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SEISMIC STRENGTH OF ADOBE MASONRY*

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* Research Project Financed by the Agency for International Development (US/AID)

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SUMMARY

This paper presents the main conclusions and recommendations of the Research Project "Earthen Buildings in Seismic Areas", developed in the Catholic University of Peru (PUC) in 1983.

The most important soil characteristics from the viewpoint of the strength of adobe masonry are first studied. Subsequently, based on the acquired knowledge, the effect of some natural additives to the soil is investigated. Simple field tests, devised to identify the most adequate materials for adobe construction and to be easily transmitted to the potential adobe builder are finally proposed.

* The first three authors are from the Earthquake Engineering Laboratory of the Catholic University of Peru, Lima, the last author is from the Civil Engineering Department of the University of California, Berkeley.

1. INTRODUCTION

In Third World countries considerable loss of life caused by earthquakes occur in earthen buildings. The scientific and technical communities of these countries can significantly contribute to control the problem by finding ways to increase the strength of this traditional building material and disseminating the improved construction techniques among the builders, the majority of whom do not have any means to develop the necessary know-how.

2. BACKGROUND AND OBJECTIVES

It was only in the 1970's that consciousness was raised in Peru about the need of studying the problem of seismic strength of adobe buildings. Initially, research at the Catholic University of Peru (PUC) was oriented towards the study of different types of reinforcement using rural materials (1-4) and the effect of some additives to the mortar (5).

In 1979, PUC and the National Autonomous University of Mexico (UNAM) developed a Joint Research Project to study the strength of adobe masonry. Differences of about 500 % in the strength of adobe wall specimens made with adobe bricks of similar strength were detected. The cause of such high difference in strength was not understood at the time (6).

Most of the research performed on adobe masonry was based on study of relationship between properties of the materials used and the strength of the adobe brick (7) and little or no attention was paid to the soil mortar used to join the adobe bricks.

The objectives of this work were, first, to study the soil characteristics fundamental to the seismic strength of adobe masonry and, second, to investigate the effect of additives and construction techniques for improving the strength of the masonry. Another objective was to develop strategies for dissemination of the results obtained.

All the information generated during the research is contained in reference 8, which includes detailed descriptions of the techniques used and the results obtained. This paper presents only the most important conclusions and recommendations.

3. SELECTION AND ANALYSIS OF SOILS

Six zones of Peru where adobe construction is traditional were selected for this study. Soil samples from these areas were collected in order to correlate their physical, chemical and mineralogical characteristics with the seismic strength of adobe masonry made with these soils.

The physical properties of the soils were studied by the evaluation of their granulometric characteristics and Atterberg Limits. A number of tests were performed to determine the chemical composition of the soils and of water samples brought from each location. The mineralogical characteristics of the clays present in each soil were evaluated by X-Ray diffraction analysis performed at the University of California, Berkeley.

Results of physical and mineralogical tests on six selected soils are shown in Tables 1-3.

4. SPECIMEN CONSTRUCTION AND MECHANICAL TESTING

In order to avoid a large variation in the test results between individual specimens, a soil mixer was used to make the soil –water mixtures, and all masonry specimens were made by the same technician. The workability of all soil mortars was maintained at a standard level, controlled by means of Vicat Apparatus, which is commonly used for testing the consistency of cement paste. The apparatus was modified by welding a small steel ball to the tip of the needle, and is shown in Fig. 1. The individual adobe bricks as well as masonry specimens were dried in the shade in order to prevent cracking due to drying shrinkage.

The diagonal compression test was used as a criterion for the evaluation of the seismic strength of the adobe masonry (Fig. 2). A simpler indirect tension test was devised for preliminary studies or for cases when a limited quantity of material was available (Fig. 3). The strength of the individual adobe bricks was evaluated by compression test on cubes. Test results are presented in Table 4.

5. FACTORS CONTROLLING THE STRENGTH OF ADOBE MASONRY

a. *Material Properties*

The characteristics of the soils which had the greatest influence on the strength of adobe masonry are those related either to the drying shrinkage process or the dry strength of the material.

No correlation was found between the chemical composition of the soils or the water and the strength of adobe masonry.

X-Ray diffraction mineralogical analysis of the clay fractions revealed that adobe masonry strength related better to the amount than to the type of clay minerals present in the soils.

As expected, granulometric properties of the soils were found to be very important with regard to the microcracking of the mortar and strength of adobe masonry.

Soils with high clay content generally had high dry strength, as measured by compression test. Adobe masonry made with these soils had, however, poor strength, since high levels of microcracking due to drying shrinkage of mortar was caused by the presence of large amount of clay in the mortar. This phenomenon is apparent in Fig. 4, which shows a seemingly negative correlation between the compressive strength of adobe cubes and the diagonal compression strength of the adobe masonry.

The presence of clay in soils is, however, fundamental to adobe construction, since clay provides for the soil the dry strength, adhesion and plasticity.

No definite relationship was found between the strength of adobe masonry and the silt or sand contents of the soil. Coarse sand content, however, shows a better correlation with strength, due probably to the restraining effect of coarse material, which reduces mortar microcracking due to drying shrinkage.

A standard mortar consistency (or workability), corresponding to 10 mm. penetration in the modified Vicat apparatus, was maintained throughout the research. It was observed that in general, stronger masonry required less water in the mortar in order to reach the standard consistency. The water content for standar consistency was therefore a characteristic parameter of the soil. This parameter, which evaluated the plasticity of the soil and was also a measure of the adhesion between mortar and brick, did not show good correlation with the ability to restrain microcracking due to drying shrinkage, which was governed by the amount of coarse material present.

Atterberg Limits are useful for standard soil classification. Unfortunately, they are not good indicators of the strength of adobe masonry. For instance, the Plasticity Index is computed using only the soil fraction smaller than No. 40 mesh, and not with all the soil; therefore its value does not necessarily reflect the actual plasticity of the soil used for adobe construction.

b. *Drying Process*

One of the most important conclusions drawn from the analysis of the test results is that the strength of adobe masonry greatly depends on the degree of microcracking of the soil mortar due to drying shrinkage. Fig. 5 shows a clear correlation between the volumetric drying shrinkage of adobe bricks –which also indicates the capacity for drying shrinkage of the mortar– and the strength of the masonry. In order to obtain a strong masonry it is therefore indispensable not only to have a material with high dry strength, but also to guarantee the integrity of the brick-mortar ensemble by eliminating or reducing microcracking of the soil mortar.

The study of the drying processes of adobe bricks and mortar was very illustrative to understand the behavior of the masonry. A correlation was found between the rate of drying and the level of microcracking due to drying shrinkage. This was relatively easy to discover in the case of the adobe bricks, since bricks dried in the shade were significantly less cracked than those dried in the sun.

