ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
CA-DOT-TL-3144-1-76-33		

4. TITLE AND SUBTITLE	5. REPORT DATE
PAVEMENT TEXTURE EVALUATION BY PHOTOGRAMMETRIC TECHNIQUES	June 1976
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John A. Apostolos and Gary W. Mann	8. PERFORMING ORGANIZATION REPORT NO. 19301-643144
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Transportation Laboratory, California Department of Transportation, Sacramento, California 95819	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS California Department of Transportation, Sacramento, California 95807	13. TYPE OF REPORT & PERIOD COVERED Final
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This study encompasses the development of a stereo-photo method in which photogrammetric techniques are incorporated to produce dimensionally accurate profiles of pavement texture.

The selection of camera equipment and fabrication of the stand is discussed. An attached section on the calibration of the cameras and photogrammetric technique is included.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Pavement surface texture, photogrammetry, profiles, stereo.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

HMRT – 1242 (ORIG. 9/72)

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

June 1976

TL No, 643144

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

PAVEMENT TEXTURE EVALUATION BY
PHOTOGRAMMETRIC TECHNIQUES

Study made by	Roadbed & Concrete Branch
Under the Supervision of	John Skog Donald L. Spellman
Principal Investigator	James A. Matthews
Co-Investigator	John A. Apostolos Gary W. Mann
Report Prepared by	John A. Apostolos Gary W. Mann

Very truly yours,

George A Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

GWM:lrb

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution of Mr. Robert Brewer of California Department of Transportation, whose pioneering effort and original concepts in the field of texture measurement by photogrammetric methods are developed in this study.

The authors wish to express their appreciation to Mr. Dick Burns and Mr. Lloyd Bartlett, who were responsible for the calibration of the equipment and for the development of the photogrammetric/computer techniques (including the writing of Section 5 and Appendix B); to Mr. Joseph Wilson who solved many technical difficulties in his construction of the photo-taking unit; and to Mrs. Frosso Apostolopoulos, who donated her time and talents to the tailoring of the complex cloth cover for the unit.

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification or regulation.

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

TABLE OF CONTENTS

		Page
INTRODUCTION		1
CONCLUSIONS		2
IMPLEMENTATION		3
DISCUSSION		4
1.	Selection of Equipment	4
2.	Modification of Equipment	7
3.	Details of Camera Stand	9
4.	Calibration	11
5.	Profile Measurements, Computations and Plots	14
6.	Resulting Data	14
REFERENCES		22
APPENDIX A	Equipment and Procedure	A-1
APPENDIX B	Non-Metric Camera Calibration For Close Range Photogrammetry	B-1

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

INTRODUCTION

Pavement surface texture is one of the most important factors that influence wet-weather skid resistance on modern highways. This texture can easily be described in a qualitative manner, i.e., as polished, smooth, rough, etc., but such descriptions are inadequate in forming specifications or in correlating texture with skid resistance, and thus allow researchers to identify superior texturing methods. Thus, it is of importance to describe texture in a quantitative manner, i.e., measure various parameters relating to its geometrics. Much research has been performed in an effort to quantify texture. The methods developed (such as the sand patch, grease patch, putty impression, profile tracer and outflow meter) reflect the considerable variety of approaches to the solution of this problem (1-8). Another approach [commonly known as the Schonfield Method (9)] has been the use of stereo photographs and the visual interpretation of several texture parameters to arrive at a skid number (coefficient of friction).

This study encompasses the development of a stereo-photo method in which photogrammetric techniques are incorporated to produce dimensionally-accurate profiles of pavement texture.

ClibPDF - www.fastio.com

CONCLUSIONS

A technique for accurately measuring pavement texture profiles using photogrammetric techniques has been developed. The standard error for the horizontal accuracy is ±0.068 mm and the standard error for the vertical accuracy is ±0.112 mm.

This equipment can be used to fulfill one of the FHWA requirements of the research project titled "New and Innovative Methods and Materials for Pavement Skid Resistance". While this method provides a measure of texture parameters not obtained with any other device, it is costly. This will limit its use to research type determinations.

ClibPDF - www.fastio.com

IMPLEMENTATION

The photogrammetric system developed in this study is a valuable tool for accurate direct measurement of pavement texture. It can also be used as a "standard" to check or correlate with other texture-measuring devices that could be less expensive to construct and operate.

This system will be used to fulfill one on the FHWA requirements in the major research effort titled "New and Innovative Methods and Materials for Pavement Skid Resistance", currently in progress. Its primary function will be to provide a record of texture appearance and geometrics of various surfaces at a specific point in time, for later evaluation.

While still under development, this unit has been used in conjunction with texture measurements using sand patch, putty impression, and a "sounding-needle" profile tracer. The results of this correlation will be published in another report. It is being used to record the pavement surface condition of several locations to assist in the State financed research study "The Effects of Studded Tires on Pavement Surfaces in California".

ClibPDF - www.fastio.com

DISCUSSION

1. Selection of Equipment

Several discussions were held between members of the Transportation Laboratory - Roadbed and Concrete Branch and the Office of Geometronics - Photogrammetry Branch in order to establish requirements and specifications for the acquisition of equipment. The following requirements had to be met:

a. For Photogrammetry:
   Lens resolution of high quality.
   Adequate depth-of-field (zone of sharp focus).
   Pressure plate for film flatness.
   Introduction of fiducial marks onto the film plane.
   Calibration of camera-lens to correct for inherent distortions.
   Use of fine-grain color transparency film.

b. For Transportation Laboratory:
   Resulting profile graphs of high resolution.
   Compactness and light weight.
   Minimum camera adjustments in the field.
   Dependability of equipment.
   Controlled lighting.
   A stereo area approximately 15 cm (6 inches ±) square.
   Provisions for data insertion in the photos.
   Occasional use of equipment for conventional picture-taking as required.

With the above requirements in mind, inquiries were made to manufacturers and dealers of commercially available stereo cameras. Their responses revealed that such cameras were unsuitable for the task, because their focal lengths, minimum

ClibPDF - www.fastio.com

focusing distances, and other specifications did not meet our requirements. Furthermore, they were in limited supply due to declining consumer interest, which could create problems for needed parts and service, and a handicap to other researchers who may wish to duplicate such a unit. Custom-made stereo cameras were considered and rejected due to their expense, and lack of versatility as "conventional" photo taking devices.

The resulting choice was thus narrowed to using conventional 35mm single-lens reflex cameras, whose high resolution lens could focus to approximately 0.3 meter. A common method of taking stereo photos is to mount a single camera on a horizontally-sliding unit, and take two photos, at either end of the slide. Another approach to taking stereo photos is using two cameras mounted side-by-side and taking both pictures simultaneously. The single-camera method has the advantage of light weight, and the fact that stereo pairs are on the same roll of film. The two-camera method has the advantage of rigidly fixed base line (distance between cameras) and of speed in the actual picture-taking procedure. In view of the planned field use of the system in areas where highway lane closures would be impractical of difficult to arrange, the speed of the two-camera system would provide additional safety to operating personnel. They could wait - as long as necessary - for a <u>substantial</u> gap in traffic, walk to the picture area, usually the outermost wheel track of the truck lane (about 3 feet from the shoulder), set the unit down, press a button - and walk off. The entire process would take less than 5 seconds. On this basis, the two-camera system was selected for development.

Two single-lens reflex cameras were procured, each with a 35mm wide angle lens capable of focusing to 0.3 meter. The wide angle lens provided adequate overlap of photos (approxmately 53% see Figure 1) while allowing for an overall compact unit.

ClibPDF - www.fastio.com

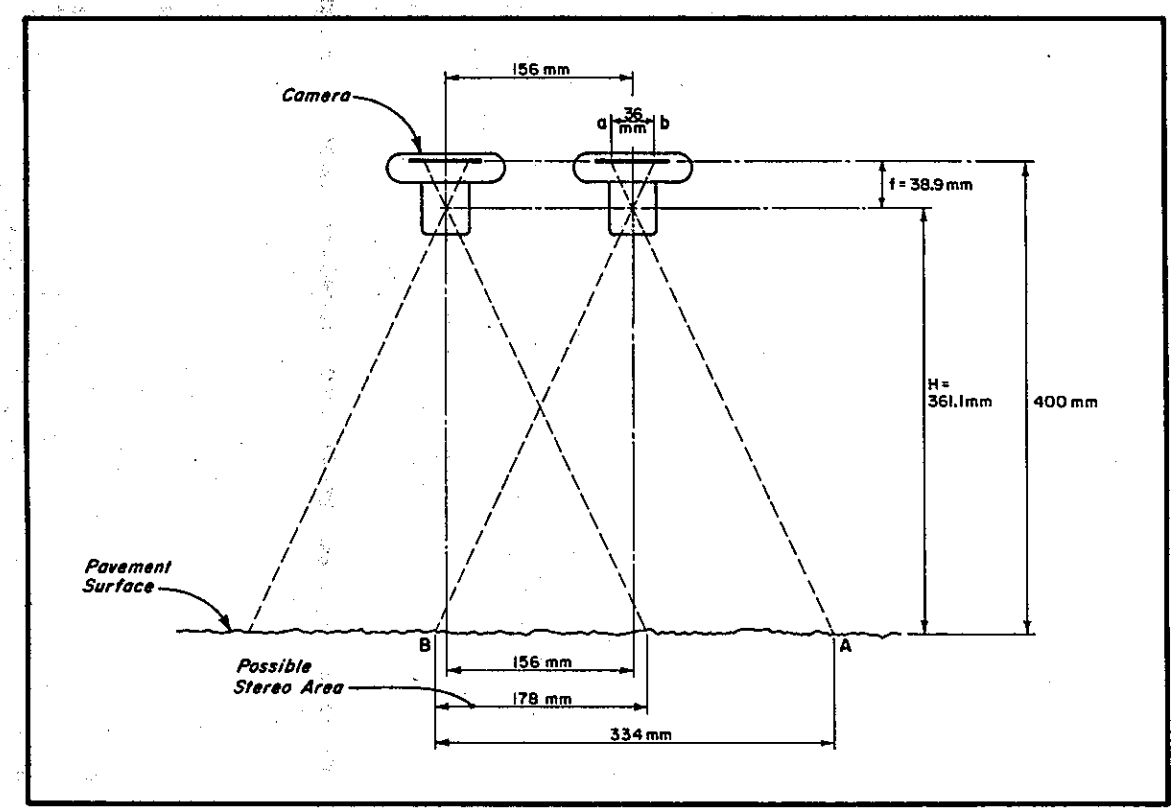


FIGURE 1. SCHEMATIC OF 2-CAMERA STEREO SYSTEM

(The principal distance (f) was determined to be 38.858mm when focusing at a distance of 400mm.)

