Development and Mechanical Properties of Construction Materials From Lunar Simulant

Chandra S. Desai
Department of Civil Engineering and Engineering Mechanics
The University of Arizona

Abstract

Development of versatile engineering materials from locally available materials in space is an important step toward the establishment of outposts on the Moon and Mars. Here development of the technologies for manufacture of structural and construction materials on the Moon, utilizing local lunar soil (regolith), without the use of water, is an important element for habitats and explorations in space. It is also vital that the mechanical behavior such as strength and tensile, flexural properties, fracture toughness, ductility and deformation characteristics are defined toward establishment of the ranges of engineering applications of the materials developed.

The objectives here include two areas: (1) thermal "liquefaction" of lunar simulant (at about 1100°C) with different additives (fibers, powders, etc.), and (2) development and use of a new triaxial test device in which lunar simulants are first compacted under cycles of loading, and then tested with different vacuums and initial confining or in situ stress. Details of the development of intermediate ceramic composites (ICC) and testing for their flexural and compression characteristics have been described in various reports and papers.[1-2] The subject of behavior of compacted simulant under vacuum has been described in previous progress reports and publications[3-4]; since the presently available device allows vacuum levels up to only 10^{-4} torr, it is recommended that a vacuum pump that can allow higher levels of vacuum is utilized for further investigation.

Principal Investigator: Chandra S. Desai

Graduate Student: Janos Toth

Undergraduate Student: Bryant Steele

Introduction and Results to Date

The development of new construction materials through liquefaction of lunar simulants with various admixtures (powders and fibers), and determination of mechanical properties using various laboratory testing devices to perform bending and flexure, tension, cylindrical triaxial, and three-dimensional multiaxial tests are the main objectives in this progress report.

The lunar simulant used, called Arizona Lunar Simulant, has been developed locally from a basaltic rock found near Hanford, WA. This material has a mineralogical composition similar to that of the lunar mare soil. The rock is ground so that its grain size distribution falls well within that of the distribution envelopes for the samples of the lunar regolith brought to Earth by Apollo missions, *Figure 1.*

In order to define various engineering properties such as flexure, compressive, tensile and fracture strengths, deformation characteristics, and ductility, the lunar simulant is combined with various powders and fibers. These include steel, stainless steel, aluminum, and fiberglass. The simulant itself, and with various percentages of powders or fibers, is liquefied in a furnace with a temperature capacity of 1700°C. The material is placed and compacted in molds made of graphite and titanium so that appropriately sized specimens for various tests can be obtained as follows:

SHAPE	SIZE	TEST	STATUS
Rectangular	1.0 cm X 2.5 cm X 25 cm	Bending	Completed
Flat	2.5 cm X 10 cm X 15 cm	Tension	Ongoing
Cylindrical	2.5 cm diam. X 5 cm	Compression	Ongoing
	5.5 cm diam. X 15 cm ht.	Triaxial (compression)	Future
Cubical	10 cm X 10 cm X 10cm	Multiaxial (compression)	Future

Diagrams of these samples with loading conditions are shown in *Figure 2*.

In the thermal liquefaction, the simulant melts at about 1100°C and forms a matrix that can be made into various specimen sizes and shapes. The resulting intermediate ceramic, formed solely by the simulant, is relatively brittle. With addition of a powder or fiber, the liquefaction may involve melting of the admixture at a lower or higher temperature than that for the soil simulant. Thus the powder/fiber melts before the heated soil particles or vice versa, resulting in a "ceramic composite."

Such composites can possess a wide range of the aforementioned mechanical properties, and can result into materials with properties similar to mortar, concrete and certain (metal) composites.

An objective of the research is to perform a parametric study in which the ratio of simulant to powder/fiber is varied, together with different levels of temperature and cycles of temperature, the latter is expected to add "prestressing" due to residual expansion of the powder/fiber. It has been noted that such powders and fibers can be manufactured from the lunar regolith.