The drying process of mortar placed between dry adobe bricks occurred in two well defined stages. Most of the microcracking occurred very rapidly, during the first stage due to the sudden loss of mortar water caused by absorption by the dry bricks. The second stage is much slower; the loss of water to the exterior is associated basically with evaporation (Fig. 6).

This result reveals that any method which tends to reduce the rate of transfer of water between mortar and bricks would be beneficial in improving the strength of adobe masonry.

c. *Effect of Additives*

In general, the addition of cementing agents to the soil was not very efficient in improving the strength of the adobe masonry. Addition of lime actually decreased the strength of the masonry. Addition of cement in amounts larger than 10%, and when mixed with sand led to increase in strength. Previous research had also shown that addition of a mixture of cement and sand to mortar was advantageous (5).

Small amounts of sodium carbonate, a dispersive agent, led to some increase in the compressive strength of adobe bricks.

Additions of small amounts of manure to the mortar increased masonry strength, since fibers in manure help to restrain the growth and propagation of microcracks in the mortar. Larger amounts of manure led to lower strength due perhaps to the presence of organic matter or other components.

d. *Constructive Process*

Quality of workmanship played an important role in obtaining a strong adobe masonry. For instance, diagonal compression tests made with specimens built with traditional techniques showed a strength of 0.23 Kg/cm^2, whereas than samples built with high quality of workmanship resisted 0.47 Kg/cm^2 (6, 8).

Masonry quality was noticeably improved by wetting the adobe bricks, letting them sit for approximately 10 minutes in a container with 1 cm. of water, before placing the mortar. This procedure reduced microcracking and improved mortar-brick integration. The use of dry but workable mortars was found to be advantageous, since the number and width of cracks due to drying shrinkage were reduced (Fig. 7).

It was also found that adobe bricks attained sufficient strength to be manipulated one week after their manufacturing and that the strength of adobe masonry stabilizes at about two weeks after fabrication.

The positive effect of "sleeping" the mud (storing it for a one or two days) before the fabrication of adobe bricks or mortar, a traditional practice in Peru, was confirmed. It seems that this procedure allows for a better dispersion and thus for a more uniform action of the clay particles.

6. IMPROVEMENT OF ADOBE MASONRY

Based on the results described above, it was decided to attempt improving the strength of adobe masonry by reducing the level of microcracking of the mortar through:

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

b. Control of growth and propagation of cracks by additon of straw to the mortar.

c. Reduction of the drying rate of the mortar by decreasing the difference in moisture between brick and mortar.

The effect of the addition of coarse sand (size of particles comprised between No. 4 and No. 40 mesh) to the six selected soils was investigated. The amounts added varied between 30 and 300°/o in volume. Sand was added in some cases to both mortar and bricks, and in other cases only to the mortar. In both instances the degree of microcracking on drying of the mortar and the strength of the masonry were studied. Additionally, the effect of previous wetting of the adobe bricks was investigated.

Addition of coarse sand led, in general, to a decrease in the number and average width of the cracks in the mortar (Fig. 8), to a better integration between mortar and brick, and to a significant increase of the strength of the masonry, specially in the cases where the natural soil had a high clay content (Fig. 9, notice Cajamarca and PUC soils which increased their strength from 0.6 to 1.3 and from 0.47 to 1.08 Kg/cm^2, respectively). It was found that there is an optimum amount of coarse sand, corresponding to the elimination of the visible cracks in the mortar (Fig. 10). Smaller amounts of coarse sand produced mortars with excessive cracking; addition of larger amounts of sand led to masonry with poor strength due to the decrease in clay content (clay provides the dry strength).

Addition of coarse sand also affected the type of failure observed in the specimens tested. In most of the specimens made with natural soils, the cracks followed the mortar-brick joints. When coarse sand was added to the soil, the cracks also cut the adobe bricks, showing the loss in strength of the bricks due to the diminution of clay. This phenomenon was corroborated with compressive tests of cubes (Fig. 11).

Two types of straw were used as additives: common grass leaves about 5 cm long, and "ichu", a straw from the Andes, chopped in pieces of about 10 cm in length. Some of the traditional peruvian techniques for the manufacturing of adobe bricks call for addition of straw to the soil in percentages smaller to 0.5 in weight. The amounts of straw used in this investigation varied between 0.5 to 8%. The effect of addition of straw on mortar workability and strength of adobe masonry were studied.

Addition of straw was found to be even more efficient than addition of coarse sand in improving the strength of adobe masonry (Compare Figs. 10 and 12). Practically the same results were obtained with both types of straw. The increase in strength can be explained by the "sewing" action of the brick-mortar interface produced by the straw fibers in the mortar. This effect helps to improve the integration, and thus the strength of adobe masonry. The compressive strength of the brick was not found to decrease, as in the case of addition of coarse sand. However, the water demand of the mortar to reach an adequate workability increased with the addition of straw. Therefore, addition of very large amounts of straw is not convenient. The optimum amount to be added to a given soil is then controlled by the workability of the soil-straw-water mixture used to make the adobes and mortar.

Simultaneous addition of coarse sand and straw was not found efficient in improving the strength of adobe masonry.

Full-scale shear tests on adobe walls were performed to corroborate the observed beneficial effects of addition of coarse sand or straw to the natural soil. Fig. 13 shows the test set-up. The improvement of strength obtained was in this case of the order of 100%, with respect to walls made with natural soil (see Fig. 14). This implied an increase in strength of the order of 400% with respect to traditional adobe masonry.

7. CONCLUSIONS AND PRACTICAL RECOMMENDATIONS

The main conclusions drawn during this investigation regarding the seismic strength of adobe buildings are:

- The most important component of the soil is clay, since it provides dry strength. Unfortunately, clay also causes drying shrinkage of the soil.
- In order to obtain strong adobe masonry, it is indispensable to control the microcracking of the soil mortar due to drying shrinkage.
- Straw and, to a lesser extent, coarse sand are efficient natural additives which can be used to control microcracking of the mortar due to drying shrinkage, and therefore to improve the strength of adobe masonry.

Based on these conclusions, the following practical recommendations were established in order to select adequate soils and additives, to improve the construction techniques and to obtain stronger adobe buildings.

a. *Procedure for Selection of Materials*

- Select an available soil, as a candidate for adobe construction.
- Perform the "dry strength test", consisting of making three or more little balls (of about 2 cm diameter) of mud made of the selected soil. Once dry after at least 24 hours each ball is crushed between the thumb and the index fingers. If all balls are so strong that none can be broken, the soil has enough clay to be used for adobe construction, provided that microcracking of the mortar due to drying shrinkage is controlled. If some of the balls can be crushed, the soil is inadequate, since it lacks clay and should be discarded.

