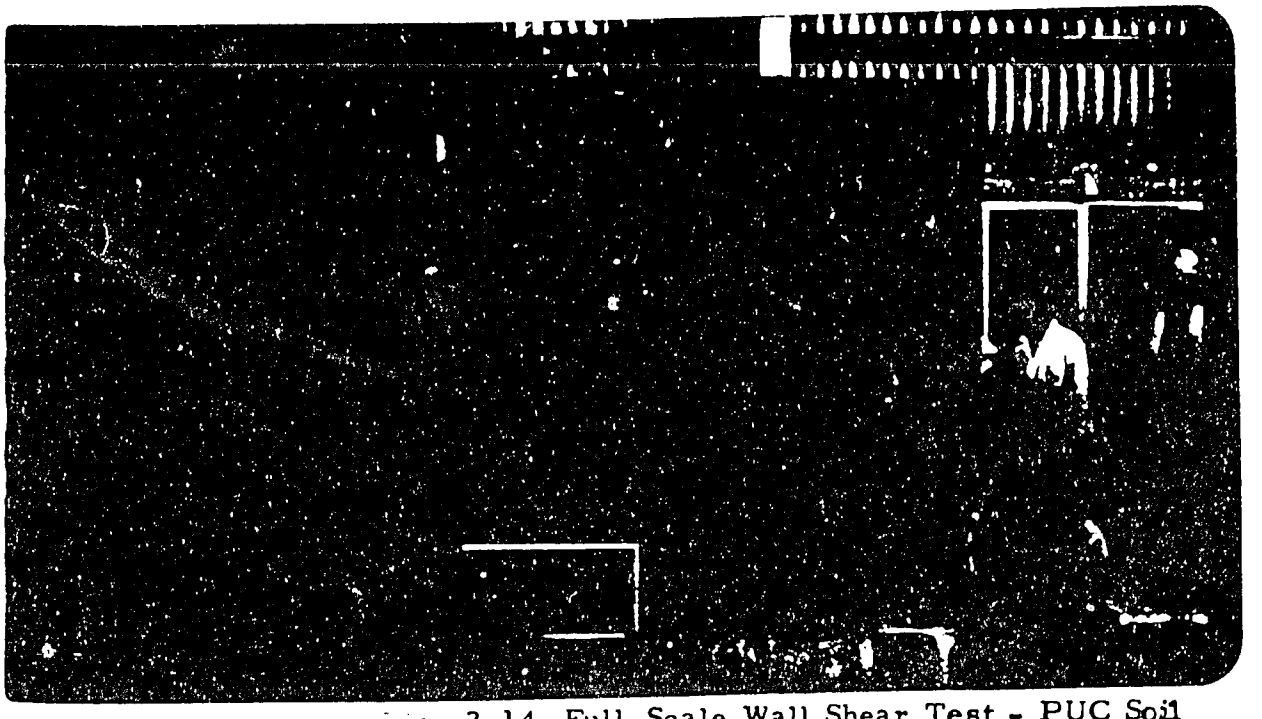

Fig. 2.14 Full-Scale Wall Shear Test - PUC Soil

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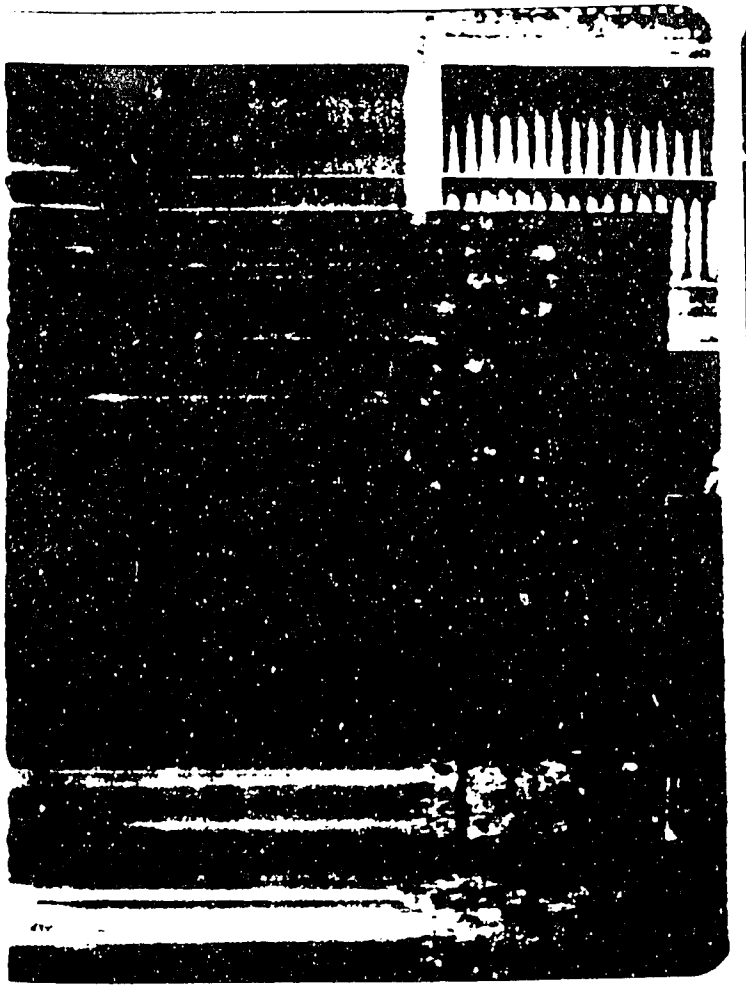