Specimens of the material combinations thus developed will be tested for bending, tension, fracture, ductility, and stress-strain-strength properties using laboratory testing methods as stated previously. This is a vital step toward potential engineering applications of the materials developed, because based on the parameters and constants determined, the ranges and type of application of the materials developed in space construction can be established.

The previous research so far has included: 1. Acquisition of the furnace, 2. development of a beam bending device as per the ASTM standard, 3. production of a number of beam specimens with varying admixture content, and 4. testing of a number of beam specimens for their load-displacement behavior, described elsewhere.[1-2] It was found that the addition of fibers contributes greatly to the load-carrying capacity and ductility of the material.

Development of flat, cylindrical and multiaxial specimens will be the subjects of continuing research. The flat specimens will be tested for tensile and fracture characteristics. The multiaxial specimens will be tested in unique three-dimensional devices that allow application of three independent principal stresses, different paths of loading, and static and cyclic loading. Future work will also involve use of the Arizona simulant and the simulant developed at the University of Minnesota to include determination of the effect of agglutinates in this type of research. Agglutinate is a small glass-welded aggregate of rock, mineral, and glass fragments formed during micrometeorite impacts into the regolith. Also considered will be the use of a pump with higher vacuum levels and testing of specimens under higher levels of vacuum, about 10^{-12} torr. This will also be used to continue the study using the new vacuum triaxial device.

Accomplishments During 91-92

A number of special issues related to the development of ICC were investigated. These include the following:

Modified Simulants. The Arizona Lunar Simulant was exhausted. Hence, a new batch was prepared from crushed and ground basalt (Pomona Flow, Hanford, WA). In order to fit better the grain size distribution (GSD) with the Apollo sample, the new batch was ground so that the GSD was as shown by the dashed curve (*Figure 1*); this provided inclusion of particle sizes in the range of 0.6 to 1.2 mm. It was found that the liquefaction temperature of the modified simulant was about the same as that for the previous batch. The chemical composition of both batches remained essentially the same.

Molds. Alternative molds so as to reduce oxidation and lead to high quality specimens.

Additives to Reduce Liquefaction Temperature. Based on a suggestion by Dr. Kumar Ramohalli, and discussion with Dr. Andrew Cutler, NASA-SERC, the publication, "Research on the Use of Space Resources", Jet Propulsion Laboratory, NASA-CR-173213, Carroll, W.F. (Editor), was reviewed. However, this report did not provide information on additives to reduce the liquefaction (melting) temperature. Then, based on discussions with Dr. F. Shadman (Ch. Eng.), lime and sodium hydroxide were considered as additives. Addition of lime ($CaOH_2$) did not cause significant reduction in the liquefaction temperature. Addition of sodium hydroxide (NaOH) reduced the temperature to about 1000°C, but the resulting material was found to be more brittle than that without the addition. This aspect will need further study. In the meantime, it is proposed to continue liquefaction without such additives.

Tensile Testing

For this purpose a new and special grip system was designed and fabricated for testing flat specimens using the available MTS Test Frame. *Figure 3* shows a flat specimens with grips that are expected to provide a central load and grip with sufficient tensile strength.

A parametric study was performed to identify a glue that can be used in addition to the grips. It was found that Magnolia 6514-65 glue can provide sufficient strength of about 4000 psi which is greater than the tensile strength of the ICC. This was determined after testing cylindrical specimens of aluminum (6061 T4 Al) and ICC with the glue, *Figures 4a,b*.

As shown in *Figure 3*, it is proposed to monitor ultrasonic characteristics (velocity, attenuation and energy dissipation) so as to identify development of microcracking and fracture within the specimen, in addition to its tensile characteristics.

<u>Specimens</u>

The flat specimens (4 x 6 x 1 inch) are prepared by appropriate grinding of the specimens obtained after liquefaction so as to obtain a smooth surface for mounting the strain gauges and ultrasonic transducers.