- Add to the mud, specially when preparing the mortar, the maximum amount of straw which allows for an adequate workability.

- If straw is not available, perform the "microcracking control test". This test consists of making two or more sandwiches (two adobe bricks joined with mortar) using existing adobe bricks and mortar made with the soil under study. After 48 hours of drying in the shade, the sandwiches are carefully opened and the mortar examined. If the mortar does not show visible cracking, the soil is adequate for adobe construction. Otherwise, use coarse sand (0.5 to 5 mm. approx.) as additive to control microcracking due to drying shrinkage.

- The most adequate soil-coarse sand proportion is determined by performing again the microcracking control test with at least eight sandwiches made with mortars with different proportions of soil and coarse sand. It is recommended that the soil:coarse sand proportions vary between 1:0 (no sand) to 1:3 in volume. The sandwich with less amount of sand which shows no visible cracking after opening 48 hours after manufacturing indicates the soil:coarse sand proportion to be used for adobe construction.

b. Construction Process

A constructive recommendation drawn from the experience acquired during this investigation is to wet the adobe bricks before laying, by moistening them. At least the two horizontal faces should be wetted for 10 to 15 minutes. This recommendation does not apply to adobe bricks made of sandy soils.

Other general recommendations are: eliminate all foreign matter from the soil; mix the mud as throughly and uniformly as possible, dry the adobe bricks in the shade; clean the bricks before laying, make uniform and complete mortar joints; and check the verticality of the wall.

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TABLE 1

SIZE FRACTION ANALYSIS (°/o)

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

TABLE 2

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 3

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

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

TABLE 4

STRENGTH OF ADOBE MASONRY AND BRICK

SOIL	DIAGONAL COMPRESSION (Kg/cm^2)	INDIRECT TENSION (Kg/cm^2)	COMPRESSIVE STRENGTH OF BRICK (Kg/cm^2)
CAJAMARCA	0.60	0.51	37.2
CUZCO	0.96	0.81	20.4
HUANCAYO	0.54*	0.54*	18.5
HUARAZ	0.98	0.52	18.8
PISCO	0.72	0.42	19.9
PUC	0.47	0.21	22.5