A particular make of camera (Nikon F) was selected because of the availability of identical units in the Transportation Laboratory - photo department. Thus, in an emergency, a substitute camera would be available if needed. The substitute camera could then be post-calibrated. The other benefit is the possible use of these cameras by the photo department when not being used for stereo photography.

An electronic, battery operated flash unit with "automatic" exposure control was procured. The automatic system adjusts the amount of light required for the bright PCC or dark AC

ClibPDF - www.fastio.com

surfaces, eliminating the need for camera exposure adjustments. The particular make selected, a Rollei 128BC, was the only one whose specifications indicated it was capable of automatic operation within 16 inches (0.4m) of the subject, allowing for a compact unit. (Most other makes do not operate automatically nearer than 24 inches from the subject.) In practice, the chosen flash has been providing adequate automatic exposure of the pavement surface.

A twin-cable release is used to trip both camera shutters simultaneously.

2. Modification of Equipment

a. Cameras

The only modification to the cameras was the incision of very small, vee-shaped grooves in the film mask edges. These grooves registered in the exposed film, producing "fiducial marks" for photogrammetric calibration. Four such fiducial marks were placed in each camera, near the four corners of the picture area. Depth of a vee was approximately 0.1-0.2mm.

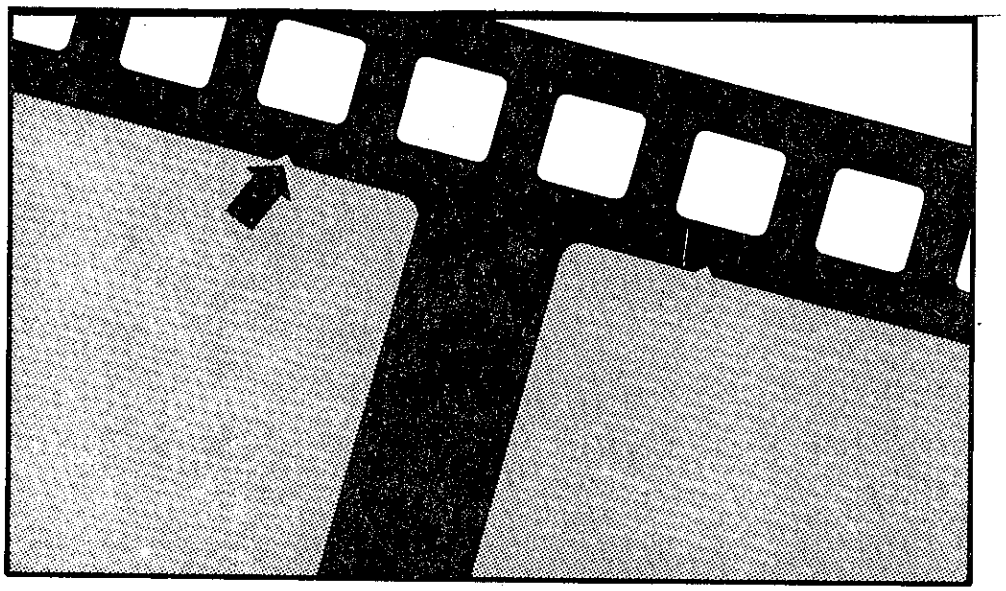


FIGURE 2. FIDUCIAL MARKS ON EXPOSED FILM (ARROW)

ClibPDF - www.fastio.com

Considerable time and effort was spent in developing techniques and "jigs" for incising these marks in the cameras. The end result, while not wholly satisfactory (the vees were not as clean-shaped as we would have liked) was adequate for photogrammetric techniques.

b. Flash

The flash unit itself was not mofified. However, the electric cable connecting the flash to the camera was modified to allow a three-way connection between the two cameras and the flash. A series circuit was designed so that both camera shutters had to be tripped before the flash would operate. Since tripping the shutters was a mechanical operation - via the twin cable release - it would be expected that one shutter would begin its operation an instant before the other, and that the role of the "fast" and "slow" cameras may interchange in practice. Thus, this circuit causes the flash to occur only after the slowest shutter has opened, regardless of which camera is the slowest. Polarity and electrical isolation of camera and flash bodies was also taken into account in the series circuit.

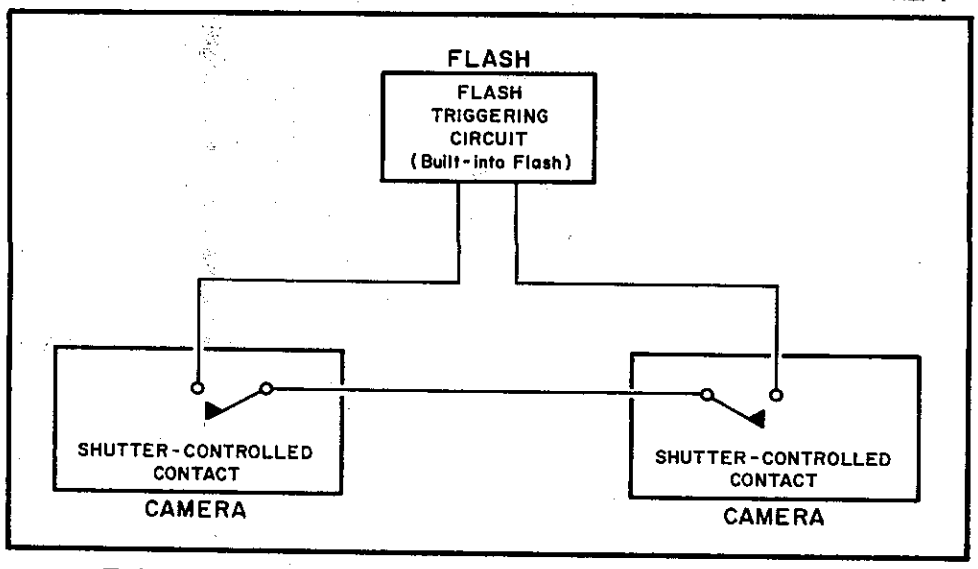


FIGURE 3. SCHEMATIC OF THE SERIES CIRCUIT CONNECTING FLASH AND CAMERAS

ClibPDF - www.fastio.com

To insure that both shutters were open at the instant of flash (duration is approximately 1/30,000 sec) the shutter speeds of both cameras are set at 1/4 second.

A specially-tailored black cloth cover, attached with "velcro" fasteners, provides a light shield to prevent ambient light from influencing the rather long 1/4 second exposures.

3. Details of Camera Stand

The primary function of the stand is to hold the two cameras and flash in rigidly fixed positions relative to each other and to the pavement surface, as well as provide support for a data-carrying plate near the pavement. An additional requirement was that it be light weight and collapsible, or "take-down", for ease of storage and travelling convenience. Thus, it was constructed of aluminum, except for steel leg tips and various screws and knobs.

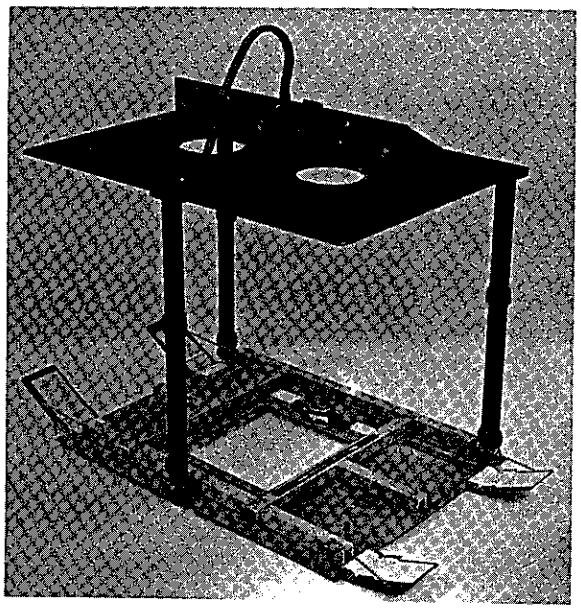


Figure 4. Assembled Stand

ClibPDF - www.fastio.com

Four hinged "flaps" at the sides of the bottom plate provide bright-colored areas, strategically located to match the fiducial marks on the film. The resulting contrast of these light areas against the dark unexposed edges of the film causes the fiducial marks to stand out clearly.

A wrist watch within the stereo area is used as a means of indexing photo pairs, which are on separate rolls of film. The time and the location of the sweep-second hand provide the indexing. The day-date calendar of the watch offers additional information.

Approximately half the picture area from each camera was outside the stereo overlap. These areas are used to record pertinent information which accompany each pavement texture. A standard 3 x 5 inch index card, carrying location descriptions and other facts, is inserted on one side of the nonstereo picture area. A specially-designed bubble level capable of indicating up to 15% $\pm$2% grade and superelevation was at one time included in the left picture area. However, problems with changing size of bubble, and uncertainty of re-zeroing due to the take-down nature of the bottom plate which supported it, made the resulting data unreliable and the level was removed. Finally, the direction of traffic is indicated within the picture area and on the cloth light shield, so the operator can align the unit properly.

The right (nonstereo) picture area will be available for the recording of additional information as needed.