Full-Scale Shear Test
Coarse Sand 1:1

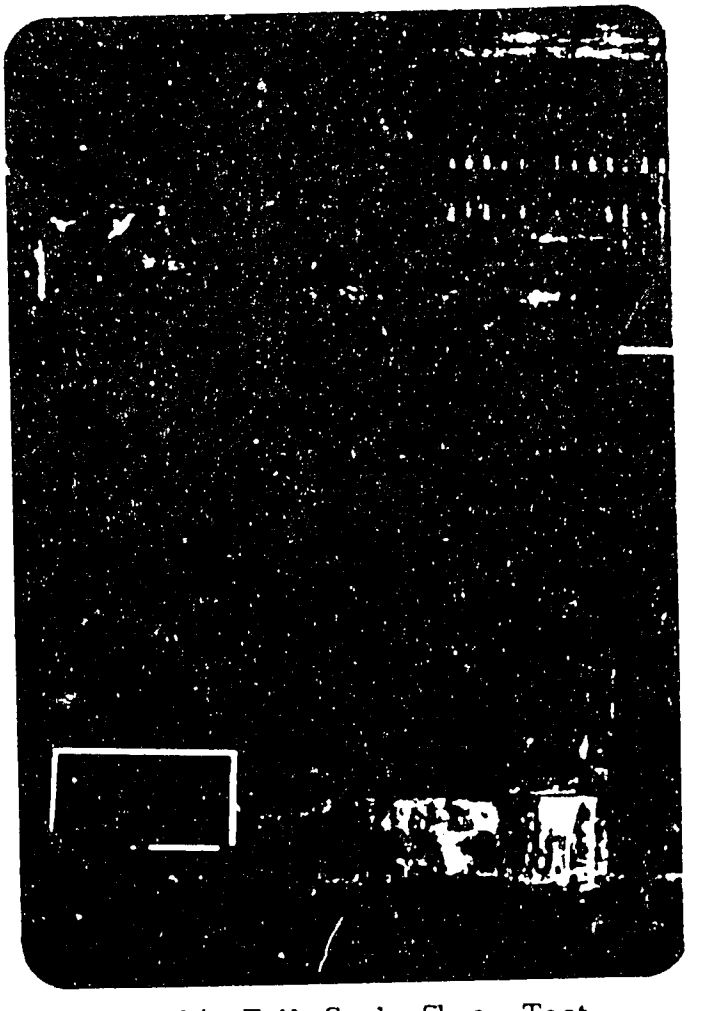

Fig. 2.16 Full-Scale Shear Test
PUC Soil+Ichu 100:2

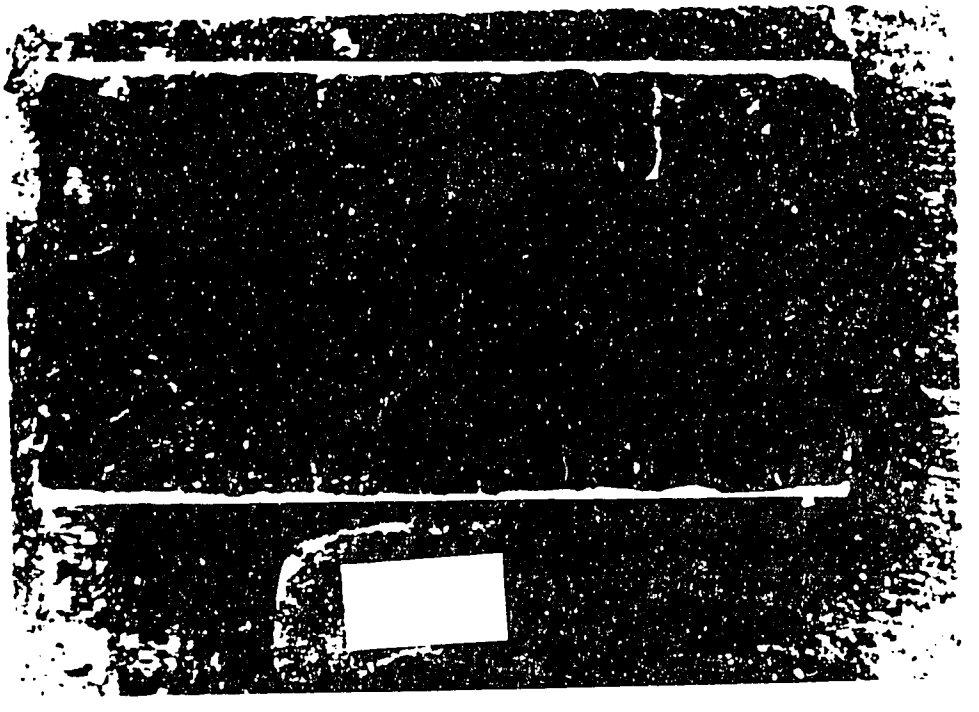

Fig. 2.17 Cracked PUC Soil Mortar

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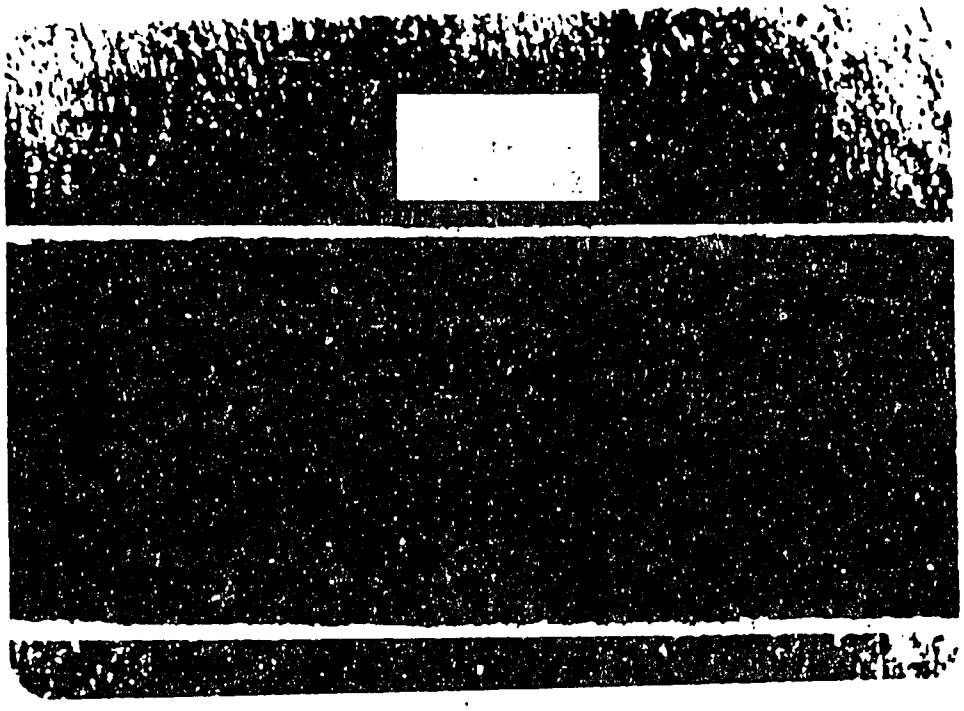

Fig. 2.18 Mortar PUC/Sand 1:2
Controlled Cracking

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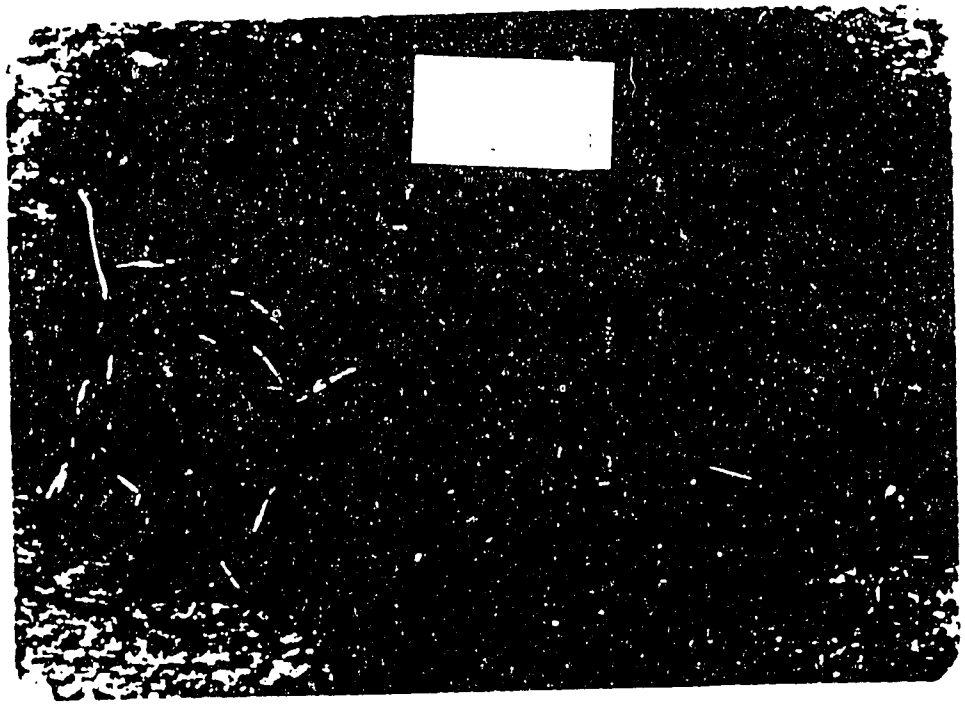