<u>Ongoing and Future Work</u>

Tension Testing

A series of flat specimens will be tested with various loading-unloading-reloading cycles for various combinations of additives. The test results will allow determination of the tensile stress-strain-strength properties. A mathematical model will be developed to define damage and fracture characteristics using the disturbed state concept (DSC), in conjunction with the ultrasonic results.

Compression Testing

Cylindrical and cubical specimens will be cast and tested by using the cylindrical triaxial and multiaxial devices under loading, unloading and reloading cycles. The results will provide compressive stress-strain-strength characteristics of specimens with various admixtures.

The final objective of the research is to develop a methodology by which structural materials can be produced on the Moon using locally available and derived (fibers, powders, etc.) materials, formed into useful shapes by thermal solar energy and compaction. In addition to the development of materials, attention must be given to the determination of the mechanical properties necessary for structural design so that the material can be used in a wide range of engineering applications such as roads, foundations, blocks, walls, floors, buildings, support systems, and shields. The research results are expected to represent a significant contribution towards construction of facilities on the Moon.

References

1.Girdner, K. and C.S. Desai. Development of mechanical properties of structural materials from lunar simulants by thermal liquefaction. *Report to NASA-SERC* (1991). Dept. of Civil Engg. and Engg. Mechs., Univ. of Arizona, Tucson.

2.Desai, C.S. and K. Girdner. Structural materials from lunar simulants through thermal liquefaction. *Proc. SPACE 92* (1992). ASCE, Denver, Colorado.

3.Desai, C.S., H. Saadatmanesh, and T. Allen. Effect of vacuum on density and stress-strain-strength behavior of compacted lunar simulants. *Report to NASA-SERC* (1990). Dept. of Civil Engg. and Engg. Mechs., Univ. of Arizona, Tucson.

4.Desai, C.S., H. Saadatmanesh, and T. Allen. Behavior of compacted lunar simulants using new vacuum triaxial device. *J. Aerospace Eng.* (October 1992). ASCE, in press.