ClibPDF - www.fastio.com

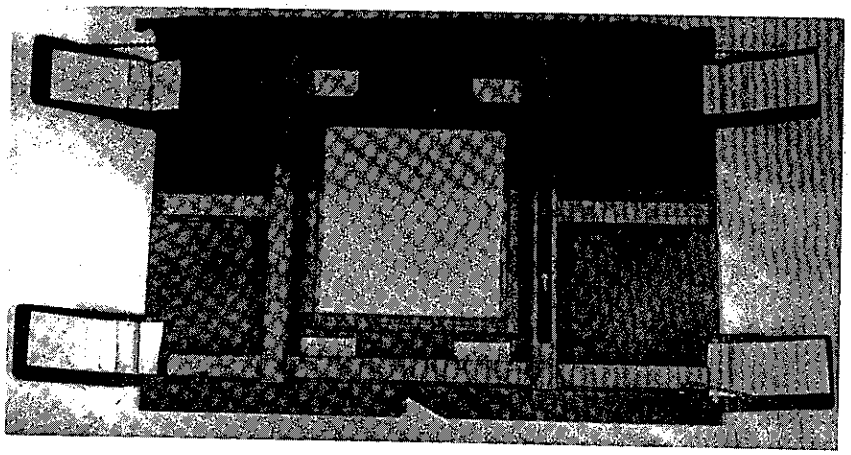


Figure 5. Base Plate - Center 1/3 of Area is the Stereo Area.

4. Calibration

Calibration of each camera for lens distortion was performed by the Photogrammetry Branch (see Appendix B). To check the calibration results, two test models were made.

The first test model consisted of eighteen machinist's gauge blocks (Johannsen Blocks) whose heights were determined photogrammetrically with the camera system (see Figure 6).

ClibPDF - www.fastio.com

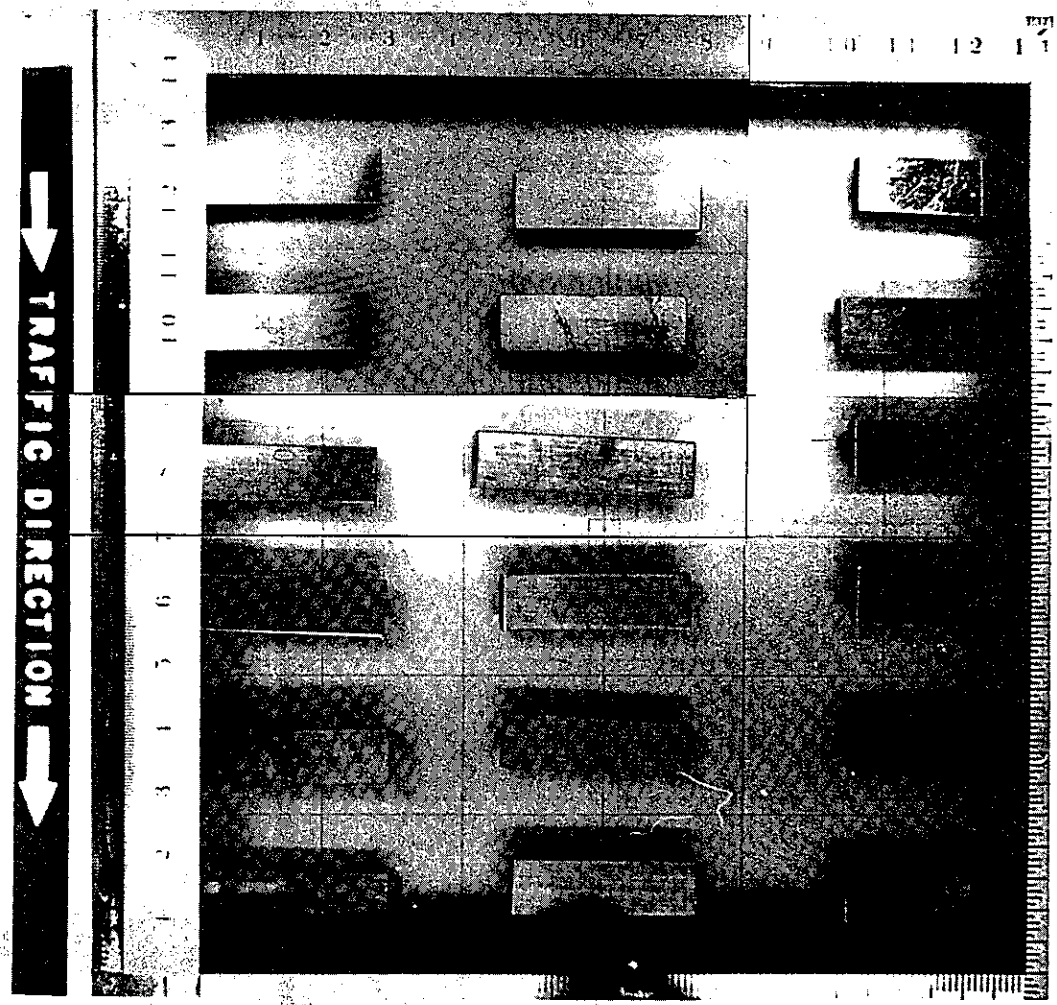


Figure 6. Machinist's Gauge Blocks Used For Calibration.

ClibPDF - www.fastio.com

Comparing the known height of these gauge blocks with those determined by photogrammetric techniques the vertical accuracy was found to be ±0.203mm.

For both vertical and horizontal determinations a second test model was used consisting of a precisely machined plastic block designed to fit into the camera platform opening. The block was milled flat across the top to a tolerance of ±0.03mm. Rounds, grooves and vees of various depths and widths were machined into it to a tolerance of ±0.05mm (see Figure 7).

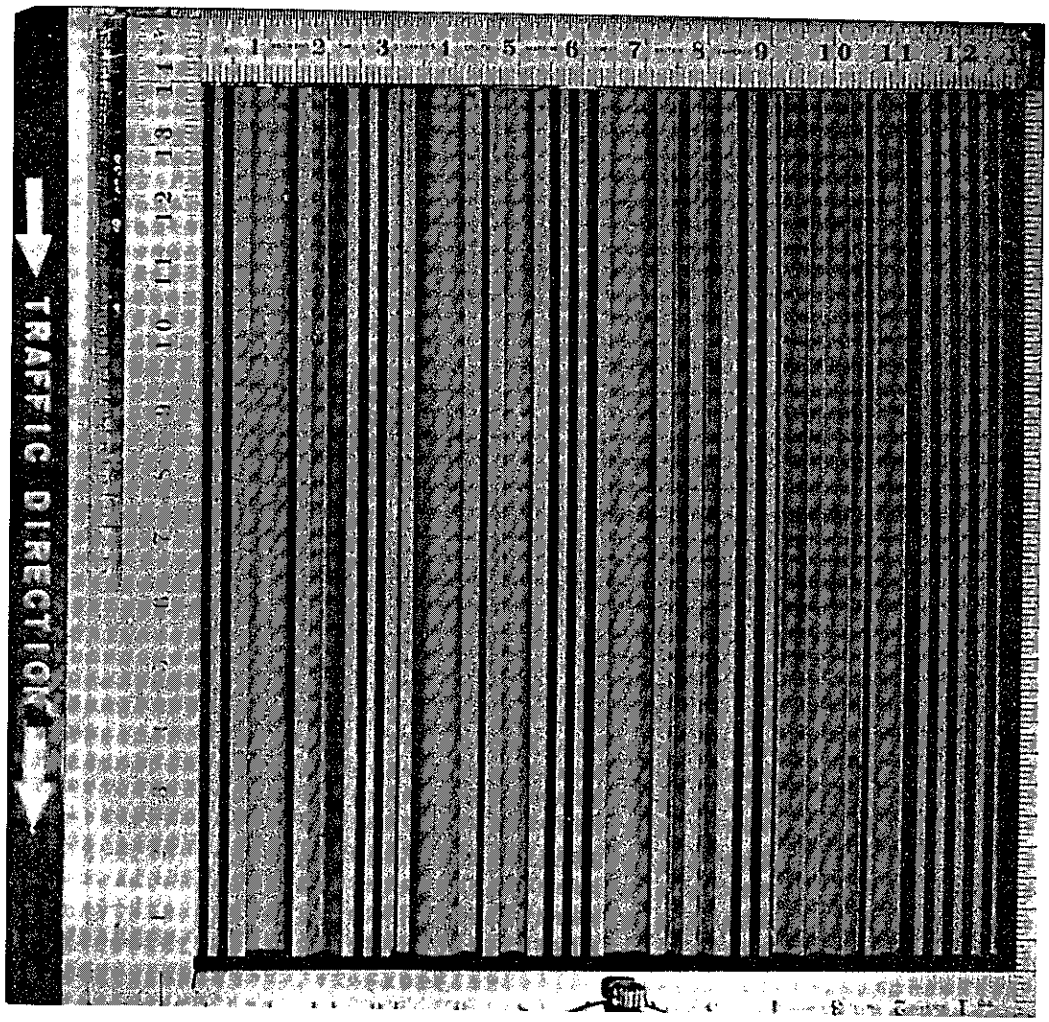


Figure 7. Machined Plastic Block Used For Calibration.

ClibPDF - www.fastio.com

The results of the comparative tests showed the Standard Error was ±0.068mm for the horizontal accuracy and ±0.112mm for the vertical accuracy.

5. Profile Measurements, Computations and Plots

Profile measurements are made on a Zeiss PSK Stereocomparator, a precise XY coordinate measuring device with a least count of 1 micrometer (0.001 millimeter).

XY coordinates along 3 profiles in the stereoscopic portion of each pair of color transparencies are read and recorded on punch cards. Readings and recordings on the fiducial marks and control points (images of metric scales) are also made.

A mathematical three dimensional model is then created with the aid of a computer. This model is corrected for all known distortions such as lens observations and film distortion. The resulting output is XYZ ground coordinates of the profiles.

From the file of XYZ profile coordinates, a plot tape is made and the final profiles are then plotted automatically on the Xynetics, Model 1200 Flatbed Plotter.

6. Resulting Data

Given sufficient time and funds, photogrammetric techniques are capable of producing any number of cross-sections of the stereo area up to a miniature topographic map of the whole area of pavement texture in the photographs. However, due to cost considerations, it was decided that three cross-sectional profiles of the texture be taken from each stereo photo. One, highly detailed, across the center of the photo - transversely to the direction of traffic - and two others, parallel to the first, at the quarter

ClibPDF - www.fastio.com

points. The latter two cross-sections would not be as detailed as the first, but would provide the maximum-minimum asperity heights and spaces between them.