Fig. 2.19 Mortar PUC/Grass 100:4
Controlled Cracking

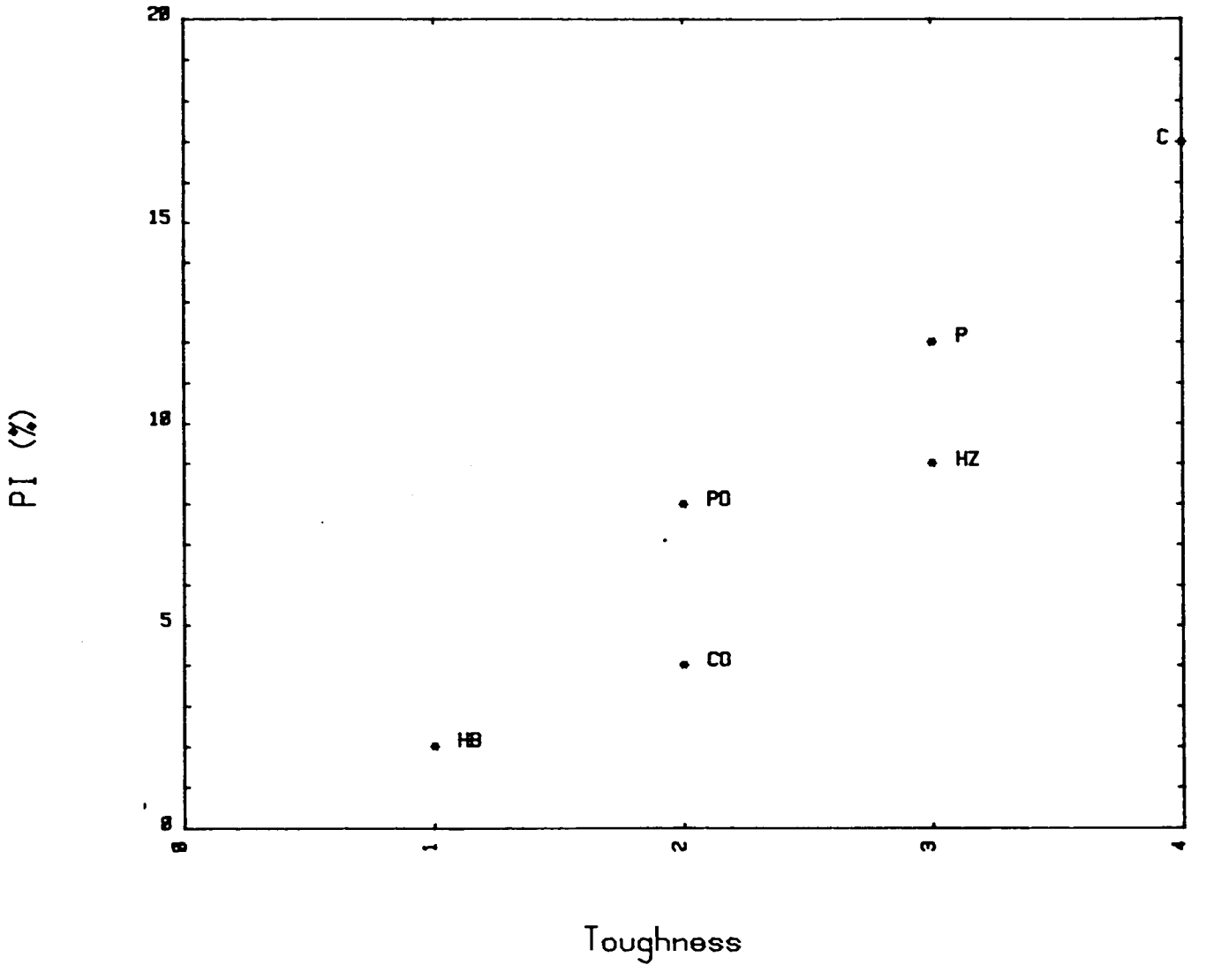

Fig. 2.20 PLASTICITY INDEX vs TOUGHNESS

Fig. 2.21 Dry Strength Field Test

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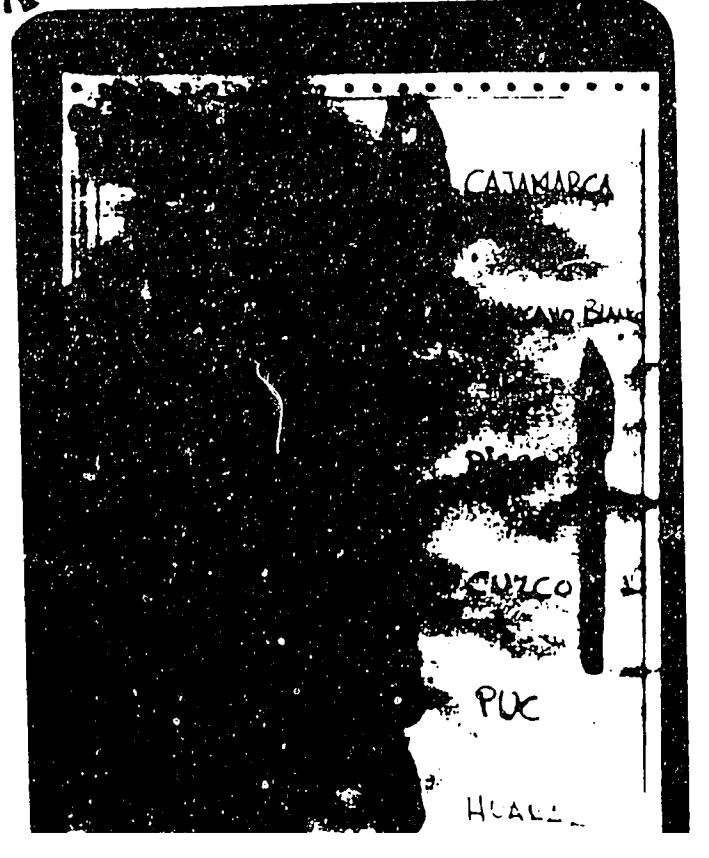

Fig. 2.22 Results of Dry Strength Test on 6 Selected Soils (Tests performed by 3 different persons)

Fig. 3.1 SOCIAL-ANTHROPOLOGICAL STUDY AREAS

Fig. 3.2 "Minka": Adobe Preparation with the Participation of Men and Women from the community.

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APPENDIX 1

LABORATORY TESTS PROCEDURES

1. SOIL ANALYSES

a) Tests performed in the Soil Mechanics Laboratory of the Catholic University of Peru, following the American Standard Test Methods (ASTM):

- Granulometry
  ASTM 442-63 (Reapproved 1972)
  "Standard Method for Particle-Size Analysis of Soils"

- Specific Gravity
  ASTM D854-56 (Reapproved 1972)
  "Standard Test Method for Specific Gravity of Soils'

- Shrinkage Limit
  ASTM D427-61 (Reapproved 1974)
  "Standard Test Method for Shrinkage Factors of Soils"

- Atterberg Limits
  ASTM D423-66 (Reapproved 1972)
  "Standard Test Method for Liquid Limit of Soils"

  ASTM D424-59 (Reapproved 1971)
  "Standard Test Method for Plastic Limit and Plasticity Index of Soils"

b) Tests performed at the University of California, Berkeley.