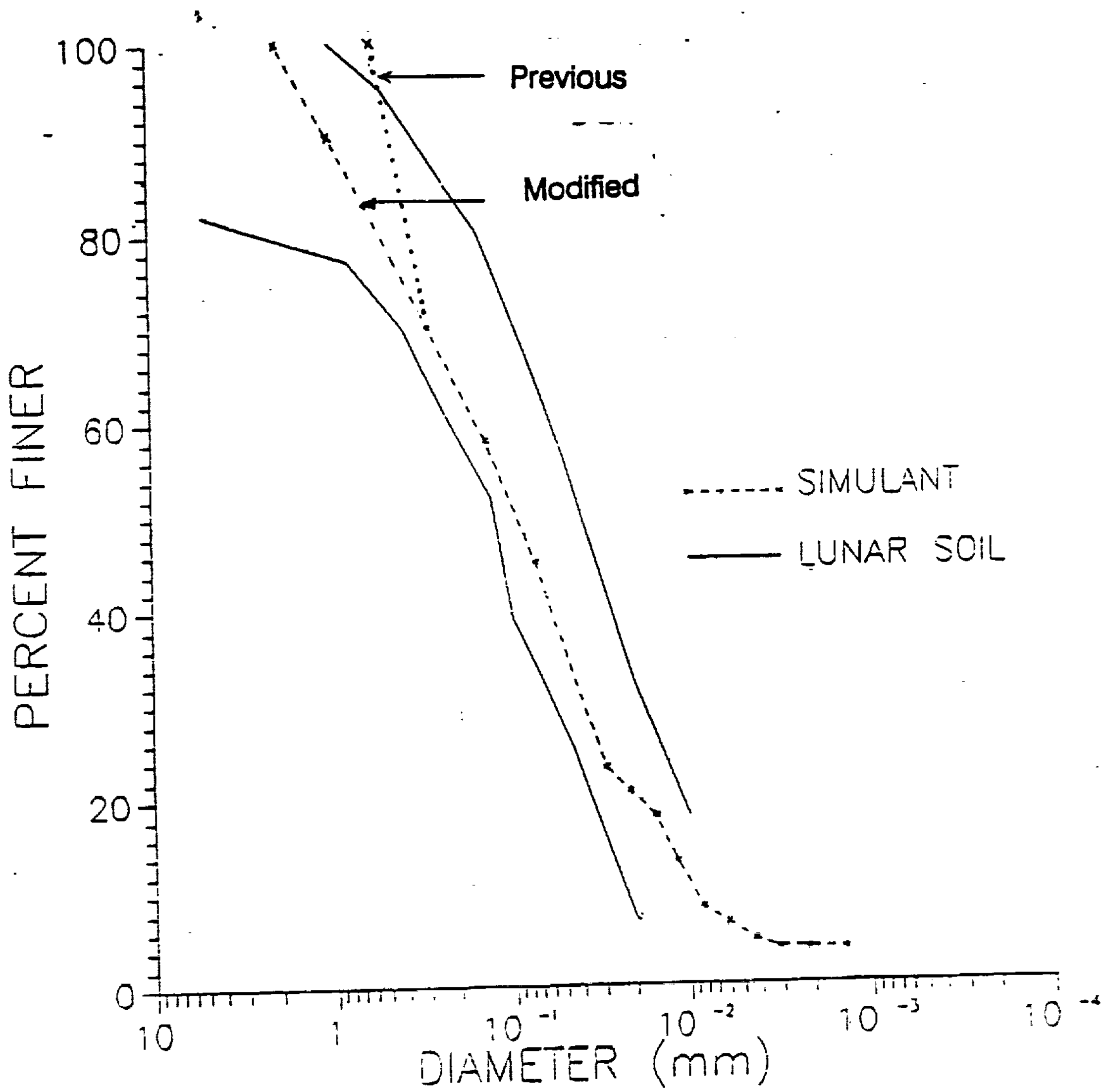


Figure 1. Grain size