The top and bottom profiles of the pavement surface are plotted on a 1 to 1 scale from which visual familiarity can be obtained for the actual pavement surface texture. The center, detailed profile, is shown at a horizontal scale of 1 to 1 with the vertical exaggerated to a 5 to 1 scale. The center profile is used to calculate the "Texture Number" which is defined as:

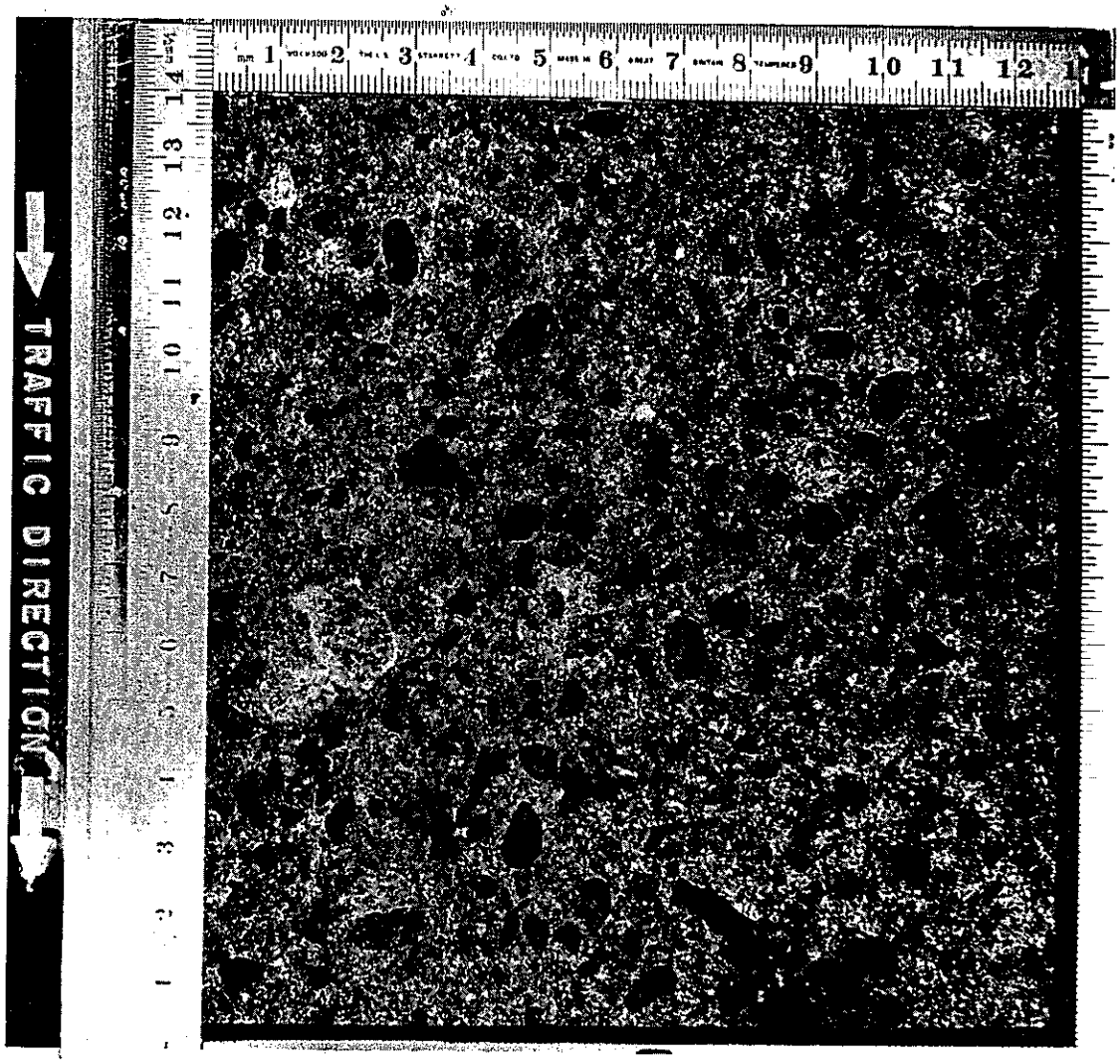
T = Length of texture line (profile) between tick marks divided by straight-line length between tick marks (110mm).

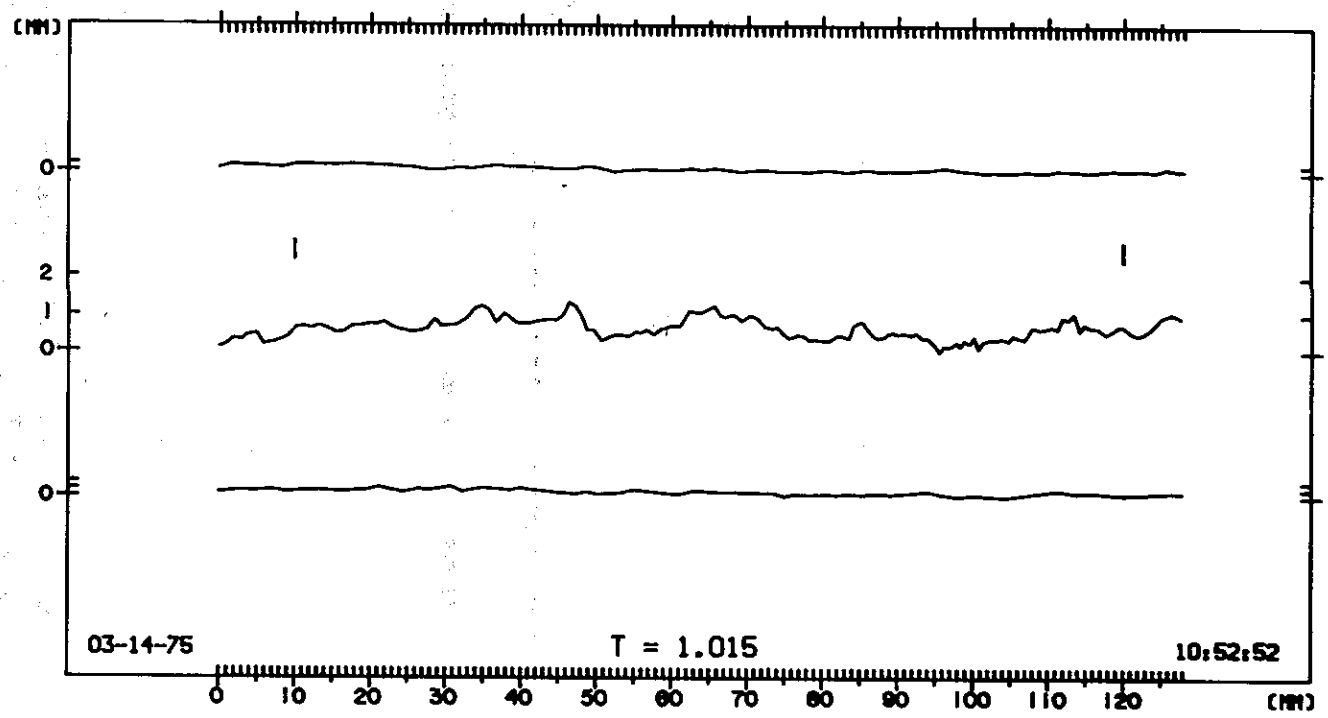
Figures 8 through 13 show typical pavement surfaces and their resulting protogrammetric plots of their profiles. The "Texture Numbers", which have been calculated by the computer are also shown along with the plotted profiles. For figure 8 the results of the equation is:

$$T = \frac{111.65\text{mm}}{110\text{mm}} = 1.015$$

ClibPDF - www.fastio.com

Figure 8

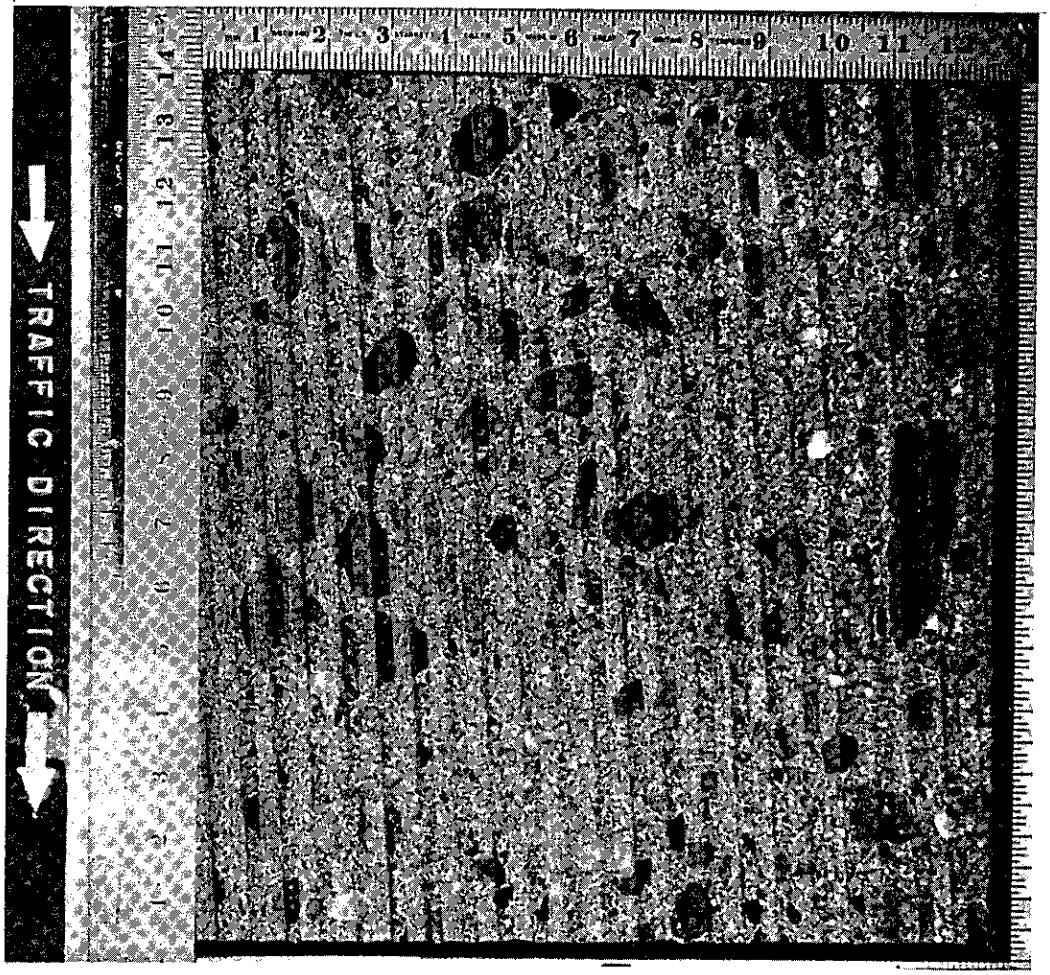


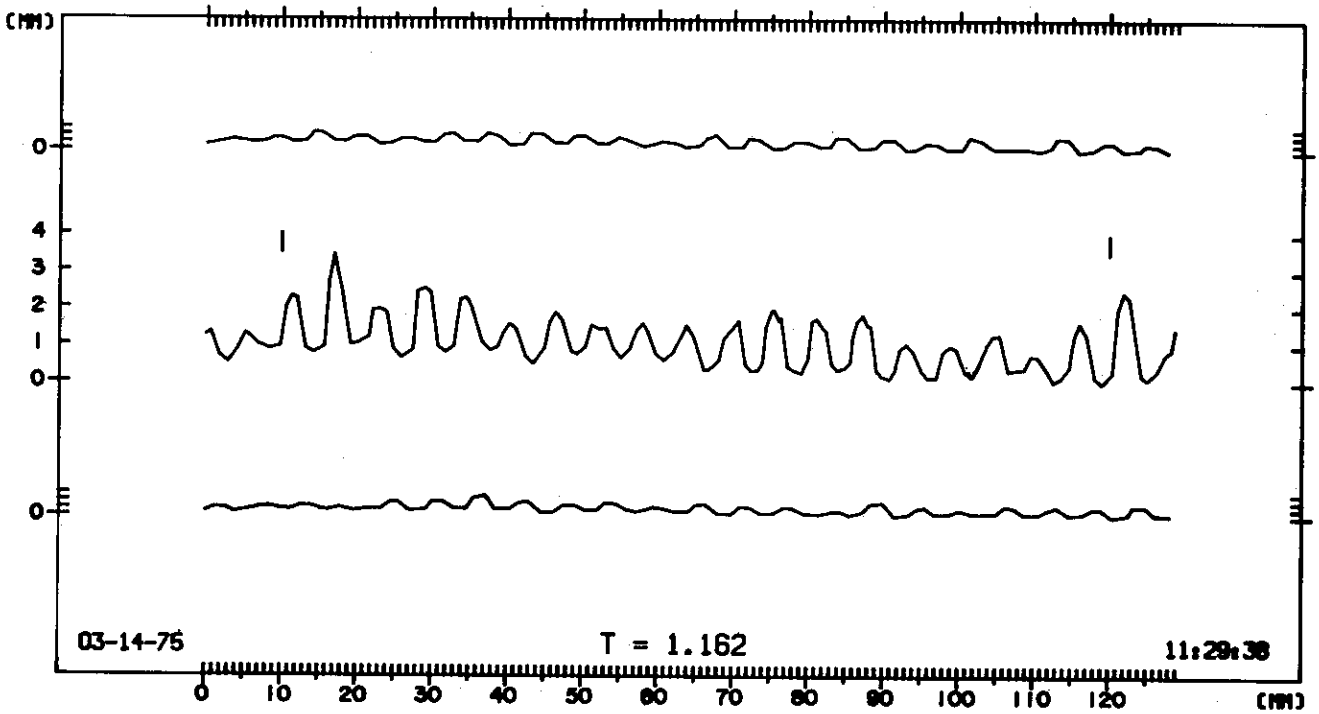


P. C. C.

ClibPDF - www.fastio.com

Figure 9

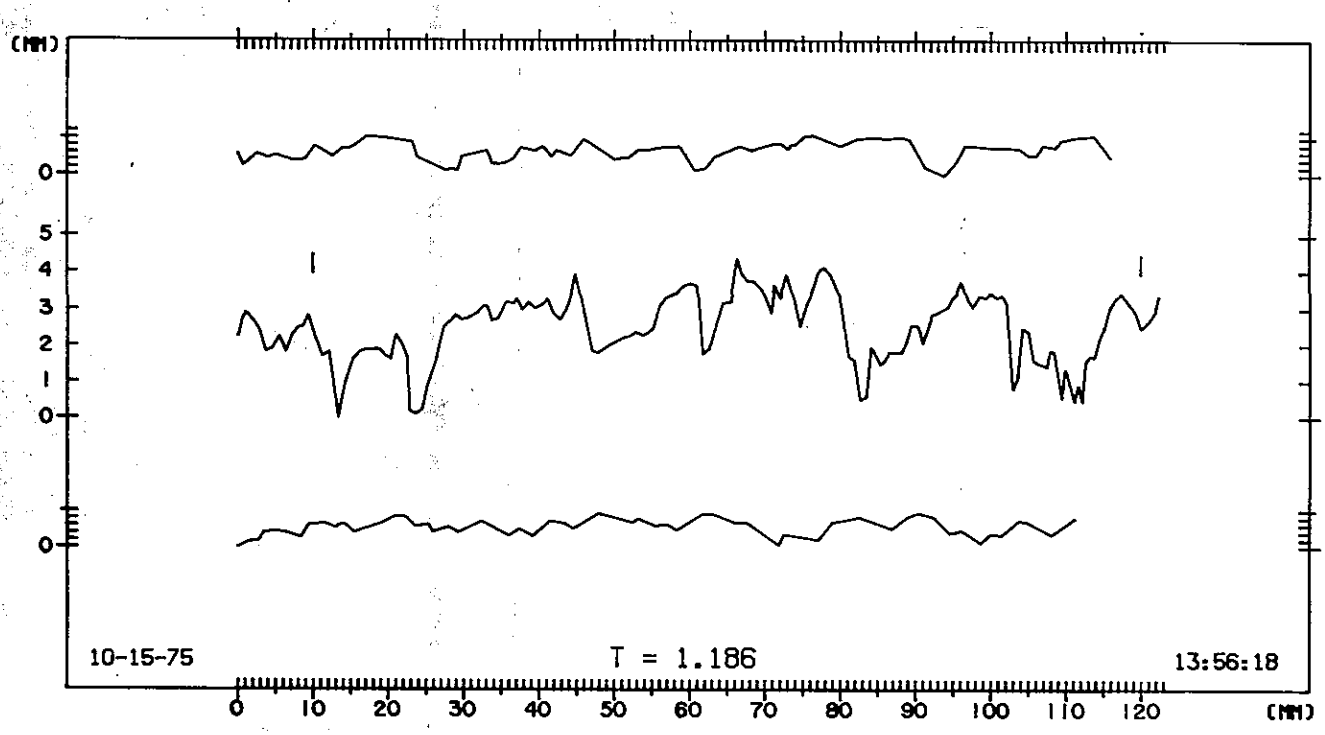




P. C. C. BUMP GROUND

ClibPDF - www.fastio.com

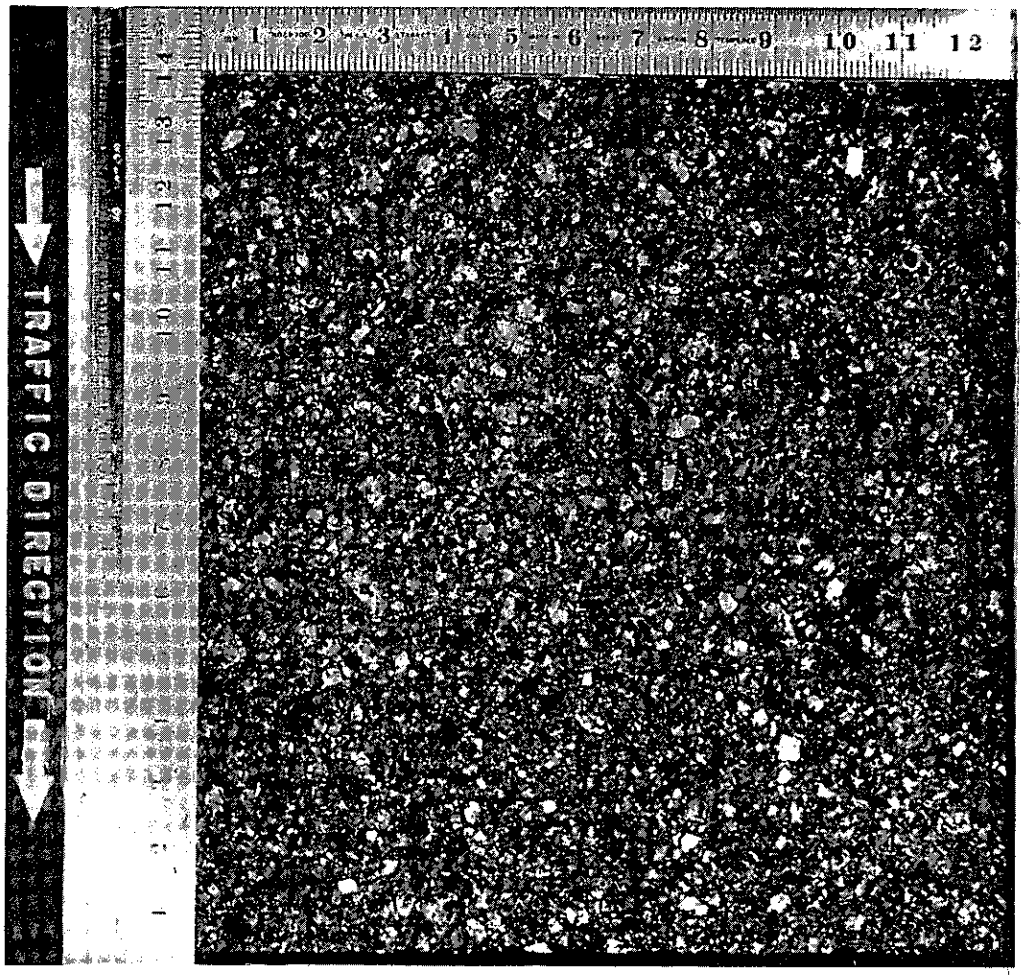
Figure 10

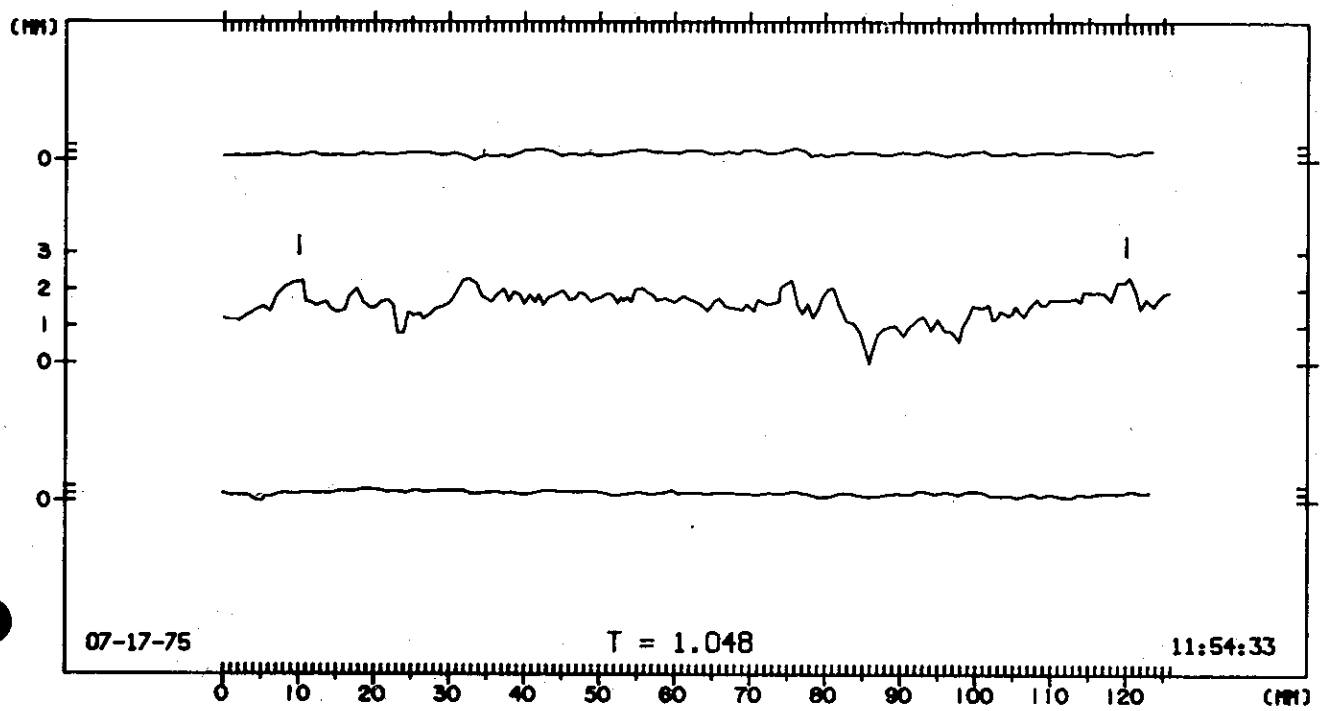


LOC 3-SAC-50 W BD # 1 LANE 3 FT RT EDGE OF LANE STA PM 18.00 PHOTO OGAC

ClibPDF - www.fastio.com

Figure 11

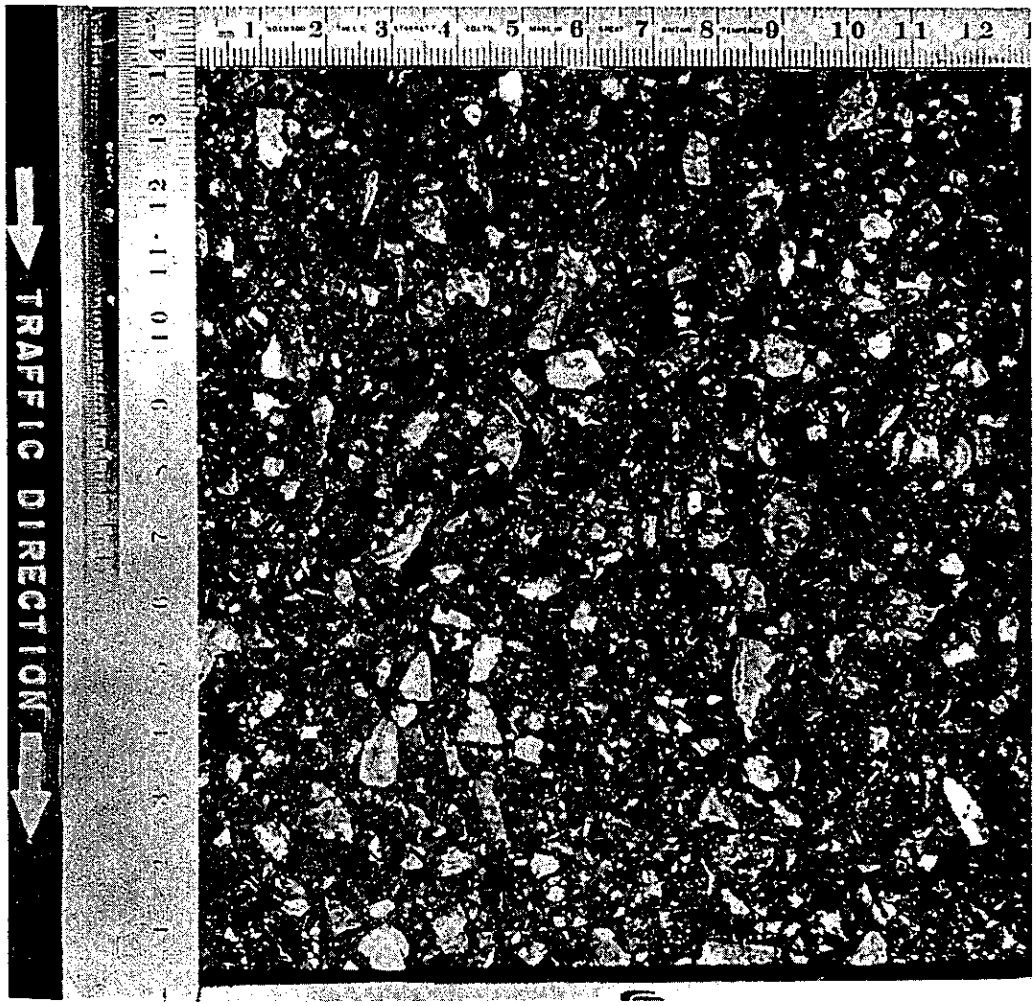


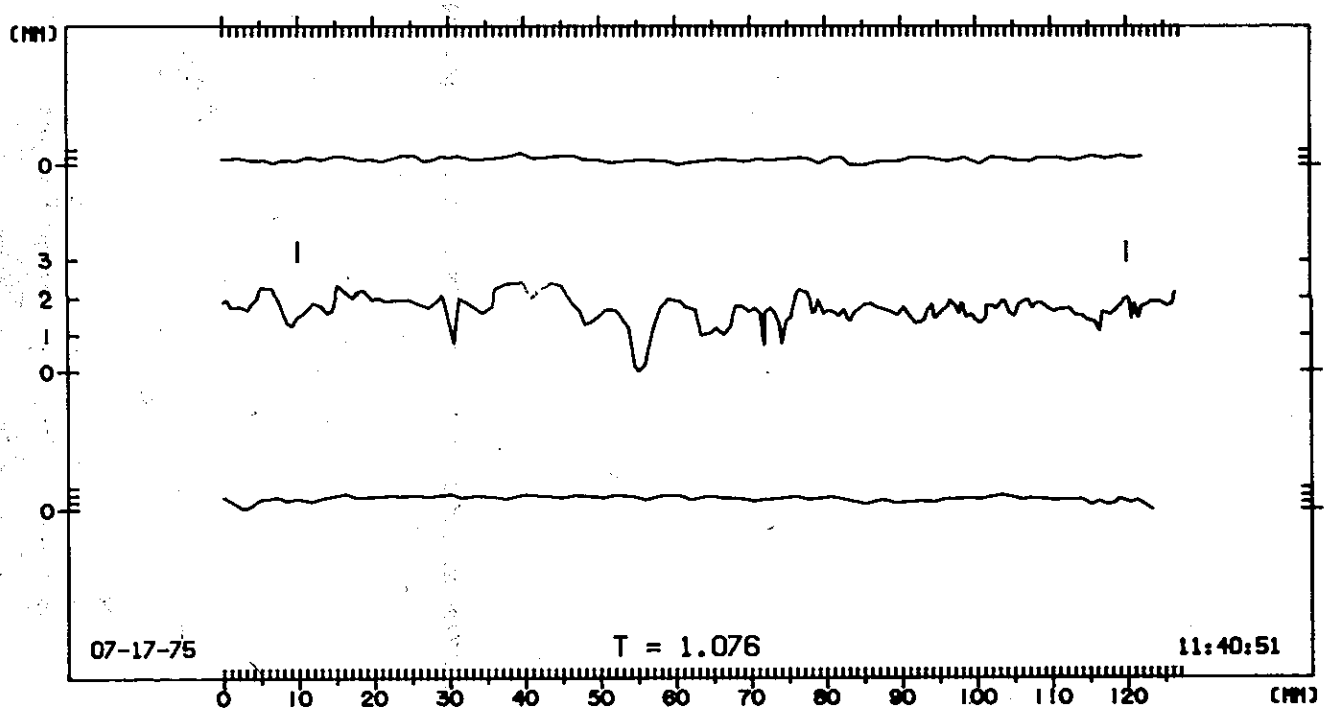


S.M.H.B.B. W-BOUND LANE 3 EPOXY AC AGGREGATE GRANITE

ClibPDF - www.fastio.com

Figure 12

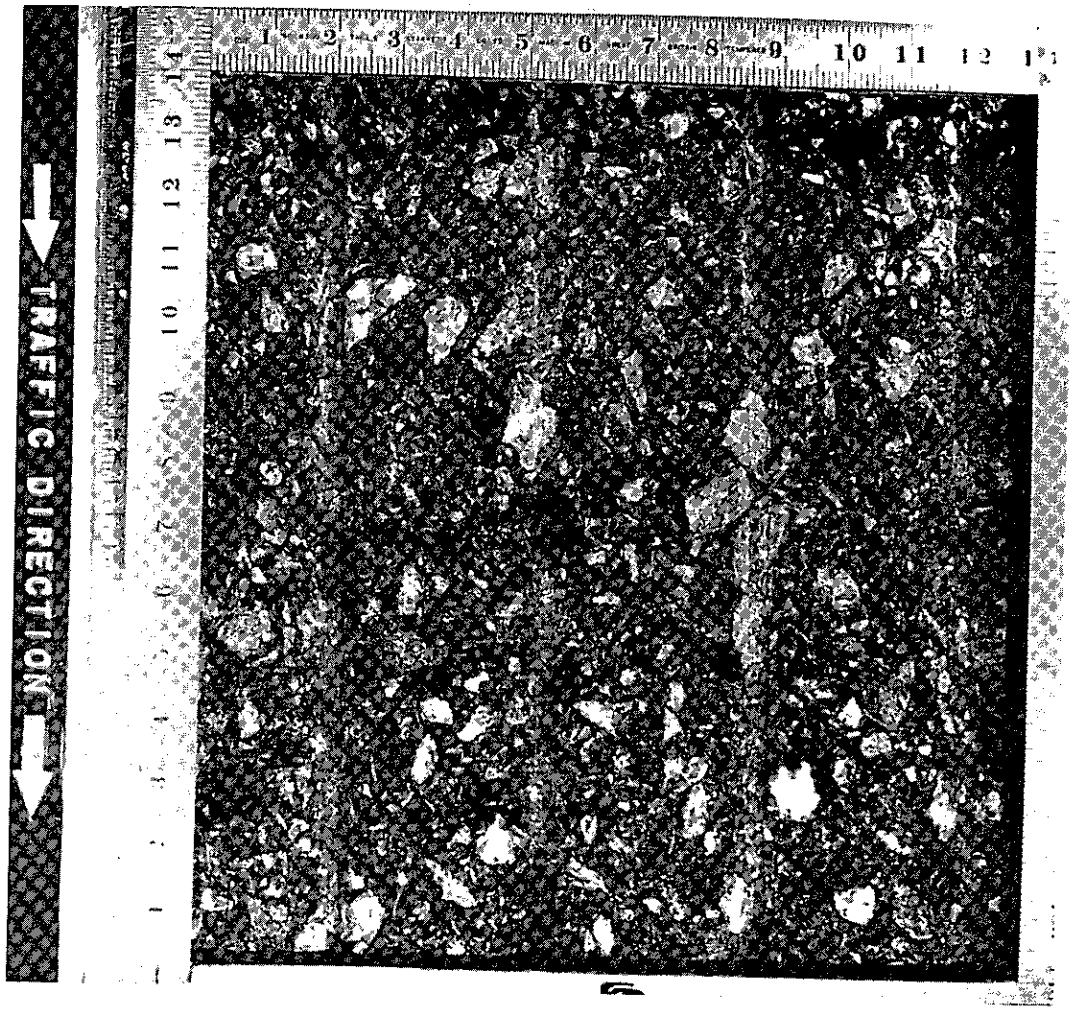


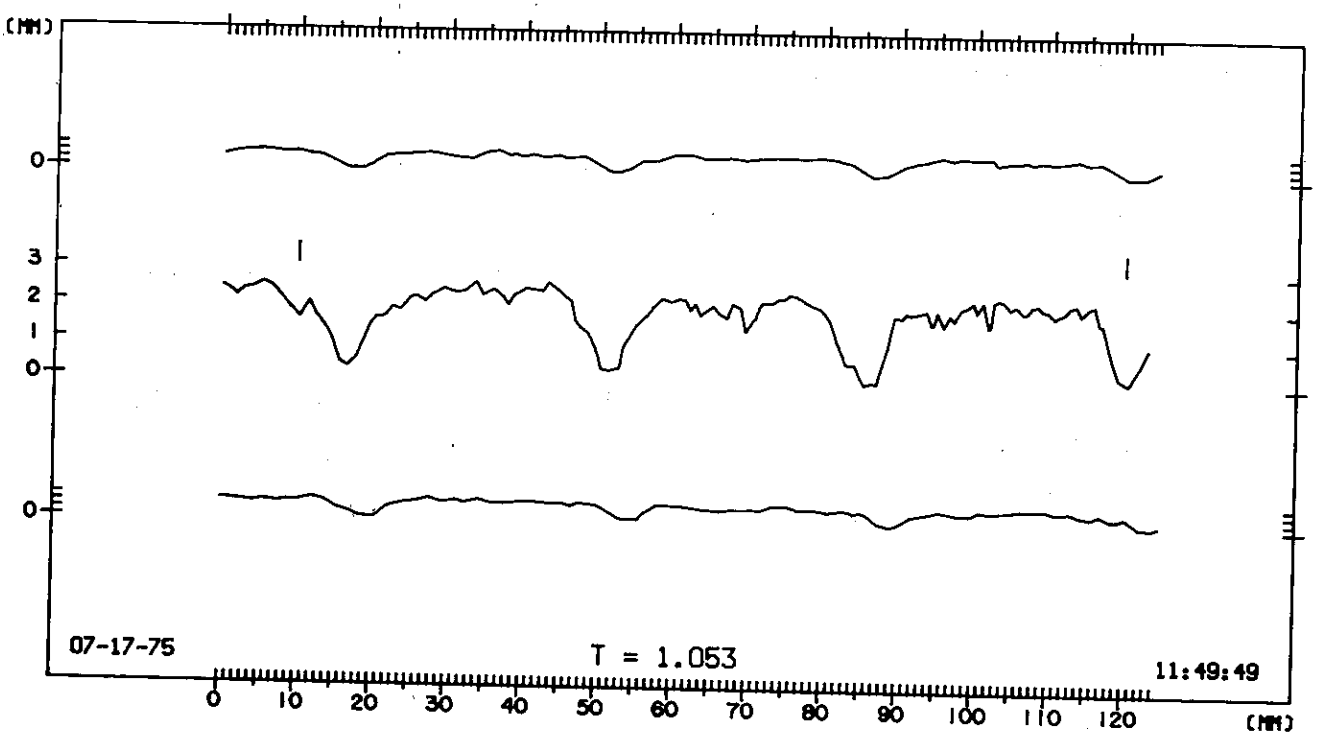


S.M.H.B.B. W-BOUND LANE 3 EPOXY AC AGGREGATE LIMESTONE

ClibPDF - www.fastio.com

Figure 13





S.M.H.B.B. W-BOUND LANE 3 EPOXY AC TEXTURE #4 AGGREGATE LIMESTONE

ClibPDF - www.fastio.com

REFERENCES

1. Gillespie, T. D., "Pavement Surface Characteristics and Their Correlation With Skid Resistance," No. 12, June 1965, Pennsylvania State University.

2. Hankins, K. D., "Pavement Surface Texture as Related to Skid Resistance," Report No. 45-4, Texas Highway Department, August 1967.

3. Goodman, H. A., "Pavement Texture Measurement from a Moving Vehicle," Report No. 19, Pennsylvania State University, March 1970.

4. Gallaway, B. M., Rose, J. G., "Macro-Texture, Friction, Cross Slope and Wheel Track Depression Measurements on 41 Typical Texas Highway Pavements," Research Report 138-2, Texas A & M University, Texas Transportation Institute, June 1970.

5. Gallaway, B. M., Epps, J. A., Tomita, H., "Effects of Pavement Surface Characteristics and Textures on Skid Resistance," Research Report 138-4, Texas A & M University, Texas Transportation Institute, March 1971.

6. Sabey, B. E., "Road Surface Texture and the Change in Skidding Resistance with Speed," Report No. 20, Road Research Laboratory, Ministry of Transport, Great Britain, 1966.

7. Hegmon, R. R., Mizoguchi, M. M., "Pavement Texture Measurements by the Sand Patch and Outflow Meter Methods," Report S40, Pennsylvania State University, January 1970.

ClibPDF - www.fastio.com

8. Apostolos, John A., Doty, Robert N., Page, Bobby G., Sherman, George B, "California Skid Resistance Studies," California Department of Transportation, Transportation Laboratory, 1974.

9. Schonfeld, R., "Photo-Interpretation of Pavement Skid Resistance," Ministry of Transportation and Communications, Ontario, Canada, 1974.