- Determination of the grain-size distribution of a fine-grained soil by the method of centrifuge. University of California, Berkeley.

2. CHEMICAL ANALYSIS OF SOILS AND WATER

Tests performed at the Laboratory of Chemistry of the Catholic University of Peru:

a) Analysis of Water.-

- Soluble salts ASTM (Part 31)
  "Standard Test Methods for Particulate and Dissolved Matter in Water", D1888-79

- Chlorides: "STM for Chloride Ion in Water and Waste Water", D512-79

- Sulfates: "STM for Chloride Ion in Water and Waste Water", D516-79

- Hardness: "STM for Hardness in Water", D1126-67

- pH: "STM for pH of Water", D1293-69

- Organic Matter: "Practices for Preparation of Sample Containers and for Preservation of Organing Constituents", D3694-79

b) Soil Analyses.-

Based on F.G. Welcher "Standard Methods of Chemical Analysis", Vol. II Part B.

Preparation SMCA II B	Page 2310-2311
SiO_2	" 2320
F_e	" 2320
Al	" 2320
Ca	" 2321
O.M. and Volatiles	" 2321
Fe_2O_3	" 2314

3. IDENTIFICATION OF CLAY MINERALS BY X-RAY DIFFRACTION

Tests performed at the University of California, Berkeley following the Standard: "Procedures for Determination of Soil Composition , X-Ray Diffraction Analysis, University of California, Berkeley.

4. MECHANICAL TESTS OF BRICKS AND MASONRY

Tests performed in the Laboratory of Structures of the Catholic University of Peru according to procedures specially developed for each purpose, standard methods, or adaption of standard methods for other materials.

These tests are the following:

a) Consistency
b) Compression
c) Bending
d) Direct Tension (Based on ASTM E144-66)
e) Indirect Tension
f) Diagonal Compression on Small Specimens
g) Diagonal Compression on Full-Scale Walls

Test Description

a) Consistency

Equipment:

- Vicat apparatus with a steel ball soldered to the rod (Figure A1-1).
- Trowel to level the sample.

Procedure:

Place the mortar in the recipient and level the surface. Let the rod fall and measure the penetration of the ball in the mortar.

Results:

The consistency is obtained as the average penetration in mm of three trials.

b) Compression Strength

b.1) Cubic 1" specimens

Equipment:

- ASTM mesh # 16
- One inch steel cubic molds.
- Porcelain bowl, rubber spatula and steel spatula.
- Testing machine.
- Oven.

Procedure:

- Sieve soils mechanically with # 16 (1.19 mm) mesh for 10 minutes.
- Quarter those soils of passing # 16 mesh by sample splitter.
- Use four cans to store quartered soils for casting.
- Determine moisture content by drying small amount of soils at 110°C oven.

There are four different mixing proportions for each soil: all soil, soil with 5% portland cement soil with 5% lime and soil with 0.1% Na_2CO_3.

- Grease 1" x 1" x 1" size of steel molds.
- Place weighed soils (and admixture) in a porcelain bowl.
- Slowly add water from graduate cylinder to soils, mix with rubber spatula by hand at the mean time. The water is added until soil-water mixture gives a good workability for casting.
- Record the amount of water added.
- Thouroughly mix soils and water by spatula for 5 minutes.
- Use thin steel spatula to transfer soils to steel mold, fill the mold to half layer, carefully rod with steel spatula 25 times, fill another half layer to the top, rod 25 times again.
- Finish the surface by steel spatula.
- Store the molds at room with 73°F temperature and 50% relative humidity.
- After 3 days, the soil cubes have dried and shrink a little bit. Slide off the soil cubes from steel molds.
- Leave the soil cubes at 73°F and 50% R.H. until the age of test.

Test:

- Use testing machine with capacity of 2400 libs, loading rate is 200 lbs/min.
- Crush three cubes for each mixing proportion.
- After test, determine the water content of specimens by drying at 110°C oven.

Results:

- Discard the numbers which deviate than 10% from the average of three numbers.
- The shrinkage of cubes is not considered, therefore the strength = $\frac{\text{Load (lbs)}}{1\ \text{in}^2}$

b.2) Cubic 10 cm specimens

Equipment:

- Cutting machine.
- Capping equipment: rule, trowel and level.
- Testing machine under displacement control.
- Plotter.

Procedure:

Preparation of Specimens.-

- Cut from adobe bricks, cubes of height equal to the thickness of the brick (10 cm)
- Apply a thin layer of gypsum as capping.

Test:

- Perform the compression test in testing machine at a displacement rate of 1.2 mm per minute.
- Plot the stress-strain curve.
- Test five specimens.

Results:

- Maximum stress (σ_c):

$$\sigma_c = \frac{\text{Maximum Load (Kg)}}{\text{Area of Cross Section (cm}^2)} \quad (\text{Kg/cm}^2)$$

- Young modulus (E): Slope of the initial linear-elastic zone of the stress-strain curve.
- Average of five specimens.

c) Bending of Bricks

Equipment:

- Capping equipment: rule, trowel and level.
- Testing machine plus arrangement to provide two simple supports plus central load, as show by Figure A1-2.

Procedure:

Preparation of specimens.-

- Lay three stripes of gypsum along the lines of loading and support.

Test:

- Perform the test in the testing under displacement control at a rate of 1.3 mm per minute.
- Record the maximum load (P_f)
- Test five specimens.

Results:

- Maximum bending stress (σ_f):

$$\sigma_f = \frac{1.5\ P_f\ L}{bh^2} \quad (Kg/cm^2)$$

where:

P_f = maximum load (Kg)

L = span (cm)

b = width of the brick (cm)

h = height of the brick (cm)

- Average of five specimens.

d) Direct Tension (Based on ASTM E149-66)

Equipment:

- Scrubbing brushes
- Testing machine and ASTM 149-66 arrangement to the adobe-brick dimensions. See Figure A1-3

Procedure:

Preparation of specimens.-

- Clean the brick surfaces with scrubbing brushes to remove sand and dust, then sprinkle with water to obtain dry-saturated surfaces.
- Lay two bricks, one on top of the other, making a cross.
- Place a 3 Kg. weight on top of specimen.
- Let the specimen dry in the shadow until test.

Test:

- Test on testing machine at a displacement rate of 0.4 mm per minute.
- Record maximum load.
- Test five specimens.

Results:

- Maximum traction strength (σ_d):

$$\sigma_d = \frac{\text{Maximum Load (Kg)}}{\text{Contact Area between Adobes (cm}^2)} \quad (\text{Kg/cm}^2)$$

- Average of five specimens.

e) Indirect Tension

Equipment:

- Scrubbing brushes
- Capping equipment: rule, trowel, level.
- Testing machine.
- Two 2.5 x 5.0 x 20.0 cm steel bars and two 0.5 x 2.0 x 20.0 plywood stripes to distribute the load.

Procedure:

Preparation of specimens (sandwiches).-

- Clean the brick surfaces with a scrubbing brush to remove and dust, then sprinkle water to obtain dry-saturated surfaces.
- Lay two bricks, one on top of the other, with a 1.5 cm thick mortar.

- Place a 10 Kg. weight on top of the specimen, and let it dry in the shadow.
- Place a thin gypsum stripe of 2 cm width on top of the mortar (long sides) as capping.

Test:

- Test in testing machine applying the load through the steel bars and plywood stripes at a displacement rate of 0.2 mm per minute.
- Record maximum load.
- Test five specimens.