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

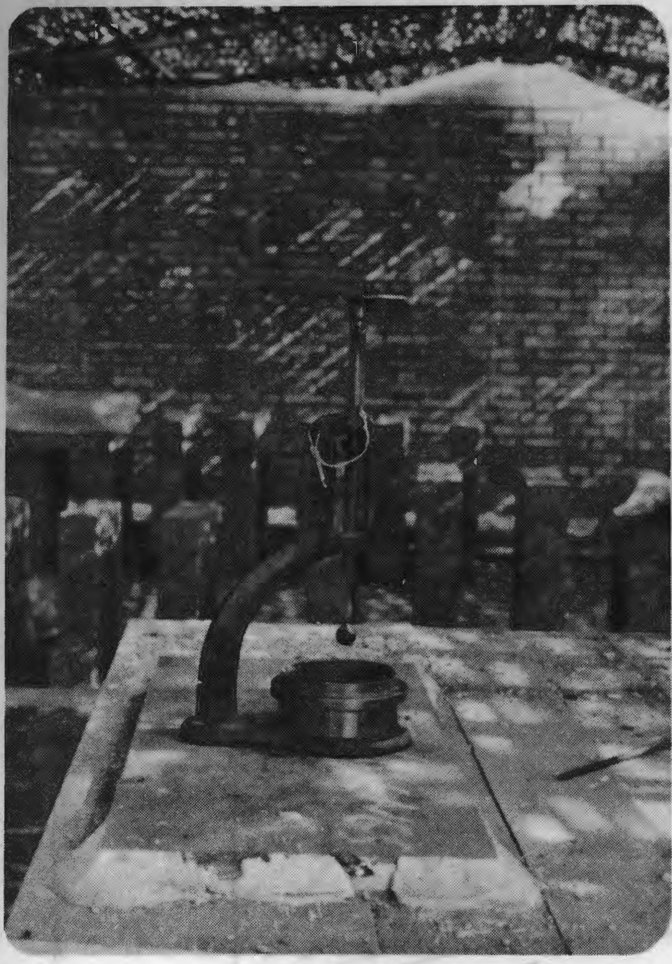


FIG. 1 MODIFIED VICAT APPARATUS

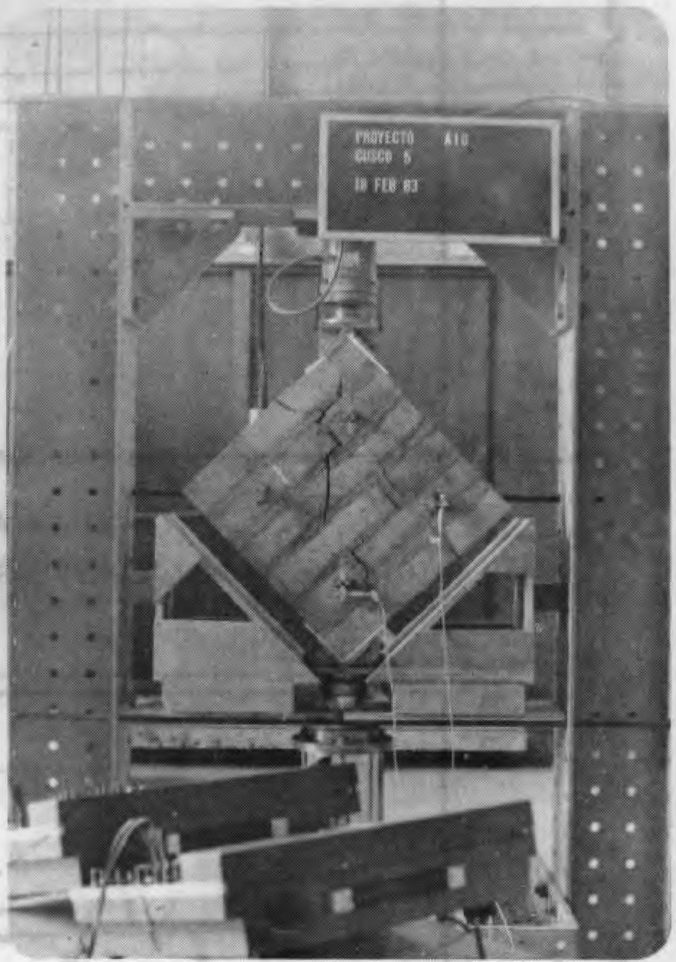


FIG. 2 DIAGONAL COMPRESSION TEST

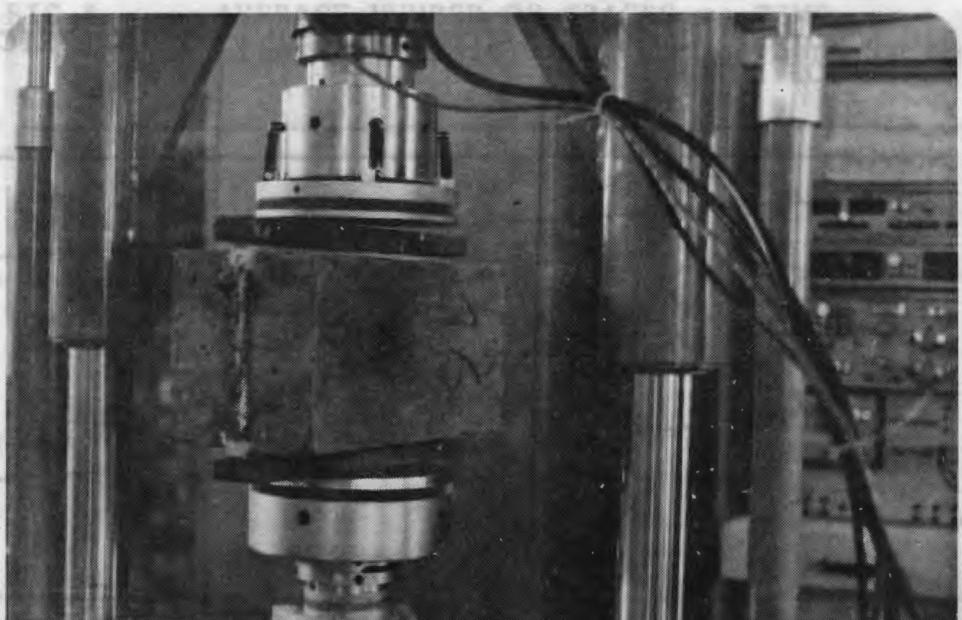


FIG. 3 INDIRECT TENSION TEST

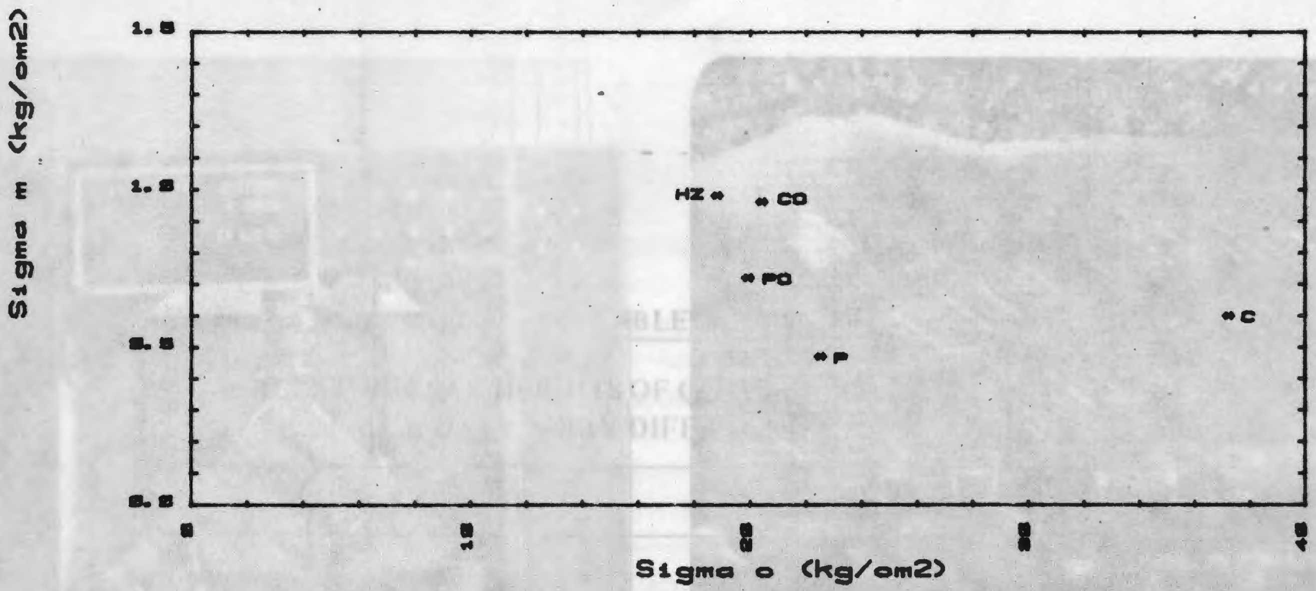


FIG.4 DIAGONAL COMPRESSION STRENGTH vs COMPRESSIVE STRENGTH OF BRICK

