US Army Corps of Engineers

MISCELLANEOUS PAPER SL-87-1

FROST RESISTANCE OF HIGH-STRENGTH CONCRETE

by

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April 1987
Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

STRUCTURES LABORATORY

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper SL-87-1	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Structures Laboratory — 6b. OFFICE SYMBOL (If applicable) WESSC	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Frost Resistance of High-Strength Concrete

12. PERSONAL AUTHOR(S)
Buck, Alan D., Burkes, Jerry P., and Ahlvin, Joyce C.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ____ TO ____	April 1987	19

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. This is Concrete Technology Information Analysis Center (CTIAC) Report No. 79.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Concrete, Effect of temperature on (LC) Frost resistant concrete. (LC)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

High-strength concrete made with crushed granite as coarse aggregate but without air entrainment showed an average durability factor of 95 after 300 cycles of freezing and thawing in the laboratory. Determination of air content by American Society for Testing and Materials (ASTM) Designation: C 457 showed the unexpectedly good results were not the effect of protection afforded by air entrainment. Petrographic examination confirmed lack of damage on a microscopical scale. It was concluded that self desiccation and low permeability associated with an 0.24 water-cementitious solids ratio (W/S) prevented development of critical saturation so that the concrete behaved during testing as if it were not critically saturated and thus was not damaged by freezing. Similar concrete at the same W/S with crushed limestone as coarse aggregate showed a durability factor of 17. It is presumed that this is brought about by the lack of frost resistance of the limestone itself since in air-entrained concrete the specimens with granite coarse aggregate gave an average durability of 92, while those with limestone coarse aggregate gave an average durability of only 55.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

Preface

This report is being published to provide information about higher than anticipated frost resistance by nonair-entrained concrete. It was prepared for publication in the open literature for the American Society for Testing and Materials (ASTM) journal Cement, Concrete, and Aggregates.

This report was prepared by Messrs. Alan D. Buck and Jerry P. Burkes and Mrs. Joyce C. Ahlvin, Concrete Technology Division (CTD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES). Mr. John M. Scanlon, Jr., was Chief, CTD, and Mr. Bryant Mather was Chief, SL.

The funds for publication of this report were provided by the Concrete Technology Information Analysis Center (CTIAC); it is CTIAC Report No. 79.

COL Dwayne G. Lee, CE, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

Contents

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals

FROST RESISTANCE OF HIGH-STRENGTH CONCRETE

Background

1. Specimens tested for resistance to freezing and thawing in connection with a study of high-strength concrete mixtures (1) were found to give good results even though they were not air entrained. The concrete contained crushed granite coarse aggregate. The test method used was ASTM Designation: C 666 (Procedure A).

2. Selected specimens were examined by petrographic and scanning electron microscope (SEM) methods. The spacing factor ($\bar{L}$) was calculated using ASTM Designation: C 457. Selected data are shown below:

Mixture No.	Specimen No.	Average DFE_{300},†† Set of 3	Air Content, %, of Fresh Concrete (ASTM Designation: C 231)	28-Day Compressive Strength, psi (MPa)	Coarse Aggregate
68	9787-9789 (9789 examined in detail)	95	0.8	16,590 (114.4)	Granite
67	9784-9786 (9784 examined in detail)	92	5.8	13,350 (92.0)	Granite
66	9781-9783	83	4.0	14,220 (98.0)	Limestone (P)†
64	9775-9777	55	4.6	14,260** (98.3)	Limestone (L)†
65	9778-9780 (9779 examined in detail)	17	1.0	16,440 (113.4)	Limestone (L)†

** 35-days age.
† P = project; L = laboratory stock.
†† Durability Factor

All of these mixtures contained silica fume, had a 0.24 water-cementitious solids ratio (W/S), and contained the project limestone fine aggregate. Therefore, the experimental variables in this group of five mixtures were coarse aggregate type and air content. A question arose as to why the nonair-entrained granite coarse aggregate mixture showed high resistance to freezing and thawing when the nonair-entrained limestone aggregate mixture had so much lower average resistance.

Procedure

3. Specimens from the five mixtures were inspected. End surfaces of beams from the two granite coarse aggregate mixtures were photographed along with selected strength specimens for comparison. Individual beams from the two granite coarse aggregate mixtures and the nonair-entrained limestone coarse aggregate mixture were cut and these sawed surfaces were ground to create a proper surface for study. These surfaces were examined with a stereoscopic microscope and photographed. A fresh fracture surface from the nonair-entrained granite coarse aggregate mixture was examined by SEM and several micrographs were made. These were compared with SEM micrographs of conventional concrete made earlier. The air-void spacing factor of the nonair-entrained granite coarse aggregate concrete was determined.

Results

4. Figure 1 shows the typical appearance of beams after several cycles of freezing and thawing. While these are dilation specimens rather than specimens tested by ASTM C 666, the scaling they show is typical. By contrast note the excellent condition of the two granite coarse aggregate concretes in Figure 2; each of these beams had been through more than 400 cycles of freezing and thawing. Figures 3 and 4 show interior surfaces of the same two granite coarse aggregate concretes. The major item to be noted is the lack of cracking even in the enlarged views. This lack of cracking in the nonair-entrained mixture was confirmed during examination of the entire smooth surface for air-void data at a magnification of 70X. By comparison note in Figure 5 the microcracks that are evident in the non air-entrained limestone aggregate concrete.

5. Figure 6 shows SEM micrographs of the nonair-entrained granite coarse aggregate concrete and of conventional strength concrete. Both micrographs represent concrete about 1 year old. Concrete represented by beam 9789

had compressive strength at 28 days of over 16,000 psi. Specimen CL-27 CON-1 represents normal concrete with compressive strength probably between 3000 and 5000 psi at 28 days (2). This pair of micrographs shows two significant differences. The first is that the microstructure of beam 9789 is significantly denser as it should be, and this is readily apparent by comparison of the two micrographs. The other point is that the micrograph of CL-27 CON-1 shows abundant calcium hydroxide (CH) while none is seen in the micrograph of beam 9789. This is considered proper since it is known from other work that CH is used in making calcium silicate hydrate when silica fume is present as it was in this concrete.

6. Table 1 shows micrometric data for the nonair-entrained granite coarse aggregate concrete along with other data for comparison. This concrete had an air content of about 1 percent with $\bar{L}$ of 0.013 in. (0.33 mm). This relatively large $\bar{L}$ value of 0.013 in. would not provide enough protection for a DFE_{300} value of 95 in normal strength concrete. While the spacing factor ($\bar{L}$) of the nonair-entrained limestone aggregate concrete (DFE_{300} = 17) was not determined, it seems a fair assumption that it would be similar since air content was similar.

Discussion

7. The question that needs to be addressed is why one high strength, nonair-entrained concrete with crushed granite as coarse aggregate had an average durability factor of 95 while specimens from a similar mixture differing only in containing crushed limestone as coarse aggregate had an average durability factor of 17. Observation verified the good physical condition of the granite concrete (Figure 4) and the cracked condition of the limestone concrete (Figure 5) from the two mixtures. Examination of the granite concrete by SEM revealed a dense microstructure, especially when compared to low-strength concrete (Figure 6). The spacing factor (L) for this beam showed the latter was 0.013 in. which would not be expected to provide frost resistance. The low water-cementitious solids ratio (0.24) resulted in self-desiccation of the granite aggregate concrete. It is believed that the permeability of this concrete was so low that the concrete was not critically saturated with water and thus was not damaged during the testing by ASTM C 666. The net result of this was that this concrete performed as well when tested by C 666 as its air-entrained, slightly lower strength granite coarse aggregate concrete counterpart with entrained air. However, since the nonair-entrained

limestone aggregate concrete was similar to the nonair-entrained granite aggregate concrete except for type of coarse aggregate it is apparent that some factor intervened to lower the durability factor of the limestone aggregate concrete. Since both coarse aggregates were also tested in air-entrained concrete and had average durability values of 92 (granite) and 55 (limestone) it is suggested the granite coarse aggregate performed better than the limestone coarse aggregate in both air-entrained and nonair-entrained concrete. The relevant factor may be pore size distribution or elastic properties or thermal properties of the rocks or a combination of these or other properties.

References

1. Saucier, Kenneth L. 1984. "High-Strength Concrete for Peacekeeper Facilities," USAE Waterways Experiment Station, Miscellaneous Paper SL-84-3, Vicksburg, Mississippi, 9 pp, 20 tables, 24 figures.

2. Daniel, J. L. and A. D. Buck. 1980. "A Comparison of the Microstructure of Hanford Type II Concrete Structures and Test Specimens," RHO-C-39, Rockwell Hanford Operations, Rockwell International, Richland, Washington.

Table 1

Data for Nonair-Entrained Granite Aggregate Concrete Beam 9789

Micrometric Data, %[a]			Air Content of Fresh Concrete, Pressure Method, %	Average DFE_{300}
Entrained Air[b]	0.7			
Entrapped Air[c]	0.3			
Total Air		1.0	0.8	
Coarse Aggregate (Granite)		49.4		
Fine Aggregate (Limestone)		23.7		
Paste		25.9		
Total		100.0		
Air-Void Spacing Factor ($\bar{L}$)		0.013 in. (0.33 mm)		95

(a) ASTM Designation: C 457.
(b) Spherical voids with circular section ≤ 1.0 mm.
(c) All other voids.

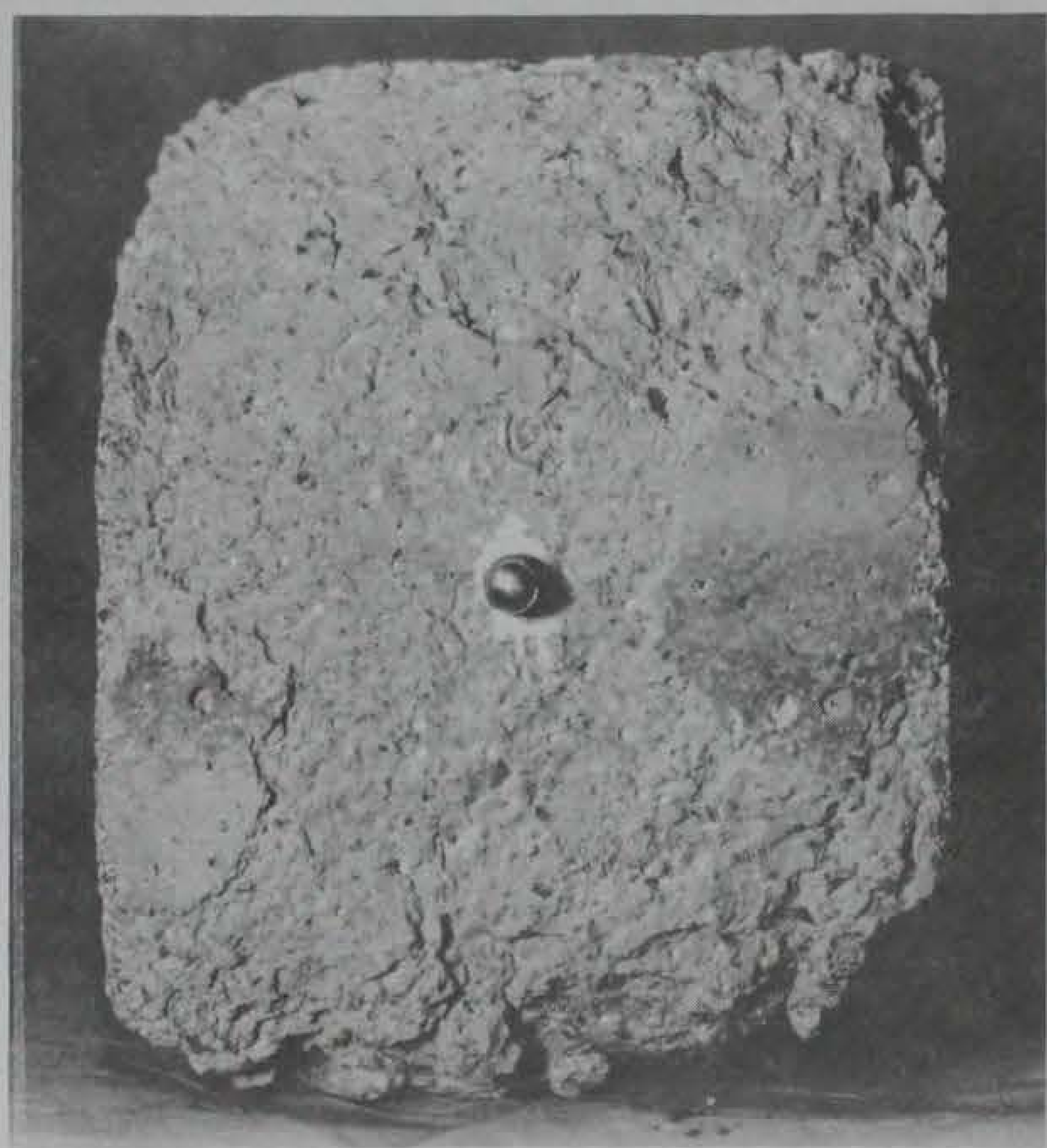


Figure 1. End view of two normal strength dilation beams from other work, ~0.7X. Top is air-entrained concrete (3C4) with compressive strength of 6500 psi and water-cement ratio of 0.49. The same concrete had DFE_{300} of 67. Bottom is nonair-entrained mortar (3M5) with compressive strength of 3800 psi and water-cement ratio of 0.8. The same mortar had DFE_{300} of 1.

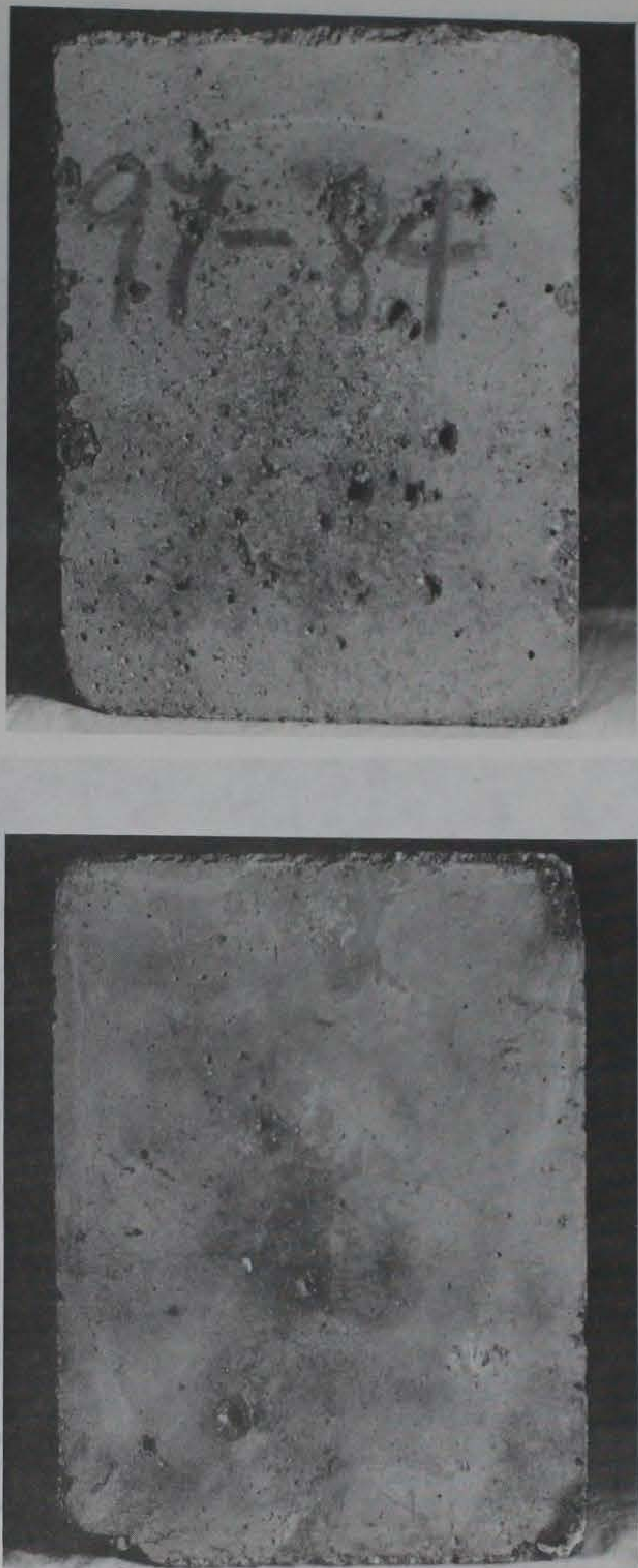


Figure 2. End view of two beams made with granite coarse aggregate after 400 plus cycles of freezing and thawing. Top, beam 9784 with 5.8 percent air, average DFE_{300} 92; bottom, beam 9789 with 0.8 percent air, average DFE_{300} 95; ~0.7X.

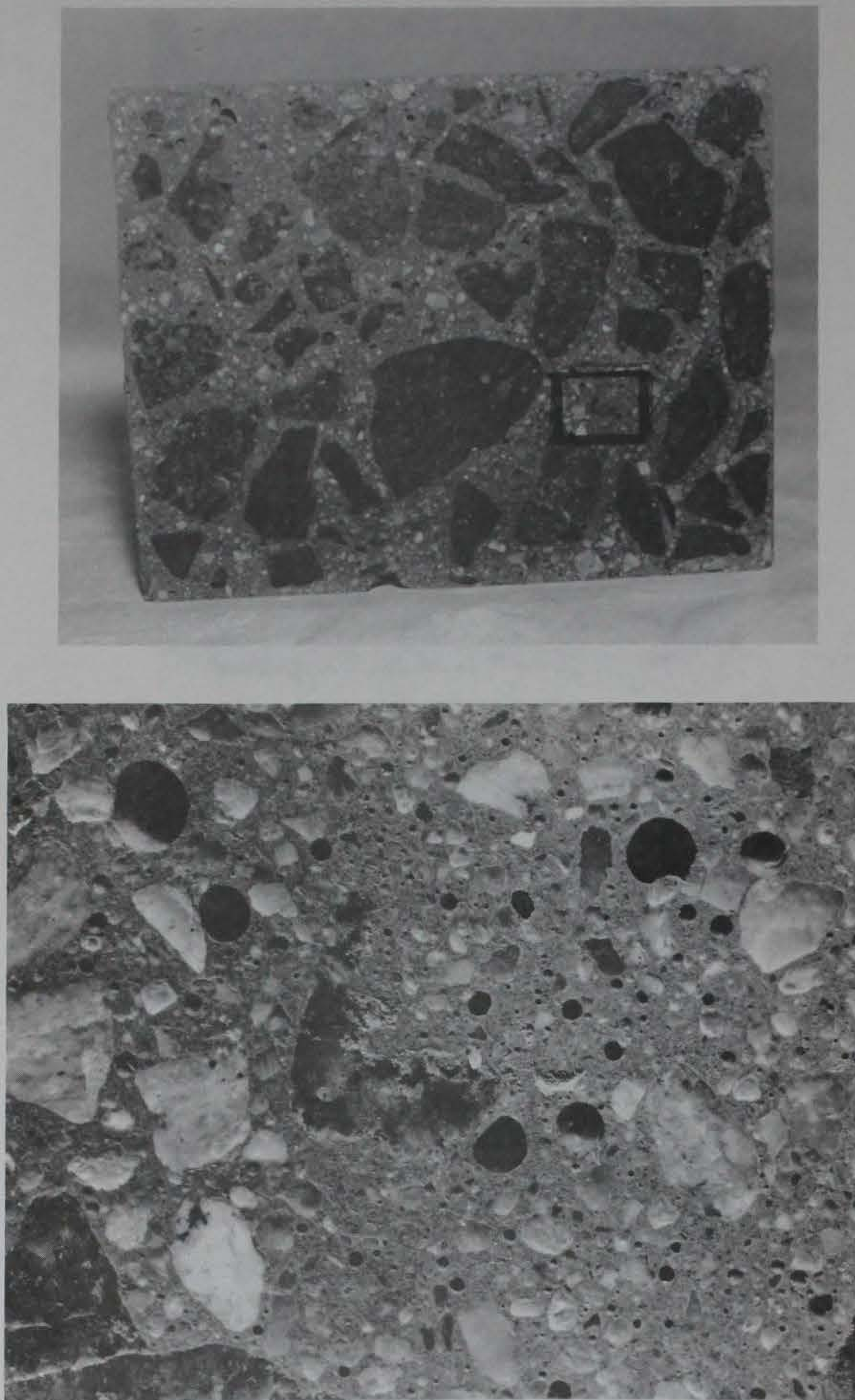


Figure 3. Sawed and ground surface of granite coarse aggregate beam 9784 with air, average DFE_{300} 92. Top, ~0.7X. Bottom, enlargement of lower right area (outlined), ~6X. No microcracks are evident, but entrained air voids can be seen.

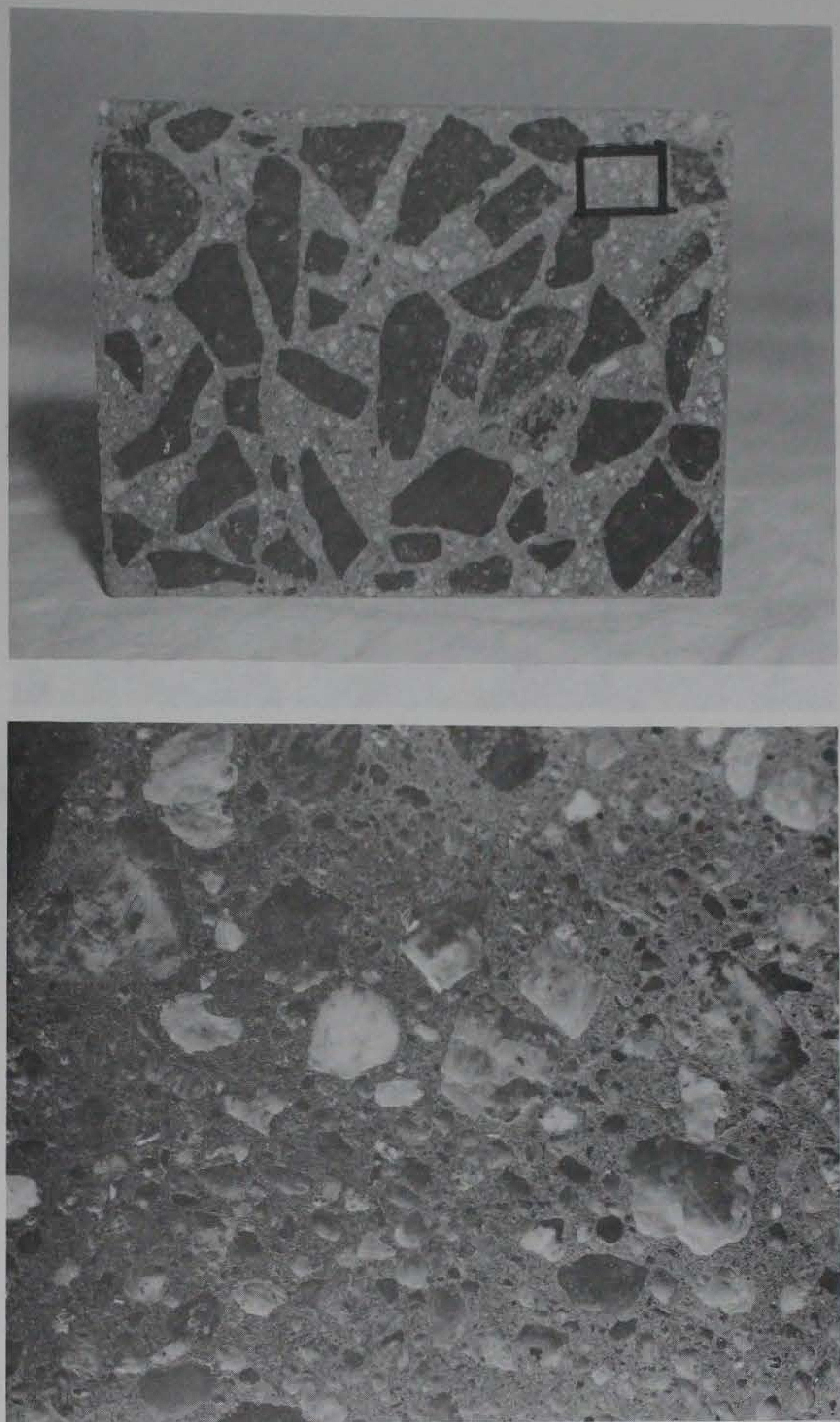


Figure 4. Sawed and ground surface of granite coarse aggregate beam 9789 without air, average DFE_{300} 95. Top, ~0.7X. Bottom, enlargement of upper right area (outlined), ~6X. No microcracks are evident.

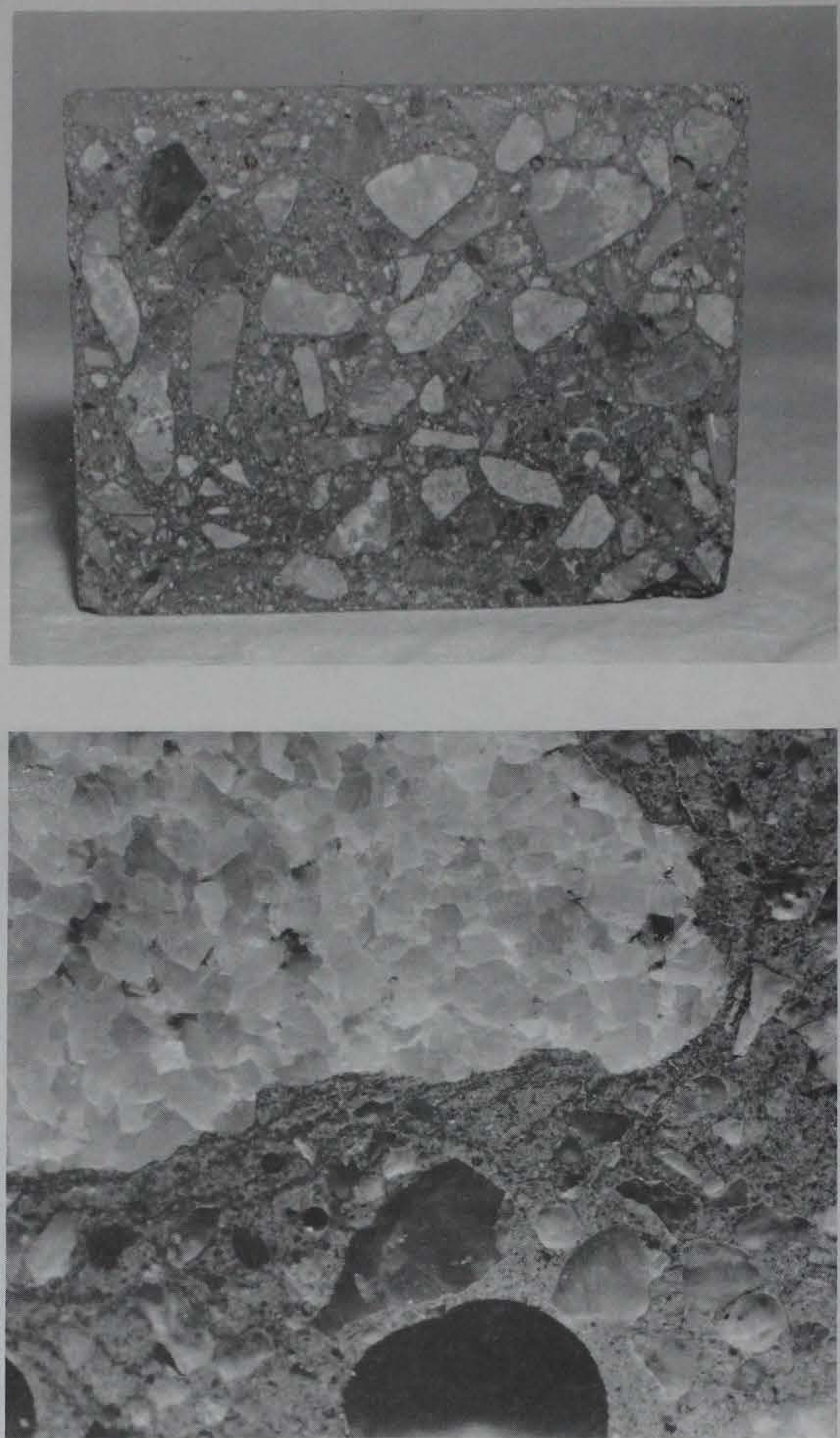
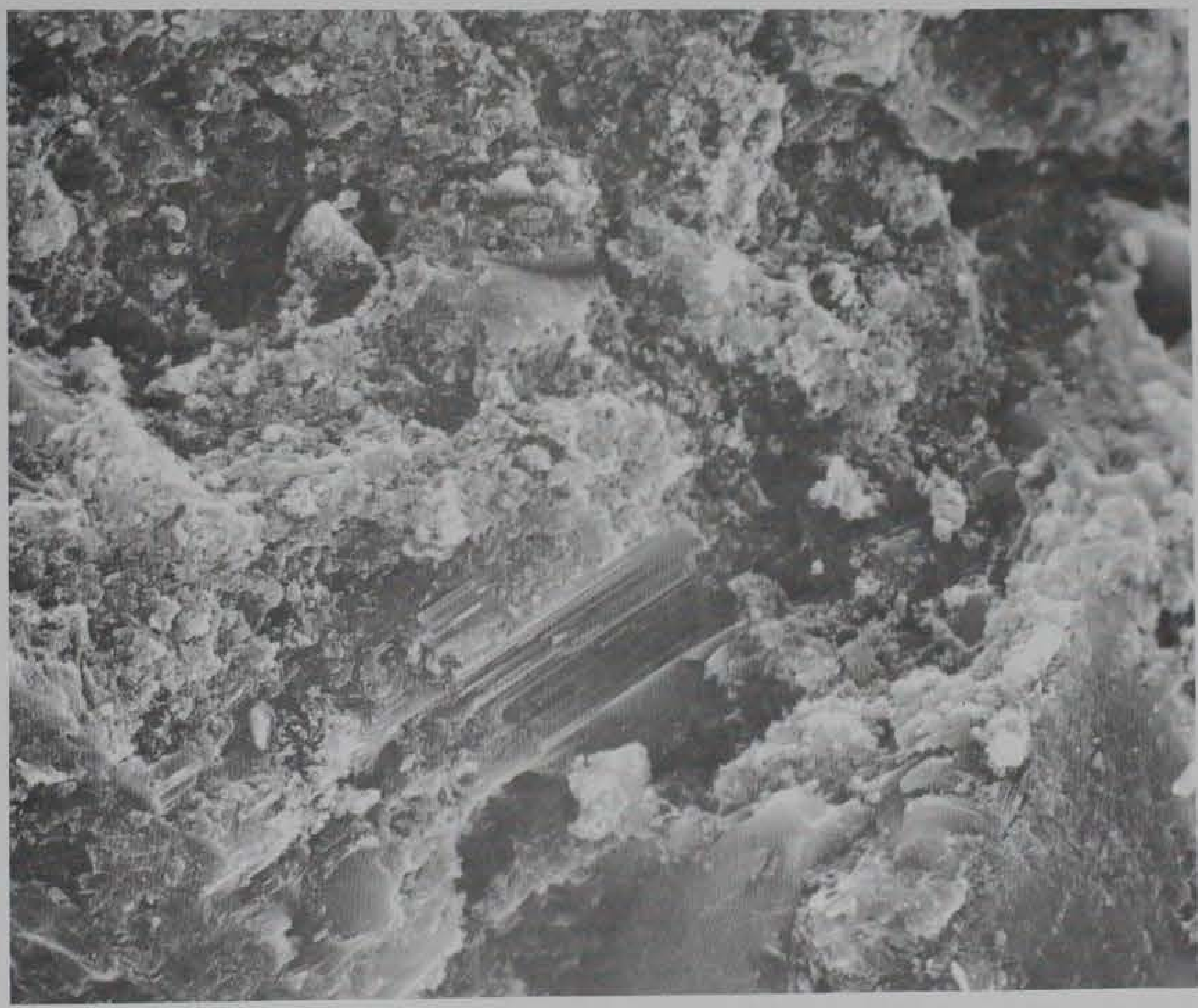


Figure 5. Sawed and ground surface of limestone aggregate beam 9779 without air, average DFE_{300} 17. Top, ~0.7X. Bottom, enlargement of lower right area showing microcracks due to freezing damage, ~10X.

a. SEM micrograph 080184-9, fractured surface of paste in granite aggregate concrete beam 9789, X2340.



b. SEM micrograph 082379-35, fractured surface of paste in concrete specimen CL-27 CON-1, X1900.

Figure 6.