Results:

- Maximum traction strength (σ_i):

$$\sigma_i = \frac{\text{Maximum Load (Kg)}}{\text{Contact Area between bricks (cm}^2)} \quad (\text{Kg/cm}^2)$$

- Average of five specimens.

f) Diagonal Compression in Small Specimens

Equipment:

- Scrubbing brushes.
- Capping equipment.
- Transporting system for specimens.
- Reaction frame.
- Hydraulic jack with capacity of at least 7 tons.
- Load cell.

- Hinge
- Two LVDT's
- Two plotters
- Amplifier

See testing set up in Figure A1-4

Procedure:

Preparation of specimens.-

- Clean the brick surfaces with a scrubbing brush to remove and dust, then sprinkle water to obtain dry-saturated surfaces.
- Fabricate walls with six layers with 6 1/2 bricks per layer and joints of 1.5 cm thickness.
- Place a layer of gypsum of 1 cm thick, 15 cm. wide and 15 cm. length as capping.
- Transport the specimens to test position.
- Locate two LVDT's on the diagonals of the specimen.

Test:

- Apply the load by means of the hydraulic jack at a rate of 200 Kg. per minute.
- Measure load and relative displacement.
- Obtain curves load vs. horizontal relative and load vs. vertical relative displacement.
- Record the maximum load.
- Test a minimum of three specimens.

Results:

- Maximum traction strength (σ_m):

$$\sigma_m = \frac{\text{Maximum Load (Kg)}}{\text{Diagonal Length x Thickness (cm}^2)} \quad (\text{Kg/cm}^2)$$

- Shear modulus (G):

$$G = \frac{\sigma_{m50\%} - \sigma_{m15\%}}{\varepsilon_{50\%} - \varepsilon_{15\%}} \quad (\text{Kg/cm}^2)$$

where:

$\sigma_{m50\%}$, $\sigma_{m15\%}$ = Traction stresses for 50% and 15% of the maximum load, respectively (Kg/cm^2).

$\varepsilon_{50\%}$, $\varepsilon_{15\%}$ = Strains (sun of the two diagonal strains). For the 50% and 15% of the maximum load, respectively.

- Average of the number of tests performed.

g) Diagonal Compression in Full-Scale Walls

Equipment:

- Capping equipment: rule, press, trowel, level.
- Transporting system.
- Steel angle for load application and reaction plate.
- Hydraulic jack (minimum 15 tons.)
- Hinge.
- Load cell.

- Tension bars.
- Reaction frame.
- LVDT's
- Data acquisition system.

See testing set up in Figure A1-5

Procedure:

- Clean the brick surfaces with a scrubbing brush to remove and dust, then sprinkle water to obtain dry-saturated surfaces.
- Build the wall on top of a concrete beam of dimensions 25 x 30 x 300 cm. with a built in reaction plate.
- Lay gypsum capping of 1 cm thick between and steel reaction plate and angle.
- Transport the wall with bracing to avoid any deformations.

Test:

- Apply the load in the diagonal direction by means of the jack at a velocity of 600 Kg. per minute.
- Measure relative displacement along the diagonals, lateral displacements of the wall and vertical displacement of the bottom of the wall.
- Record load and displacements with the data acquisition system.

Results:

- Load and displacements histories.

- Maximum shear strength:

$$\sigma = \frac{\text{Maximum Load (Kg)}}{\text{Diagonal Length x Thickness}} \quad (\text{Kg/cm}^2)$$

- Shear modulus (similar to case of diagonal compression in small walls).

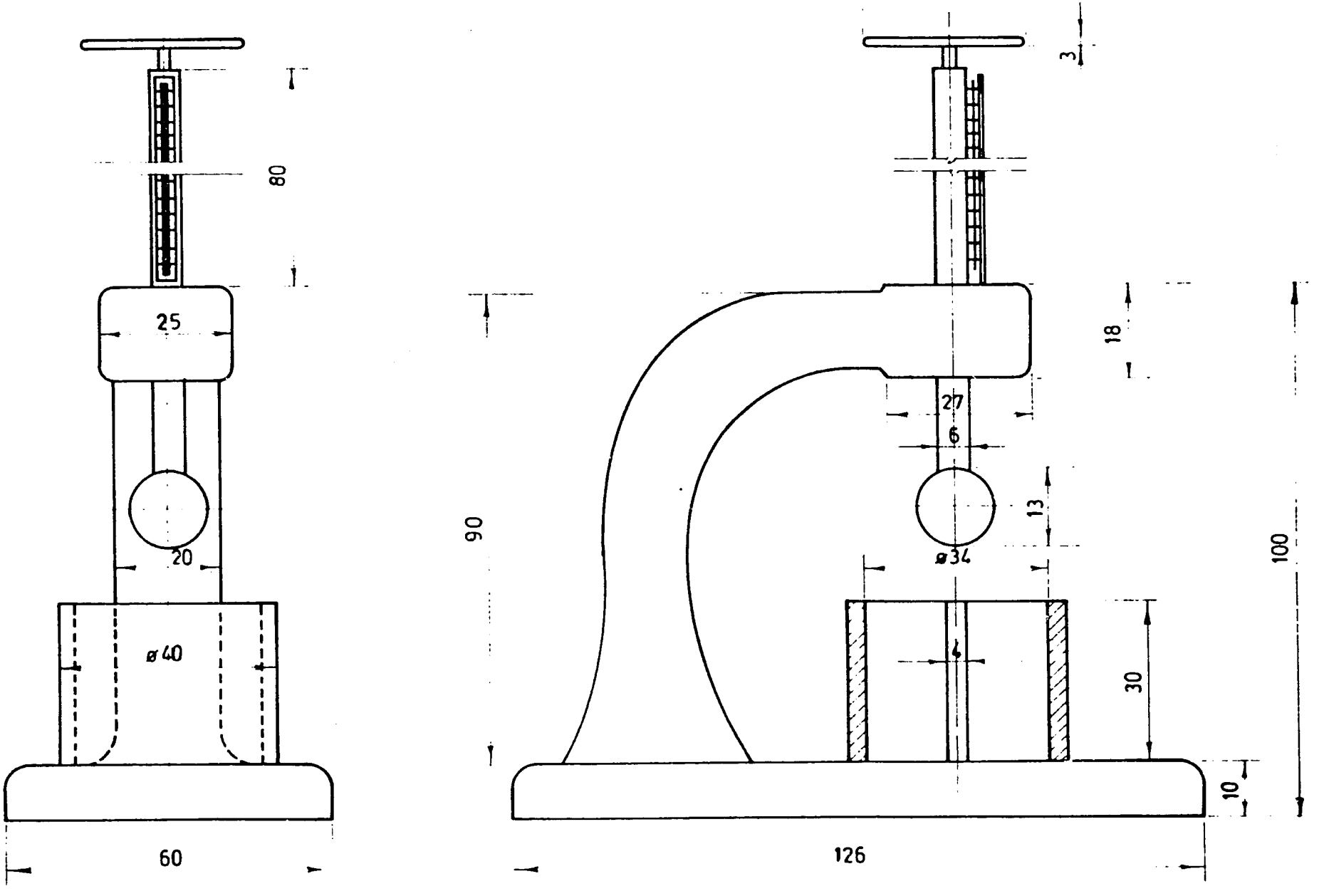


Fig A.1-1. Instrument for mortar consistency determination
(Modified Vicat Apparatus)

Not to scale
(dimensions in mm)