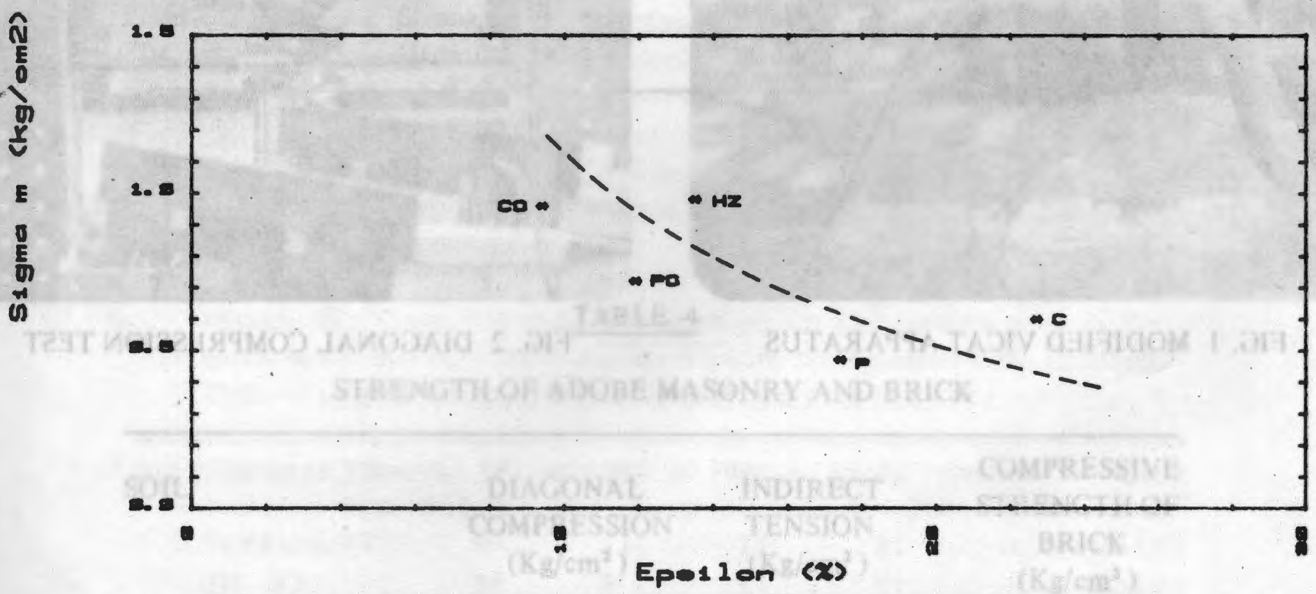


FIG.5 DIAGONAL COMPRESSION STRENGTH vs VOLUMETRIC SHRINKAGE OF BRICK

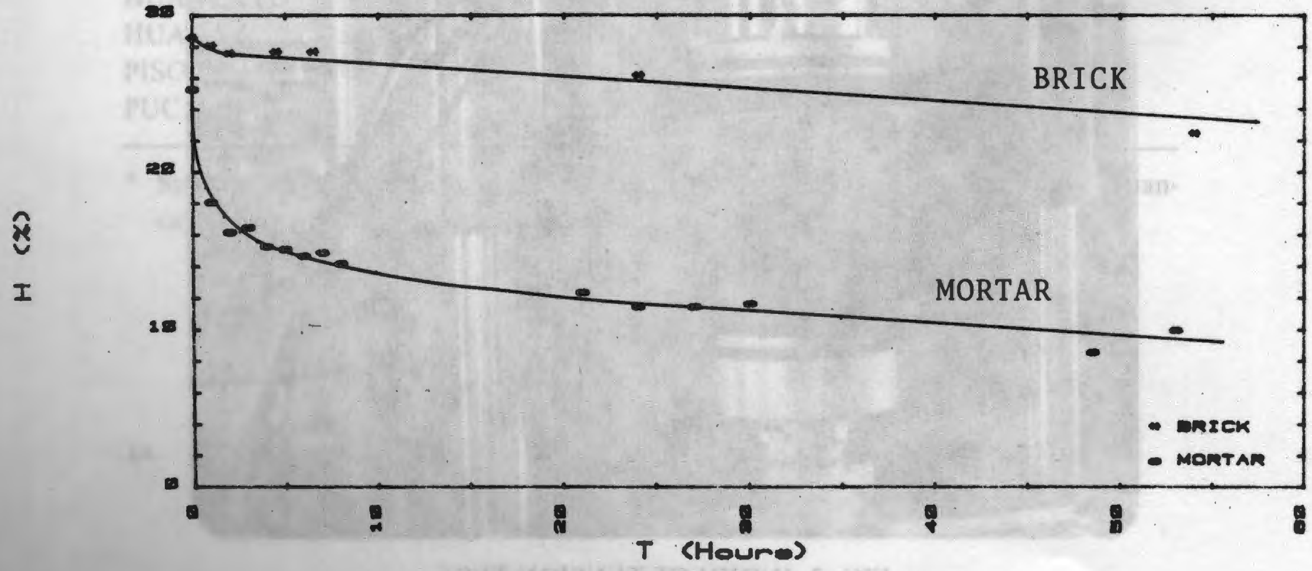


FIG.6 WATER CONTENT vs TIME

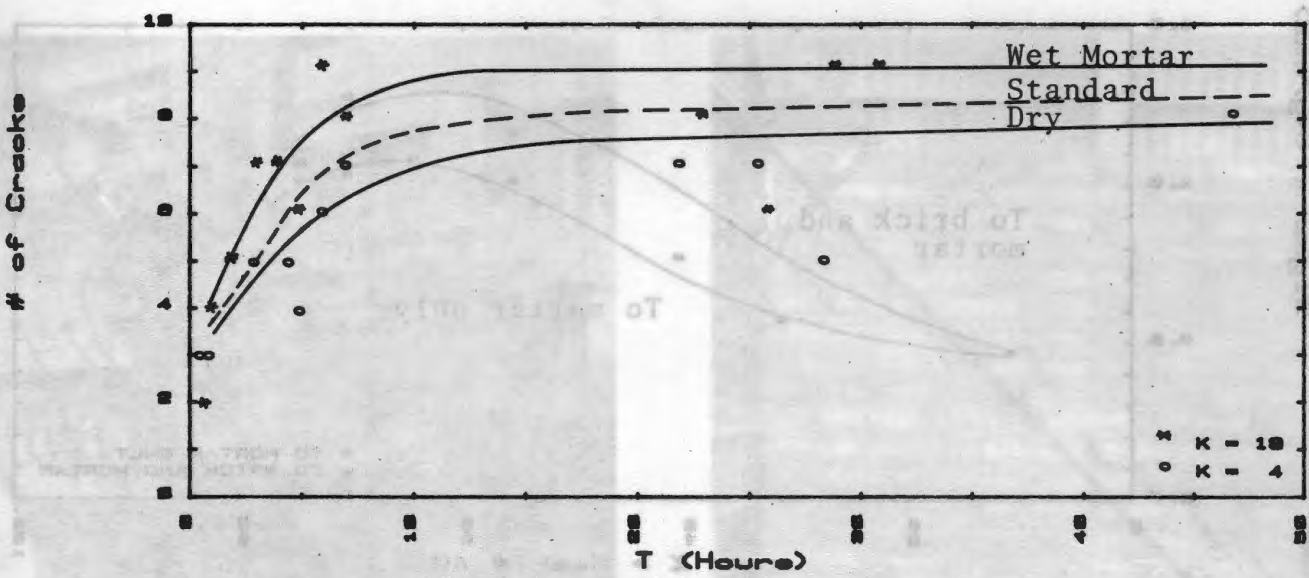


FIG.7 AVERAGE NUMBER OF CRACKS vs TIME
Effect of Initial Consistency of Mortar

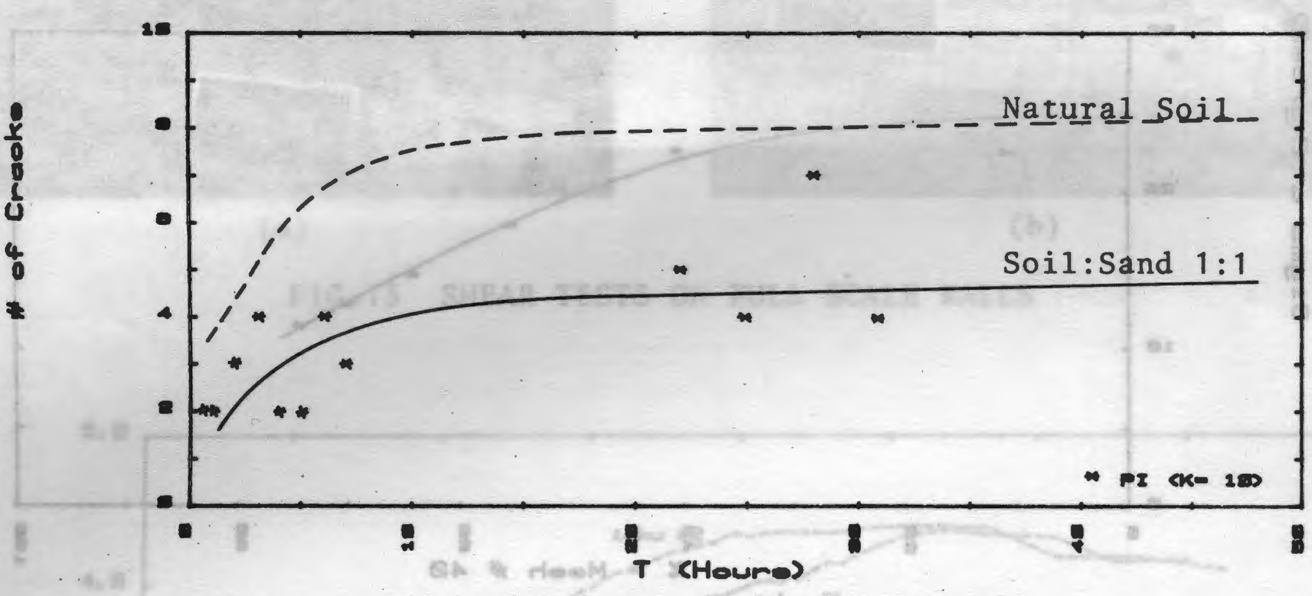


FIG.8 AVERAGE NUMBER OF CRACKS vs TIME
Effect of Addition of Coarse Sand to Mortar

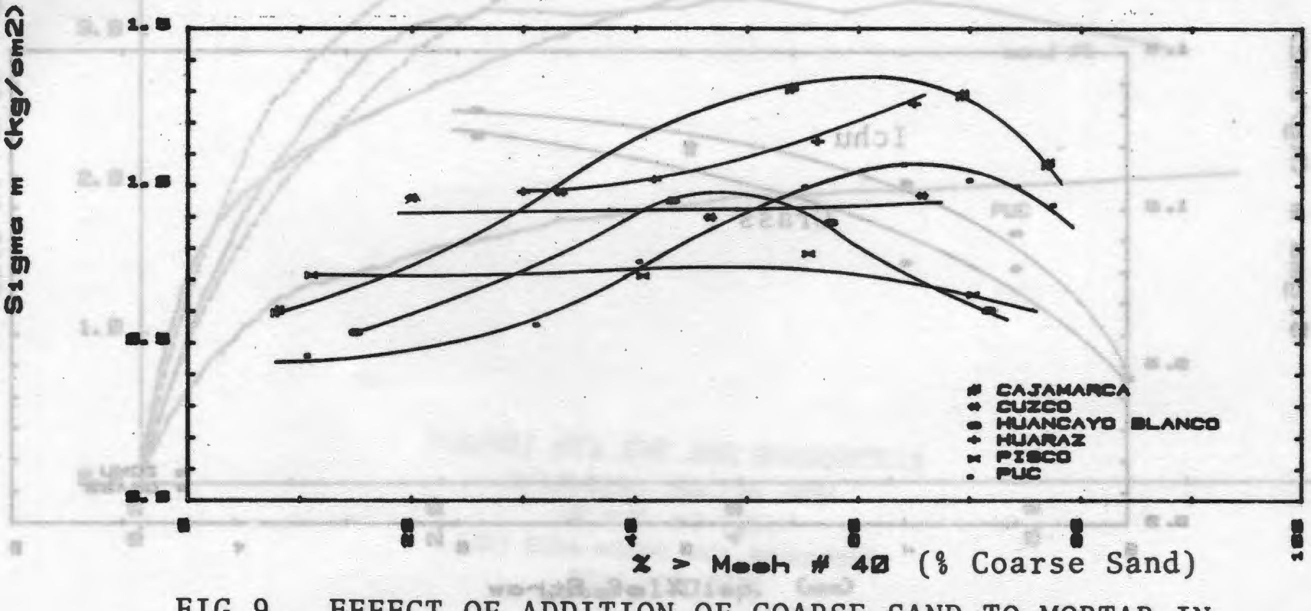


FIG.9 EFFECT OF ADDITION OF COARSE SAND TO MORTAR IN
DIAGONAL COMPRESSION STRENGTH

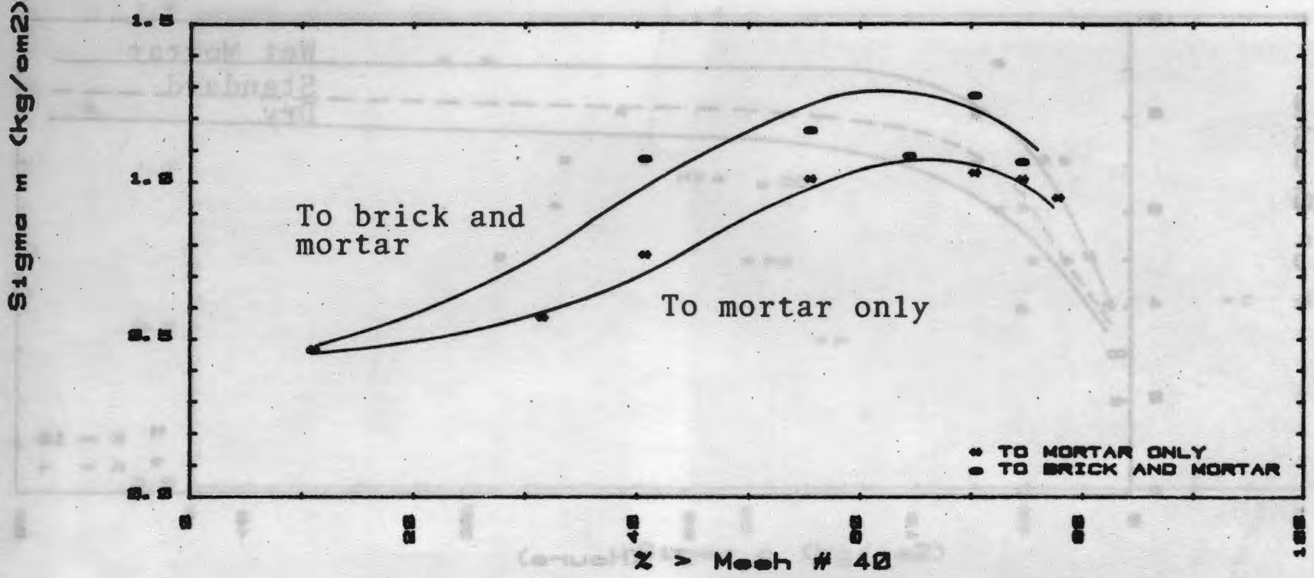


FIG.10 EFFECT OF ADDITION OF COARSE SAND TO PUC SOIL

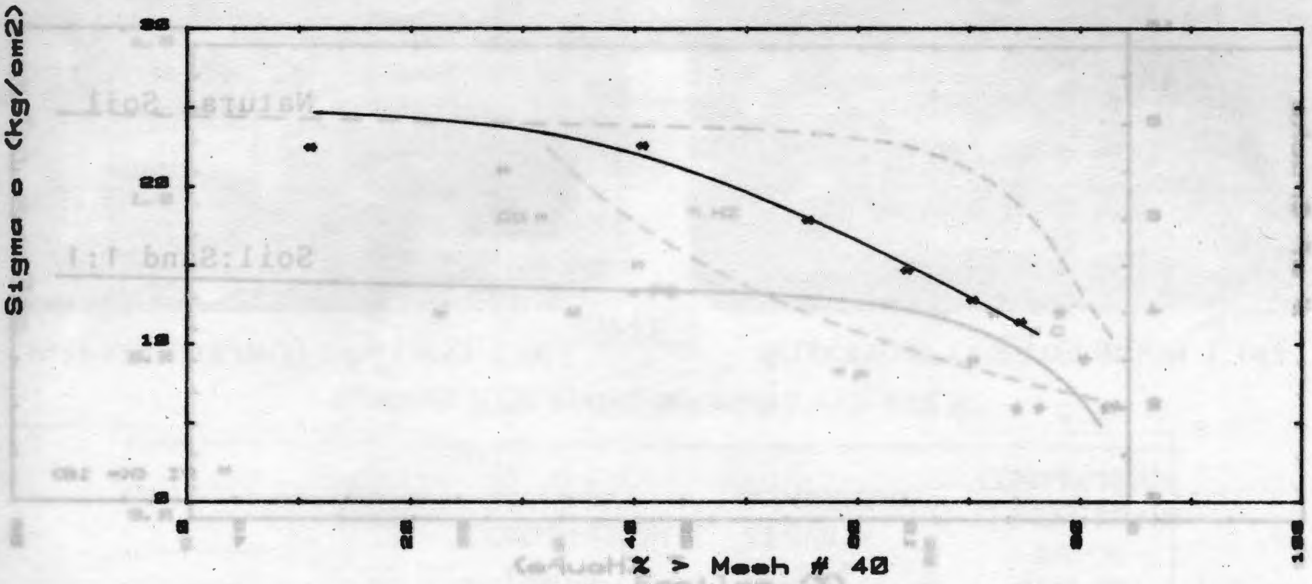


FIG.11 EFFECT OF ADDITION OF COARSE SAND IN COMPRESSIVE STRENGTH OF BRICK

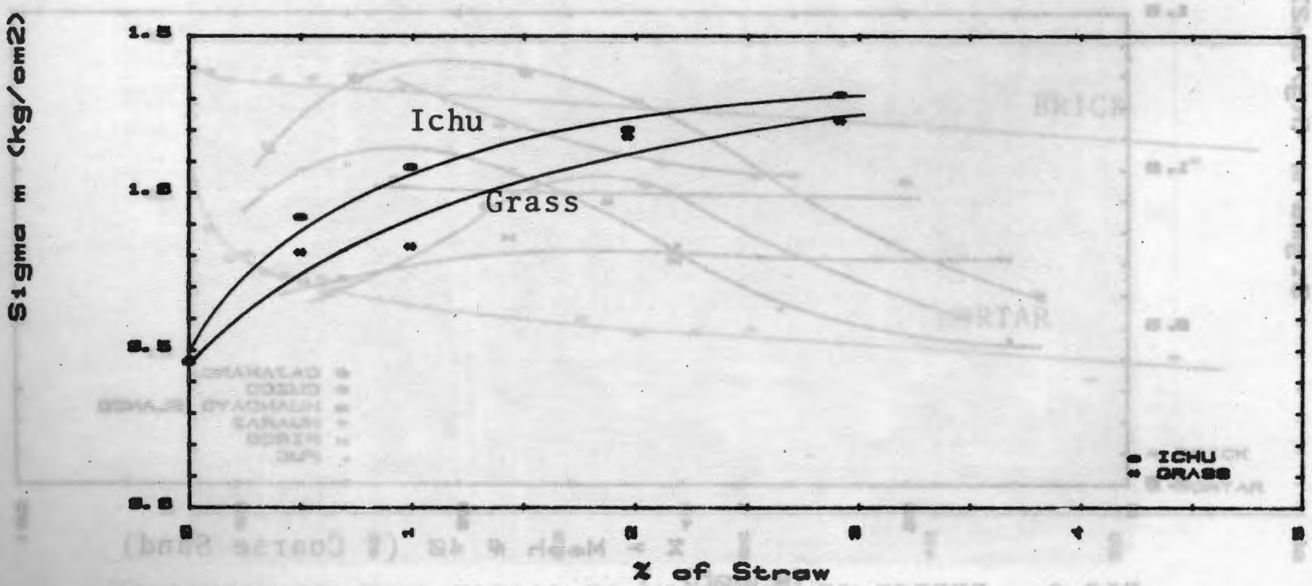
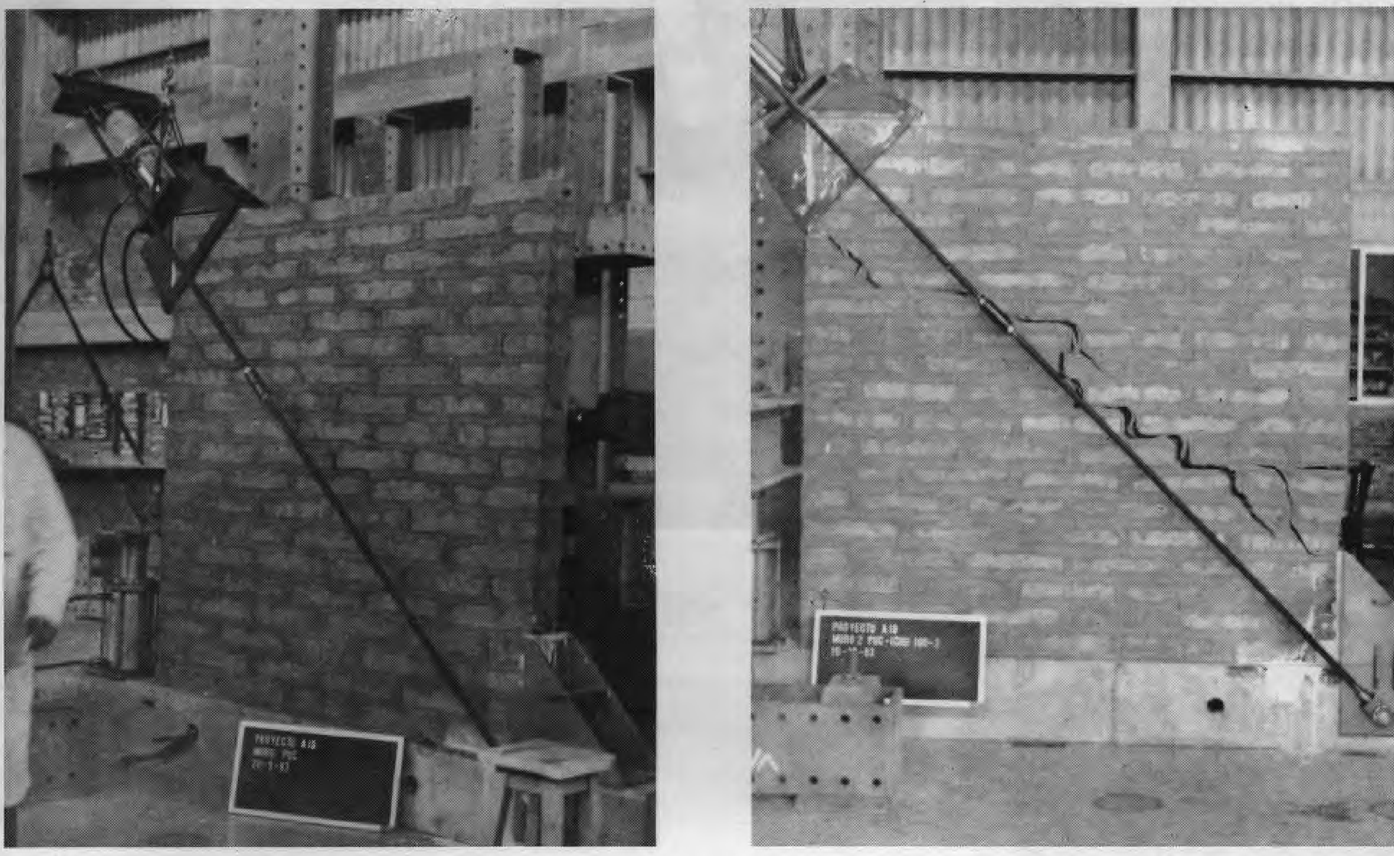


FIG.12 EFFECT OF ADDITION OF STRAW TO PUC SOIL



(a) (b)

FIG.13 SHEAR TESTS ON FULL SCALE WALLS

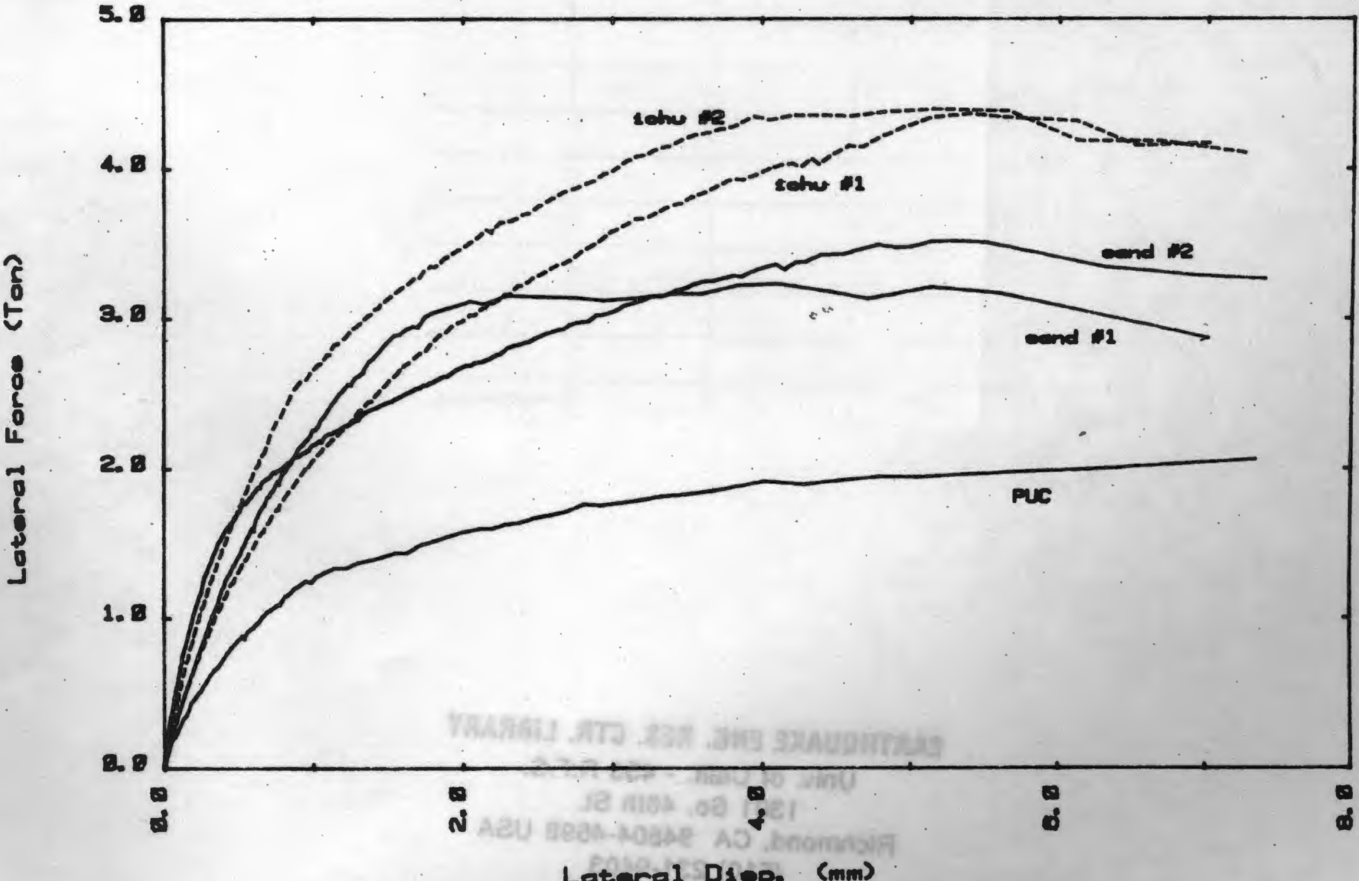


FIG.14 FULL SCALE WALL TEST RESULTS