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

APPENDIX A

EQUIPMENT AND PROCEDURE

Standard equipment and settings:

Film: ASA 64 (Color Slide Film)
Camera Shutter Speed: 1/4 second
Camera Aperture: f8
Camera Flash Synchronization: FX
Flash Setting: Automatic

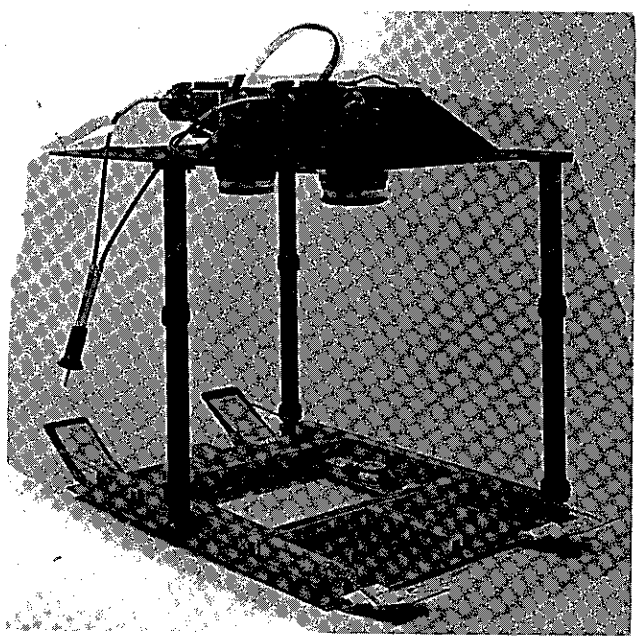


Figure 1A - Assembled Stereo-Photo Unit (Double exposure to show black cloth cover.)

ClibPDF - www.fastio.com

Recommended Operating Procedure

1. Load camera with film (see owner's manual for instructions), use color slide film ASA64.
2. Check batteries on flash (see owner's manual for instructions).
3. Assemble stand. Note red, green, black color coding for proper assembly of parts. Extend and secure outer flaps of bottom plate with chains provided.

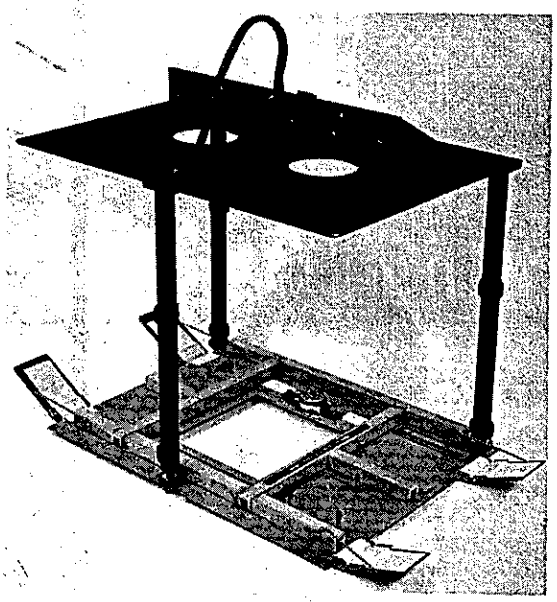


Figure 2A Assembled Stand

4. Set and wind watch to proper date and time.
5. Mount cameras and flash. Note color coding.

MOST IMPORTANT: Cameras must always be placed in their respective left-right positions; lens must always be matched to the same body.

ClibPDF - www.fastio.com

Left Camera	Right Camera
CHC 12216	CHC 12215
Body Serial No. 7436613	Body Serial No. 7424405
Lens Serial No. 370696	Lens Serial No. 336596
Prism: Black	Prism: Silver
Color: Red	Color: Green

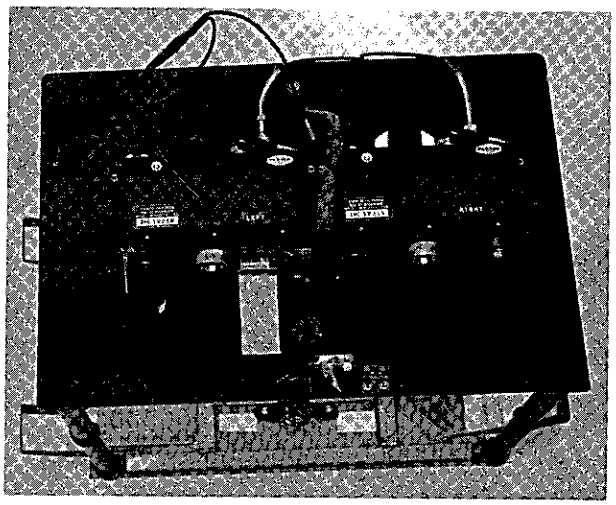


Figure 3A Mounted Cameras and Flash

6. Attach twin cable release and flash wires to cameras (Figure 3A). Note color coding.
7. Advance film and cock shutters (due to closeness of cameras, several short strokes are required for full cocking of the left camera, see Figure 3A).
8. Turn flash switch ON (set to "automatic" mode).

ClibPDF - www.fastio.com

9. Check the following:

   a. Both camera shutters cocked.
   b. Wires and cable releases fit snugly.
   c. Both shutters at 1/4 sec.
   d. Both apertures at f-8 (if pavement seems unusually dark, use f-5.6).
   e. Both lens focused at 0.4 meter mark (set the decimal point of the 0.4 mark opposite the index).
   f. Flash in "automatic" mode.
   g. Lens covers off - lens clean.
   h. Flash "ready-light" is glowing.

10. Place index card with appropriate information in slot of bottom plate.

11. Cover entire unit with black cloth cover - secure by pressing "velcro" fasteners. Leave cable release outside the cover (see Figure 1A). Check that outer flaps of bottom plate are not obscured from the cameras.

12. Place unit over area to be photographed - align unit with the direction of traffic.

13. Press button of cable release with one quick and vigorous move. (A very slow pressing motion may prevent both camera shutters from tripping simultaneously.

14. Note if flash occurred; it can usually be noticed through the cloth; also, the flash ready-light would be out for approximately 10 seconds after firing. If flash did not occur, re-start procedure beginning with step 9.

15. When sending film out for processing, tape a label to the film container marked "Do Not Mount".

ClibPDF - www.fastio.com

APPENDIX B

NON-METRIC CAMERA CALIBRATION FOR CLOSE RANGE PHOTOGRAMMETRY*

To achieve the desired accuracy for the pavement study it was considered necessary to calibrate two 35 mm cameras for the following parameters:

1. Focal Length
2. Principal Point Location
3. Symmetric Radial Lens Distortion

The cameras are single-lens-reflex, 35 mm Nikon F's and 35 mm lenses (24 mm x 36 mm format) and were calibrated at the distance they will be used (400 mm from object plane to focal plane). To determine the principal point location, four fiducial marks were carefully cut in the film mask as close to the corners as was practical. Glass plates with photographic emulsion were cut to the correct size, placed in the camera and exposed in the dark-room with a strobe flash. The "flash plates" which show the fiducial marks were developed and read in a Zeiss PSK Stereo-comparator to determine the relative location of the fiducial marks in each cameras. This information is necessary to correct for film distortion and to provide reference points for a rectangular coordinate system on the photographs.

A calibration target field was prepared consisting of a one inch grid plotted by a high precision flatbed plotter. Eight oblique photographs were taken of the test field with each camera, i.e., one from each of the four sides of the test field with the long

*Memorandum from Division of Project Development, Office of Geometronics

ClibPDF - www.fastio.com

side of the format parallel to the target surface and one from each side with the short side of the format parallel to the target surface (Brown, '72). The cameras were titled approximately 25° from a vertical lens axis position and were aimed at the center of the target field. Ideally, a 45° angle should have been used but a 25° angle was necessary to keep the target intersections in reasonable focus at the desired aperture (f8). Approximately one hundred intersections in the target field were visible in each of the eight exposures but, of course, all intersections were not common to all eight exposures due to the camera orientations and format. Approximately fifty intersections were common to all eight exposures on each camera.

The eight unmounted film negatives from each camera were placed in the stereocomparator and all target intersections on all negatives were measured. These coordinate values were corrected for film distortion in the Image Coordinate Refinement Program (Erio, '74) and the refined image coordinates were run in the Small Block Adjustment Program (Erio, '74) beginning with initial approximations of the exterior (spatial) orientation of the eight camera positions. This program is based on the linearized collinearity condition and will perform a simultaneous adjustment and camera calibration of as many as twenty-five photographs at a time. Both cameras were calibrated using this program for focal length (principal distance), principal point location, and symmetric lens distortion.

After the calibration was finished, two tests were devised to check the system by comparison of photogrammetric values with known values. For these tests both cameras were mounted in the platform to simulate conditions in production situations.

ClibPDF - www.fastio.com

The first test used an ultra-flat glass grid plate with eighteen steel machinists blocks (Johannsen Blocks) of various known thicknesses placed on it. Stereo color transparencies were taken and the grid plate intersections and the tops of the blocks were measured with the stereocomparator. The grid intersections were used for horizontal and vertical control. The comparator coordinates were run through the adjustment program using the newly determined camera calibration values and a statistical analysis was made to evaluate vertical accuracy. Then the same comparator coordinates were run without camera calibration to again evaluate the accuracy. Film distortion corrections were used on both runs because the purpose was to determine the improvement due to camera calibration only. The results of vertical readings on the 18 blocks are shown below:

	Without Camera Calibration	With Camera Calibration
	mm	mm
Average Error	-0.457	-0.025
Standard Error	±0.559	±0.203

The second test used color transparencies of a precisely machined plastic block which fit perfectly into the camera platform opening. The block was milled flat across the top to a tolerance of ±0.03 mm and had various width grooves, rounds and vees machined into it with all widths and depths known to a tolerance of ± 0.05 mm. The block was cross-sectioned on the stereocomparator in the same manner as a production job and the final results were compared with the true measurements. The test was successful except some of the grooves were too narrow for the bottom to be photographed from both camera stations. The horizontal and vertical accuracy of this test is as follows:

ClibPDF - www.fastio.com

	Horizontal	Vertical
	mm	mm
Average Error	-0.009	-0.068
Standard Error	±0.068	±0.112

Mean Surface Reading	87.773 mm
Standard Deviation	± 0.116 mm
Maximum Deviation from Mean Surface Reading	+ 0.374 mm

Vertical accuracy statistics do not include depth readings in the vees of the calibration block due to lack of correlation with the given measurements. The depth readings in the open grooves and on the Johannsen Blocks attest to the validity of the system.

References

1. Brown, D. C., "Calibration of Close-Range Cameras," Invited Paper, Commision V, XII International Congress of Photogrammetry, Ottawa, Canada, 1972.

2. Erio, G., User Instructions for the Computer Programs 'Image Coordinate Refinement' and 'Small Block Adjustment', California Department of Transportation, March 1974 (unpublished).

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com