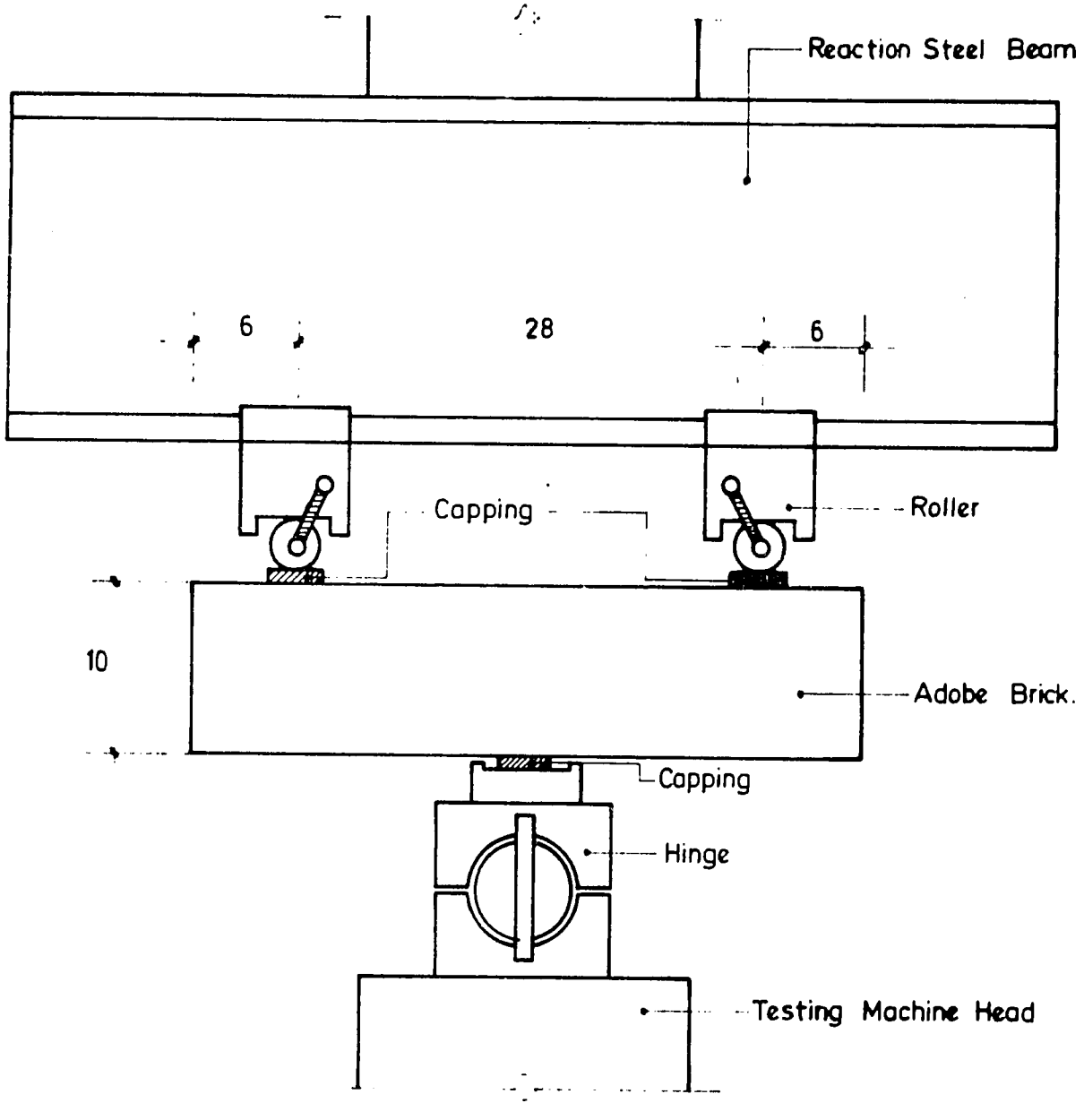
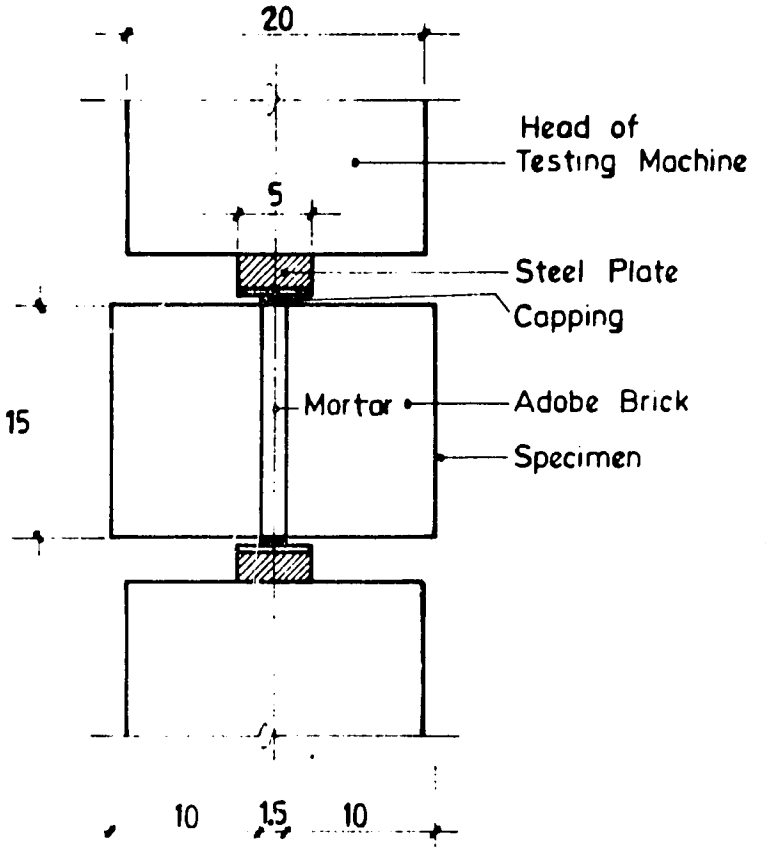
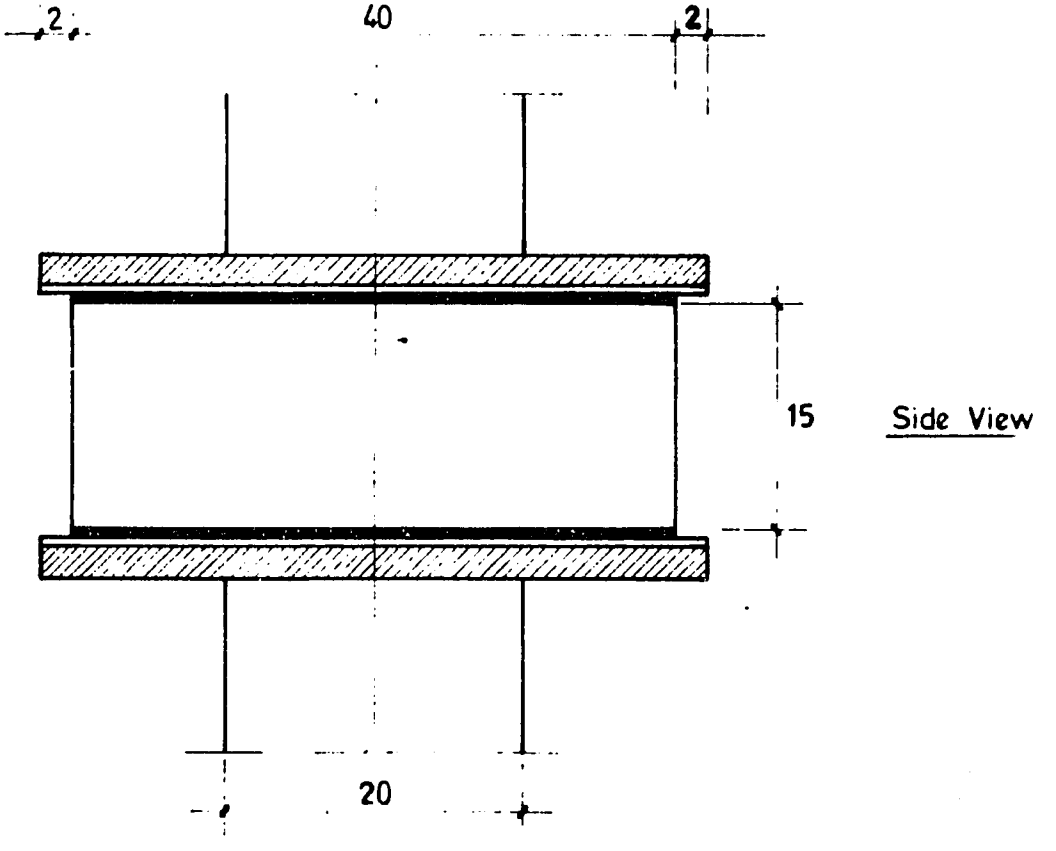
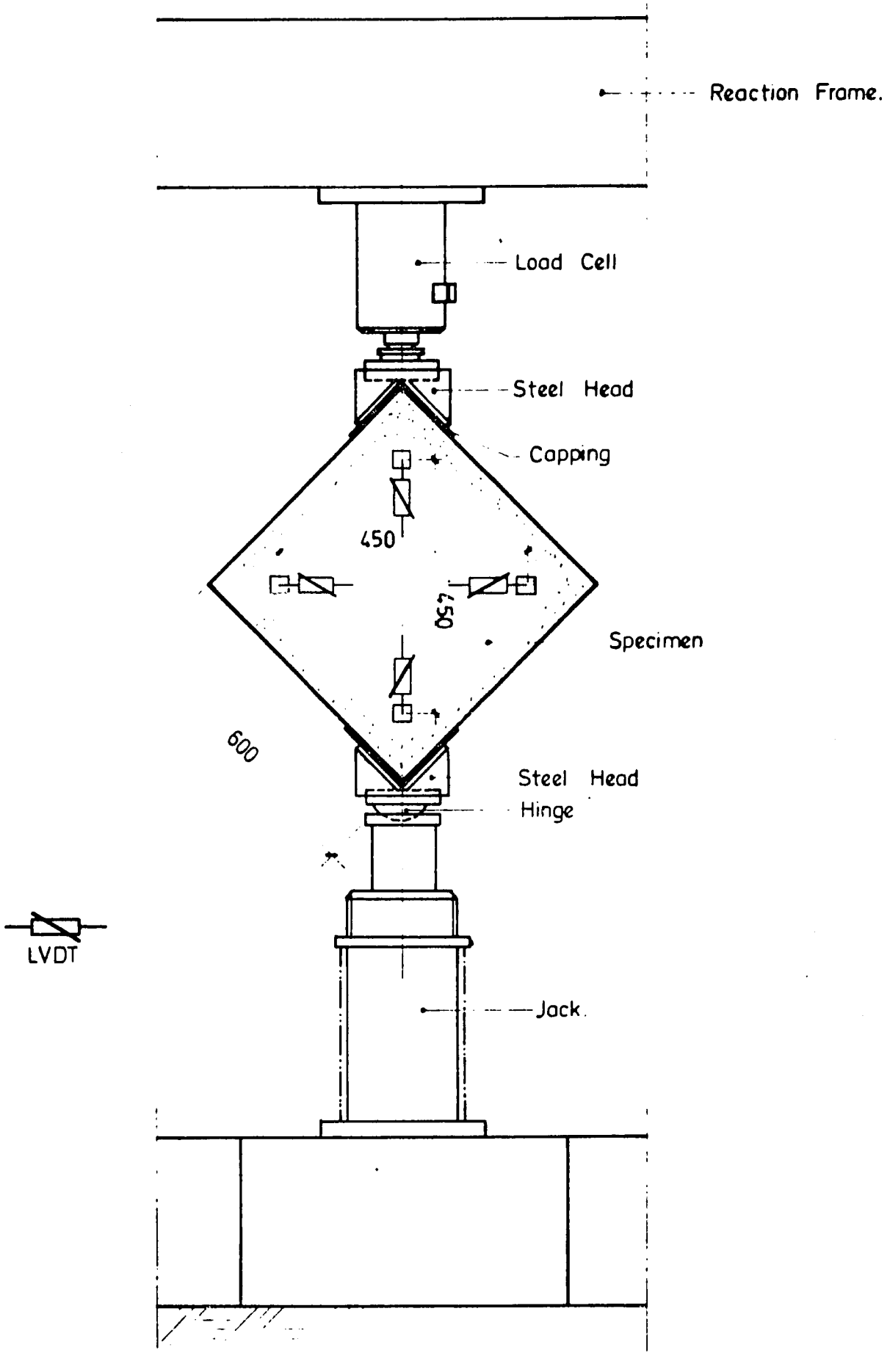


Fig. A1-2.. Adobe Brick Flexural Test Setup.


20
Head of
Testing Machine
5
Steel Plate
Capping
15
Mortar
Adobe Brick
Specimen
10
1.5
10


2
40
2
15
Side View
20


Reaction Frame.
Load Cell
Steel Head
Capping
450
450
Specimen
600
Steel Head
Hinge
LVDT
Jack.

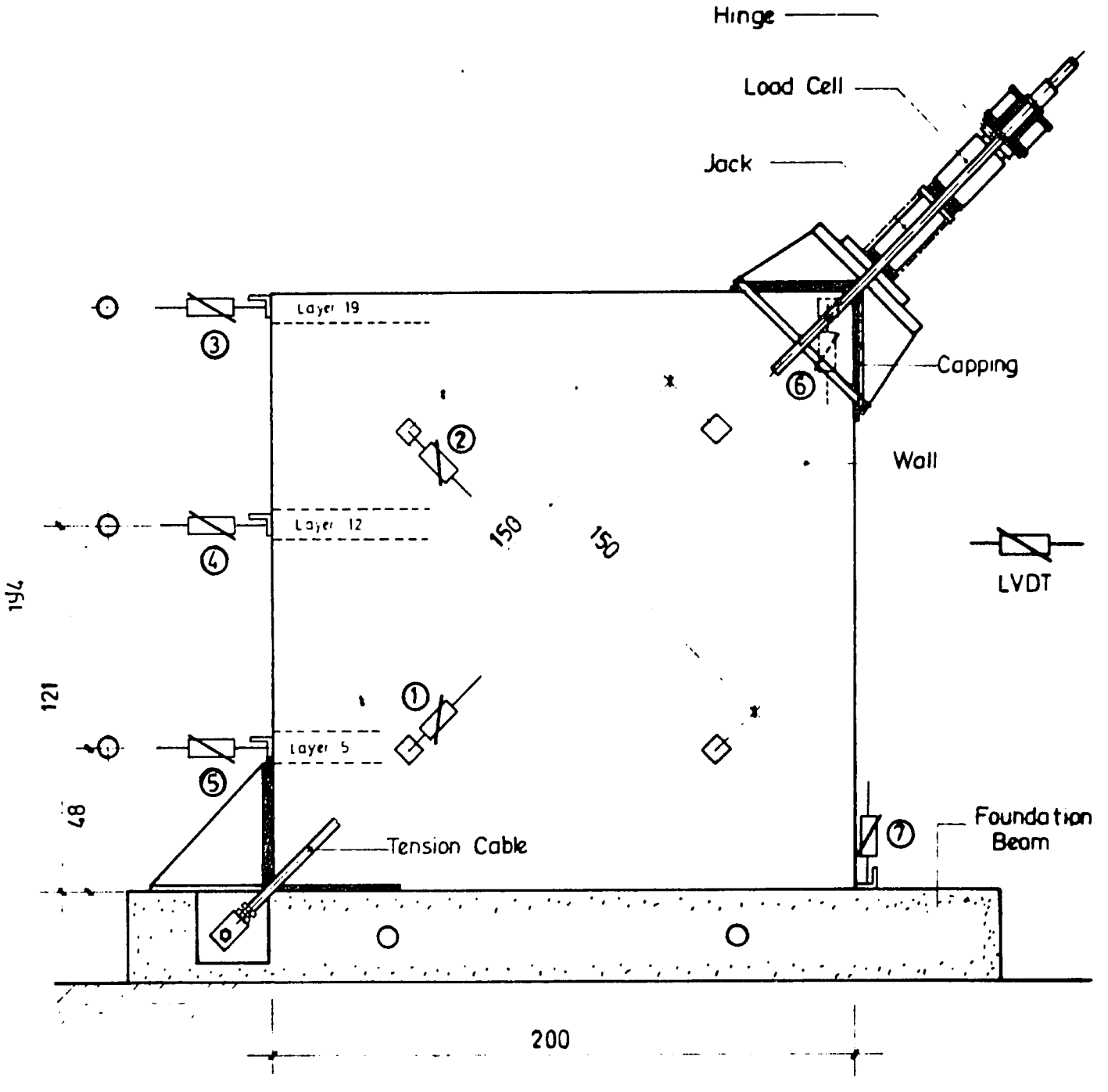


Fig. A1-5.- Full Scale Shear Test of Adobe Walls Set up.

APPENDIX 2

FIELD TESTS FOR SOIL IDENTIFICATION

This Appendix describes field tests used in the selection of soils during the first part of this research. These tests were taken from Ref. 10 .

All the field tests were performed after sifting the soil with a # 40 mesh.

Some tests required to prepare a soil-water mixture with a "putty' consistency. This consistency is attained when the soil begins to crumble when rolled out into thin threads.

The tests carried out are:

1. Color
2. Smell
3. Hand wash
4. Brightness
5. Dilatancy
6. Toughness
7. Ribbon Test
8. Adhesion to Hands
9. Adhesion to Instruments
10. Granulometry Field Test

DESCRIPTION OF TESTS

1. Color

Objective	:	To identify the chemical composition and organic matter content.
Procedure	:	Note the color and natural humidity.

Interpretation of Results:

Color	Component or Type of Soil
Black Dark green Light brown	Organic Soil
White Greyish white Dark coffee brown	Active Organic Material
Light grey	Calcium Carbonate
Clear and bright	Inorganic Soil
Red Brown Dark	Iron Oxides
Red Reddish coffee	Dehidrated Iron Oxide
Yellow Yellowish coffee	Iron Hidrates
White Greyish	Coral bearing soils, Calcareous stone, gypsum

2. Smell

Objective : To identify the presence organic material, associated with rancid smell.

3. Hand Wash

Objective : To identify the soil

Procedure : Rub the palms of the hands with the soil and then wash hands with water.

Results : The following situations can be observed:

- If the soil is soapy and difficult to wash off, it is a clayish soil.
- If the soil is dusty when the hands are rubbed and is not difficult to remove, it is a silty soil.
- If the soil is very easily washed off, then it is a sandy soil.

4. Brightness

Objective : To identify the soil.

Procedure : Cut a sample of soil previously moisted to the "putty" consistency and observe the cut surfaces.

Results :

- If the surface is opaque, it is a sandy soil.
- If the surface is bright and discontinuous, the soil is silt or a low plasticity clay.
- If the surface is bright and continuous, the soil is clay.

5. Dilatancy

Objective : To determine the quantity of clay present in the soil.

Procedure :

- Prepare a 10 cm^3 tablet of soil in "putty" consistency.
- Place the tablet in the palm of the hand and agitate horizontaly, striking vigorously with the other hand.

- Count the number of strikes necessary for water to appear on the surface of the tablet.
- Press the sample with the thumb and index observing if the water disappears or not and if cracks are formed.

Results :

# of Strikes	Clay Content	Comment
30	high	Water may or may not appear with a great number of strikes in the case of soils with a high amount of clay content.
20-30	regular	-----
10-20	low	-----
5-10	none	Fine sand or silt.

5. Toughness

Objective : To determine the quantity of clay present in the soil.

Procedure : Form a 2 cm diameter ball with soil in "putty" consistency and press with the fingers, recording the strength required.

Results :

- The ball is very strong, it is not split or crushed. This result is characteristic of soils with high clay content.

- The ball is moderately strong, it splits and falls apart. This result is proper of soils with a medium amount of clay.
- Putty consistency cannot be attained (the threads cannot be made). This result corresponds to soils with lime and sand and little clay.
- The ball is spongy. This shows that it is an organic soil.

7. Ribbon Test

Objective : To determine the quantity of clay present in the soil.

Procedure :

- Take enough soil in "putty" consistency to form a roll the size of a cigarette.
- Place the roll on the palm of the hand and, starting with one end, crush with the thumb and index forming a ribbon of 3 to 6 mm width.
- Measure the length of ribbon that can be made without breaking.

Results :

Length of the Ribbon (cm)	Clay Content
20	high
10-20	regular
5-10	low
5 or the ribbon cannot be made	none

8. Adhesion to Hands

Objective : To determine the quantity of clay present in the soil.

Procedure : Make a ball with soil in the "putty" consistency and observe the residues on the hands.

Results :

Amount of Residue	Clay Content
High	high
Medium	medium
Minimum	minimum

9. Adhesion to Instruments

Objective : To determine the quantity of clay present in the soil.

Procedure : Make a ball of soil in the "putty" consistency, introduce a spatula and observe:

- The resistance of the soil to penetration.
- The adhesion to the instrument.

Results :

Resistance	Clay Content	Comments
High	high	The ball clings to the instrument.
Regular	regular	The ball clings to the instrument.
Low	low	The ball does not adhere to the instrument.

10. Granulometry Field Test

Objective : To determine the granulometric composition of the material.

Procedure :

- Fill with soil one fourth of a thin bottle or test tube of 1/2 liter capacity.
- Add water up to three fourths of the height of the bottle.
- Vigorously agitate the bottle,making sure that all the soil particles are in suspension.
- Leave the test tube in vertical position during one hour; afterwards record the heights of the different sediment layers.
- Agitate again and let rest.
- Record the heights of the layers after 45 minutes, 8 hours,and when all the soil particles have sedimented.

Results : It will be observed that sand sediments inmediately, silt after a few minutes and that clay stays in suspension for 8 or more hours. Once all the layers have sedimented, the distribution of sand, silt and clay in the soil can be estimated from the relation between the different heights of the corresponding layers.

APPENDIX 3

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