distribution of actual lunar soil and simulant

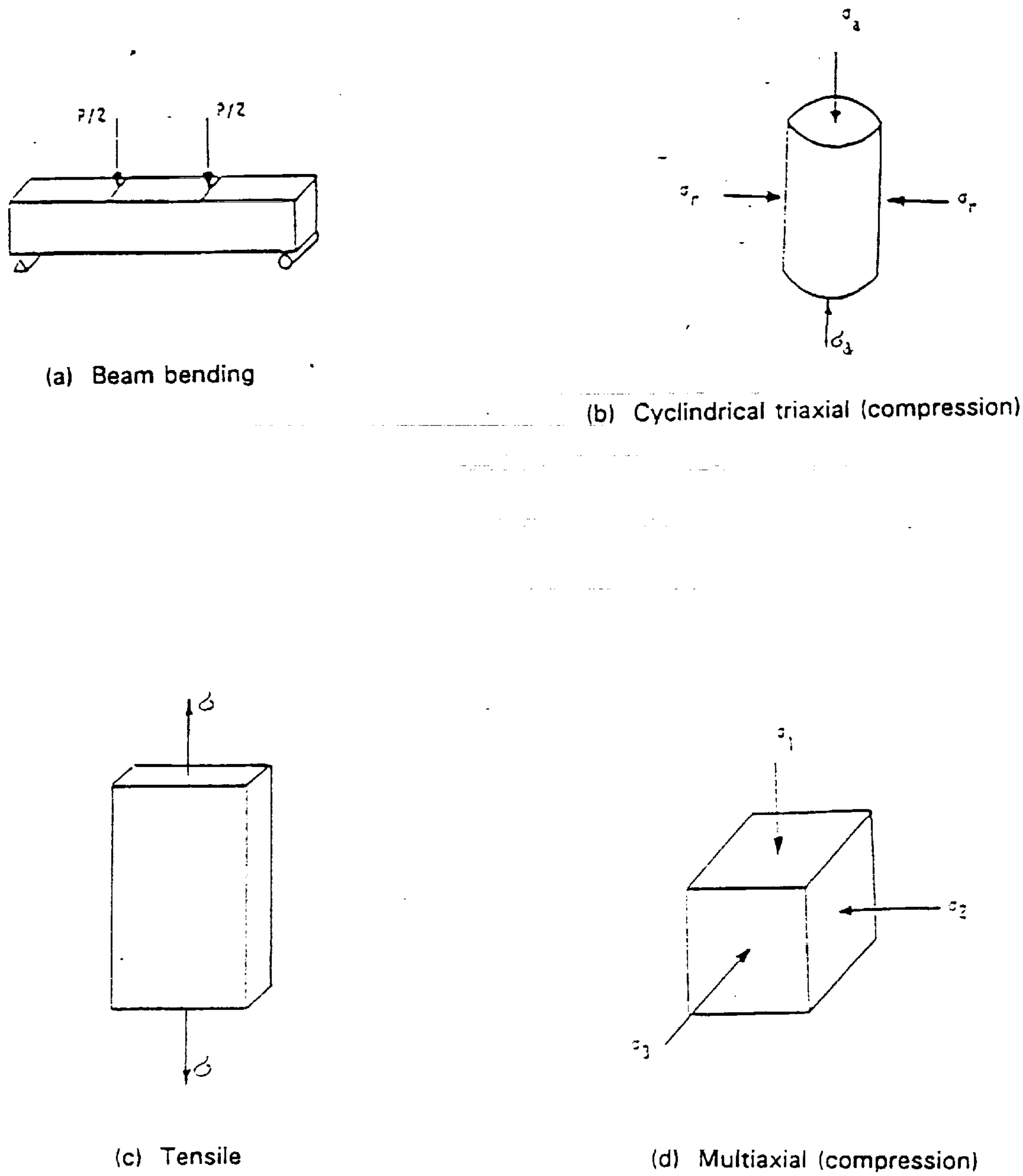
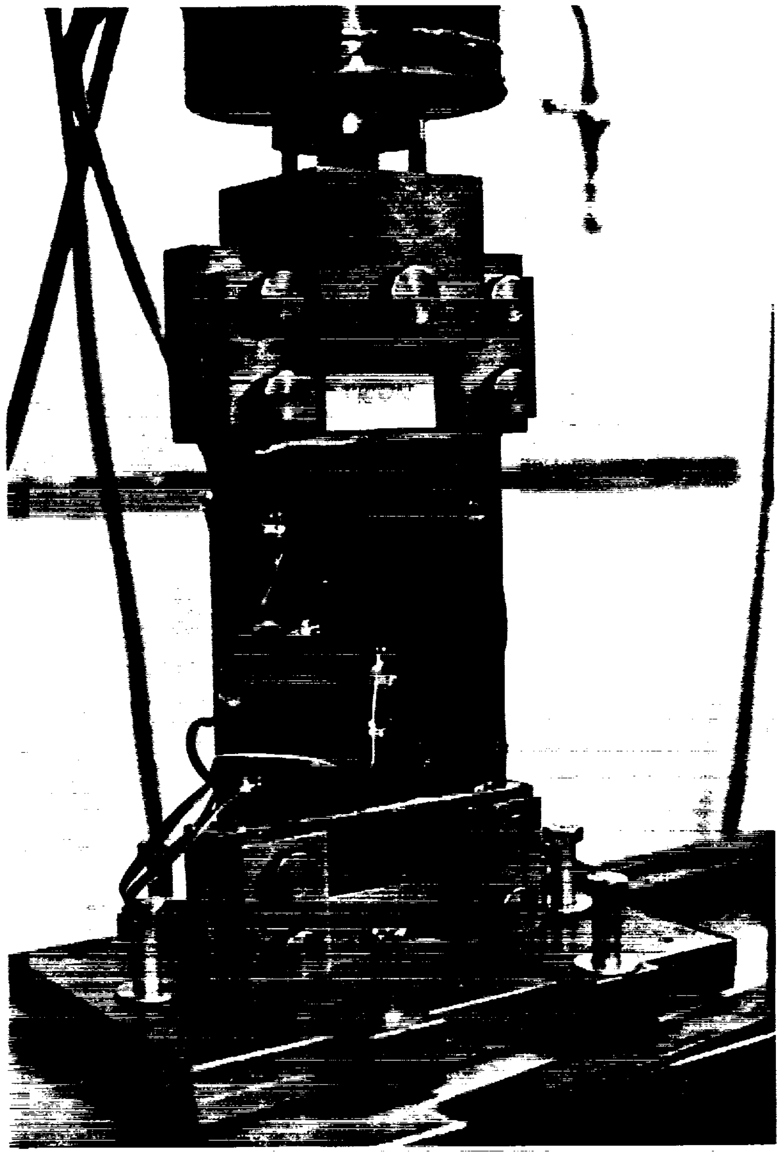


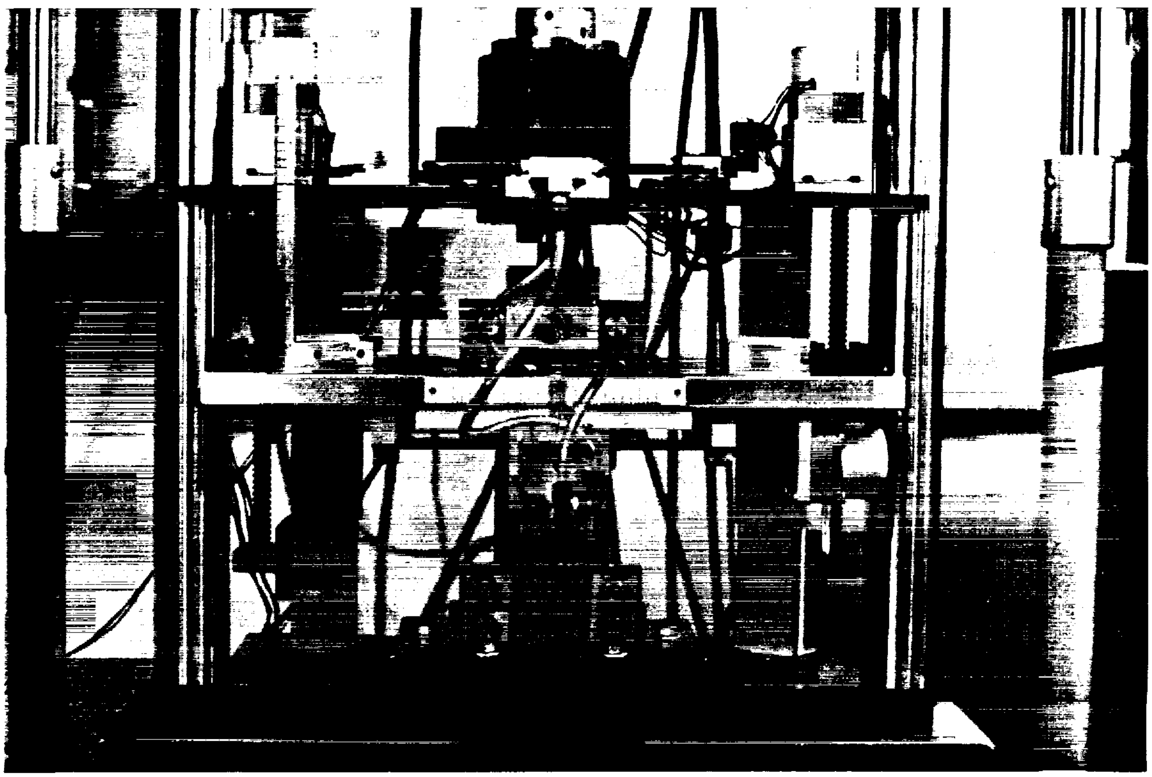
Figure 2. Schematic of Specimens



(a) Flat Specimen with Grips and Strain Gauges

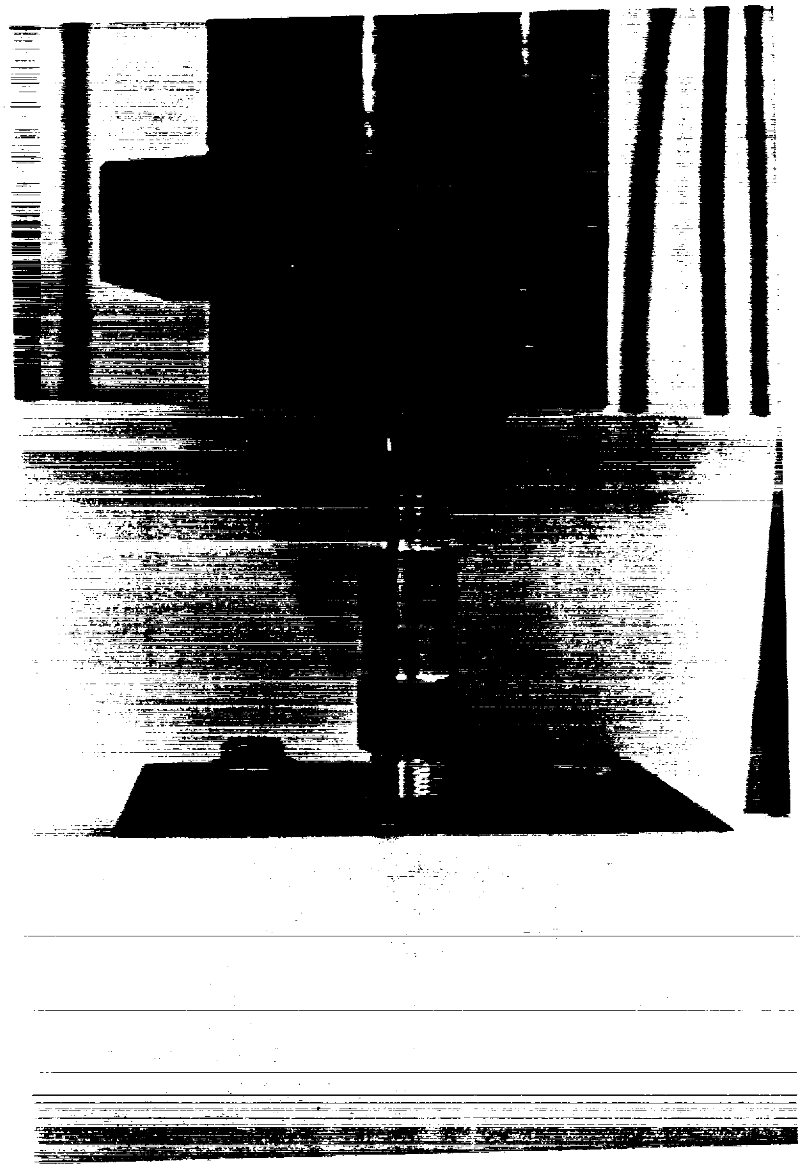
Figure 3. Flat Specimen in MTS Frame

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



(b) Flat Specimen with Ultrasonic Device

Figure 3 (continued).



(a) Glue on Aluminum Specimen

Figure 4. Testing for Glue

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

(b) Glue on ICC Specimen

Figure 4 (continued).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH