Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

USE OF RECYCLED CONCRETE AS A NEW AGGREGATE

V.M. Malhotra

Industrial Minerals Laboratory

Construction Materials Section

MAY 1976

MINERALS RESEARCH PROGRAM
Mineral Sciences Laboratories
CANMET REPORT 76-18

Available by mail from

Printing and Publishing
Supply and Services Canada,
Ottawa, Canada K1A 0S9

CANMET
Energy, Mines and Resources Canada,
555 Booth St.,
Ottawa, Canada K1A 0G1

or through your bookseller.

En vente par la poste:

Imprimerie et Édition
Approvisionnements et Services Canada,
Ottawa, Canada K1A 0S9

CANMET
Énergie, Mines et Ressources Canada,
555, rue Booth
Ottawa, Canada K1A 0G1

ou chez votre libraire.

Catalogue No. M38-13/76-18
ISBN 0-660-00522-0

Price: Canada: $1.50
Other countries: $1.80

Price subject to change without notice.

N° de catalogue M38-13/76-18
ISBN 0-660-00522-0

Prix: Canada: $1.50
Autres pays: $1.80

Prix sujet à changement sans avis préalable.

MINERAL SCIENCES LABORATORIES
CANMET REPORT 76-18

USE OF RECYCLED CONCRETE AS A NEW AGGREGATE

by

V. M. MALHOTRA*

ABSTRACT

Large urban centres in Canada and the United States are finding it increasingly difficult to locate and develop natural aggregate sources for use in concrete. The reason for this is twofold: first, the increased tempo of construction during the last three decades has exhausted most of the easily accessible sources; second, the pressure from environmentalists has increasingly affected exploration and exploitation of new sources. The study reported herein was therefore undertaken to investigate the possibility of producing aggregates from discarded concrete control test cylinders, normally sent to waste dumps after testing.

A series of 2.2-ft^3 (0.062-m^3) concrete mixes were made covering the low, medium and high strength levels. Two sets of mixes were made at each strength level, one set consisted of a control mix and a mix made using coarse aggregate prepared from recycled concrete and reference fine aggregate; the second set consisted of a control mix, and a mix using fine aggregate prepared from recycled concrete and reference coarse aggregate. Cylinder and prism specimens were cast from each mix to determine mechanical properties of concretes at various ages and to study the durability of concrete after exposure of freeze-thaw cycling.

The analyses of the test results have shown that satisfactory concrete can be made with aggregates prepared from recycled concrete. At higher water:cement ratios, the compressive and flexural strength of concrete made with aggregates prepared from recycled concrete are somewhat lower than the strength of concrete made with reference aggregates; however this can be overcome with suitable adjustments in mix proportions. At lower water:cement ratios, strength of the two types of concrete are comparable.

The durability of concrete made with aggregates prepared from recycled concrete is comparable to the durability of concrete made with reference aggregates.

*Head, Construction Materials Section, Mineral Sciences Laboratories, Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources, Ottawa, Canada.

LABORATOIRES DES SCIENCES MINERALES

RAPPORT DE CANMET 76-18

L'UTILISATION D'UN NOUVEL AGREGAT FAIT DE BETON RECYCLE

par

V.M. MALHOTRA*

RESUME

Les sources naturelles d'agrégats deviennent de plus en plus rares à cette époque. La preuve en est que les grands centres urbains du Canada et des Etats-Unis ne trouvent plus de ces sources à exploiter pour la fabrication du béton. Et ce, premièrement à cause du rythme avec lequel la construction s'est épanouie depuis les trente dernières années et par conséquent épuisé les dernières sources accessibles, et deuxièmement la pression exercée par les protecteurs de l'environnement a ralenti l'exploration et l'exploitation des nouvelles sources. Cette présente étude vise donc à analyser la possibilité de produire des agrégats à partir des cylindres en béton utilisés pour les essais de contrôle et qui, habituellement, sont jetés après usage.

Ainsi, une série de mélanges de 2.2 pi^3 (0.062 m^3) ont été faits pour obtenir des niveaux de résistance bas, moyens et élevés. A chacun de ces niveaux, deux sortes de mélanges ont été effectués: la première comprenait un mélange de contrôle fait d'un gros agrégat préparé à partir de béton recyclé et d'un petit agrégat standard; la deuxième comprenait un mélange de contrôle fait d'un petit agrégat préparé à partir de béton recyclé et d'un gros agrégat standard. Chaque mélange a été utilisé pour former les échantillons cylindriques et prismatiques afin qu'on puisse déterminer les propriétés mécaniques des bétons de différents âges et afin d'étudier la durabilité du béton après avoir été soumis au cycle du gel-dégel.

---

*Chef, Section des matériaux de construction, Laboratoires des sciences minérales, Centre canadien de la technologie des minéraux et de l'énergie, Ministère de l'Energie, des Mines et des Ressources, Ottawa, Canada.

A la suite des résultats obtenus, nous avons pu conclure que du béton de qualité satisfaisante peut être fait avec des agrégats préparés à partir de béton recyclé. La résistance à la compression et au plissement des bétons faits d'agrégats préparés à partir de béton recyclé est inférieure à celle du béton fait avec des agrégats standards lorsque les proportions eau/ciment sont augmentées; par contre ceci peut être remédier en changeant les proportions du mélange. A de moindres proportions eau/ciment, la résistance des deux sortes de béton est comparable.

De plus, la durabilité du béton fait d'agrégats préparés à partir de béton recyclé est aussi comparable à la durabilité du béton fait d'agrégats standards.

CONTENTS

CONTENTS (cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

INTRODUCTION

Metropolitan cities in both Canada and the U.S.A. are experiencing an increasing shortage of aggregates for the concrete industry. The reason appears to be two-fold. First, the large volume of construction activity during the past thirty years has depleted most known reserves of good quality aggregates. Second, awareness of the need for environmental pollution control and opposition from environmentalists has discouraged the development of new sources within metropolitan areas. A recent study (1) commissioned by the Province of Ontario on the prospective supply and demand for aggregate in the central Ontario region, reached some alarming conclusions. The study indicated a total demand of 2.8 billion tons by the year 2000 with an available supply within the region of 3 billion tons (Table 1). The study concluded:

> ". . . with the present conditions, the region could only remain self-sufficient in mineral aggregate for perhaps 15 to 20 years."

It is therefore of paramount importance to find and evaluate new sources of mineral aggregates. One obvious source is waste concrete which can be recycled to produce aggregate. A literature survey revealed little or no data on the subject in North America except for a recent limited study by the U.S. Corps of Engineers (2) in which a discarded concrete driveway containing siliceous aggregate and a laboratory concrete beam containing limestone as coarse aggregate and natural siliceous sand as fine aggregate were recycled.

In addition to discarded pavements and other discarded concrete members, another source of aggregate is the waste concrete in the form of test cylinders sent to disposal dumps after control testing. Granted, that waste concrete can supply only a small proportion of total needs of the concrete industry, nevertheless this proportion combined with other compatible solid wastes can provide, in certain instances, a substantial source of aggregate. Another consideration is that recycling of waste concrete to replace conventional aggregate overcomes disposal problems and can thus be considered as a pollution control measure. A study was therefore undertaken to investigate the performance in concrete of aggregate from recycling discarded concrete test cylinders.

This research is a work element of the project dealing with Processing of Materials for Resource and Energy Conservation. The project is part of the Processing Activity of CANMET's Minerals Research Program.

SCOPE

Twelve 2.2-ft^3 (0.062-m^3) concrete mixes were made covering the low, medium and high strength levels. Two sets of mixes were made at each level. One set consisted of a control mix and one using coarse aggregate prepared from recycled concrete and natural sand; the other set consisted of a control mix and one using fine aggregate prepared from recycled concrete and crushed limestone as the coarse aggregate. Both coarse and fine aggregates were obtained by recycling 6 x 12-in. (152 x 305-mm) cylinders which had been discarded after control testing. These cylinders had originally been made from concrete containing crushed limestone and natural sand as coarse and fine aggregates. Six 6 x 12-in. (152 x 305-mm) cylinders and six 3.5 x 4 x 16-in. (89 x 102 x 406-mm) prisms were cast from each mix for determining mechanical properties at various ages and for studying durability after exposure to freeze-thaw cycling.

RECYCLING OF DISCARDED CONCRETE CYLINDERS

The concrete cylinders for recycling were obtained from an earlier laboratory investigation in which crushed limestone and natural sand were used as coarse and fine aggregates respectively. Three different strength levles, i.e., low, medium and high, had been studied in the above investigation. It was ensured that the test cylinders for each strength level were processed in separate lots and the resulting aggregates stored in separate bins. The cylinders from all three lots weighed approximately 3.5 tons.

The cylinders were processed in an identical manner as follows:

> All cylinders were subjected to one pass through a 7 x 10-in. (178 x 254-mm) jaw crusher set at 2 in. (51 mm). The resulting material was screened on 1/2-in. and 3/8-in. (12.7-mm and 9.5-mm) screens.
>
> The plus 1/2-in. (12.7-mm) material was then subjected to one pass through a 7 x 10-in. (178 x 254-mm) jaw crusher set at 3/4 in. (19-mm). It was then screened through a nest of sieves from 3/4 in. (19 mm) down to 100 mesh (150 μm).

The minus 4-plus 8-mesh (minus 4.75 plus 2.36-mm) fraction was subjected to two passes through a 2 x 6-in. (51 x 152-mm) jaw crusher set at approximately 1/16 in. (1.6 mm). The resulting material was then screened through a nest of sieves from minus 8 mesh down to 100 mesh (minus 2.36 mm to 150 μm).

The actual screen fractions together with the percentage losses are given in Table 2.

Figures 1 and 2 compare aggregates prepared from recycled concrete with those from crushed limestone and natural sand.

The scanning electron photomicrographs (SEM) of the aggregate prepared from recycled concrete and that of reference crushed limestone and natural sand are shown in Fig. 3 and 4.

CONCRETE MIXES

A total of 12 concrete mixes was made in the Mines Branch (now CANMET) laboratory between May 1972 and June 1973 using a 2.5-ft^3 (0.071-m^3) laboratory counter-current mixer. The materials used are described below:

Cement

Normal portland cement, ASTM Type I, (CSA Type 10) was used for the mixes. The physical properties and chemical analysis of the cement are given in Table 3.

Crushed Limestone

Minus 1-in. plus No. 4 (minus 25.0-mm plus 4.75-mm) crushed limestone was the reference coarse aggregate in all control mixes and also in those mixes where fine aggregate was obtained from recycled concrete.

Natural Sand

Natural Ottawa Valley sand was the reference fine aggregate both in the control mixes and in those in which recycled concrete was the coarse aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions and then combined to give a specific grading.

Coarse Aggregate Prepared from Recycled Concrete

The minus 1-in. plus No. 4 (minus 25.0-mm plus 4.75-mm) fraction of the recycled concrete was used as coarse aggregate in three of the mixes investigated.

Fine Aggregate Prepared from Recycled Concrete

The minus No. 4 plus No. 100 (minus 4.74-mm, plus 150 μm) fraction of the recycled concrete was used as fine aggregate in three of the mixes. In these mixes, the minus No. 100 (minus 150-μ) fraction was replaced by the similar fraction from natural sand. As with the natural sand, to keep the grading uniform for each mix, the different sized fractions were combined to give a specific grading.

Grading of Aggregates

The grading of both natural aggregates and those prepared from recycled concrete are shown in Table 4. The specific gravity and absorption of the two types are given in Table 5.

Mix Proportioning

Mix proportioning data for the concrete mixes are given in Table 6. The aggregates were room dry and the mixing water was adjusted to take absorption into account.

An air-entraining agent was used in all mixes.

As mentioned earlier three separate lots of aggregates were prepared by recycling concrete cylinders according to the strength level of the discarded cylinders. While making concrete mixes employing aggregates prepared from recycled concrete, it was ensured that for high strength concrete mixes only that aggregate, be it coarse or fine, was used which had been prepared from the discarded cylinders corresponding to that strength level.

Properties of Fresh Concrete

The properties of the fresh concrete-temperature, slump, unit weight and air content-are given in Table 6.

PREPARATION AND CASTING OF TEST SPECIMENS

Six 6 x 12-in. (152 x 305-mm) cylinders and six 3.5 x 4 x 16-in. (89 x 102 x 406-mm) prisms were cast from each mix. The cylinders were cast by filling steel moulds in approximately two equal layers, each compacted by an internal vibrator. The prisms were cast by filling brass moulds in approximately two equal layers, each compacted by placing the moulds on a vibrating table for 30 seconds. After casting, all the moulded specimens were covered with water-saturated burlap, left in the casting room at 75 ± 3°F (25 ± 1.7°C) and 50% relative humidity for 24 hours. They were finally demoulded and transferred to the moist-curing room until required for testing.

TESTING OF SPECIMENS

At 7, 28 and 91 days, two of the cylinders from each concrete mix were removed from the moist-curing room, capped with a sulphur and flint mixture and tested in compression on an Amsler testing machine. Also at 14 days, two prisms were tested in flexure according to ASTM Standard C78-75 using a third-point loading.

DURABILITY STUDIES

Although durability cannot be measured directly, prolonged exposure of concrete to repeated freezing and thawing produces measurable changes in test specimens which may indicate deterioration. Measurements made on the test specimens after freeze-thaw cycling provide data that can be used to evaluate the relative frost resistance or durability.

In this investigation, test prisms were exposed to repeated cycles of freezing in air and thawing in water according to ASTM Standard C666-75. The automatic freeze-thaw unit* has the capacity to perform eight cycles per day. One complete cycle, from 40 ± 3°F to 0 ± 3°F (4.4 ± 1.7°C to -17.8 ± 1.7°C) and back to 40 ± 3°F (4.4 ± 1.7°C) requires about 3 hours.

At the end of the initial moist-curing period of 14 days, the temperature of each set of two prisms was reduced to a uniform 40 ± 3°F (4.4 ± 1.7°C) by placing in the freeze-thaw cabinet

*Manufactured by the Canadian Ice Machine Company Ltd., Toronto, Ontario at the thawing phase for one hour. The initial and all subsequent measurements of the freeze-thaw and the reference test specimens were made at this temperature. After initial measurements of the test prisms were taken, two test prisms were placed in the freeze-thaw cabinet and the two companion prisms placed in the moist-curing room for reference purposes.

The freeze-thaw test specimens were visually examined, weighed and tested by an ultrasonic pulse velocity* method at the intervals varying from 100 to 750 cycles. At the end of the test, the freeze-thaw and reference specimens were tested by ultrasonic velocity and broken for flexural strength. No resonant frequency measurements were possible due to malfunctioning of the equipment.

TEST RESULTS AND THEIR ANALYSES

Seventy-two cylinders and seventy-two prisms were tested in this investigation. The density of all specimens was taken at one day as shown in Table 7. A summary of the compressive and flexural strengths of cylinders and prisms and the changes in the pulse velocity of test prisms during freeze-thaw cycling and of reference prisms during storage in a moist-curing room are given in Tables 8 to 12. The standard deviation and coefficient of variation calculated for the test data are shown in Table 13 and 14.

The age versus compressive strength relationships are shown in Fig. 5 and 6; the flexural strength of prisms at 14

* Equipment used was "PUNDIT", manufactured by C.N.S. Instruments Ltd., 61-63 Holmes Road, London, England.

days is illustrated in the form of bar charts in Fig. 7. The relationships between water:cement ratio and compressive and flexural strengths expressed as a percentage of the control strength are shown in Figs. 7 to 10.

DISCUSSION OF TEST RESULTS

Recycling of Discarded Test Cylinders

The crushing of discarded test cylinders, or for that matter of any discarded concrete, should be considered in the same way as crushing of ordinary rock. The energy required per ton of aggregate is believed to be the same order of magnitude for both types of material. To avoid contamination of aggregate prepared from discarded test cylinders, sulphur caps must be removed, if these have been used in the capping of cylinders prior to testing. Extra cost in the removal of these caps is offset by the sulphur recovered.

A SEM micrograph of a minus 3/8 in. plus No. 4 (minus 9.5-mm plus 4.75-mm) particle of coarse aggregate prepared from recycled concrete, together with the qualitative X-ray fluorescence analysis (Fig. 12), shows that very little, if any, contamination occurred during the recycling process. The existence of cement paste coating on the aggregate particles is confirmed.

If concrete from discarded pavements and buildings is to be recycled, caution should be exercised to ensure that this is free of coating material, plaster, etc.

High Absorption and Low Specific Gravity of Aggregates Prepared from Recycled Concrete

The absorption of both coarse and fine aggregates prepared from recycled concrete was higher than the reference aggregates; however the reserve was true for specific gravity. Similar results have been documented elsewhere (2). A comparison of the photomicrographs of the crushed reference limestone and of the coarse aggregates prepared from the recycled concrete (Fig. 3) shows that a number of cracks are present in the cement paste. The width of the cracks is of the order of 2 to 4 microns and the presence of these cracks in the hydrated cement paste may explain the high absorption of the aggregates prepared from the recycled concrete.

Particle Shape and Surface Texture of Aggregates Prepared from Recycled Concrete

The photomicrographs (Fig. 1 and 2) of the reference coarse and fine aggregates and the aggregates prepared from the recycled concrete show that the particle shape of the latter are more rounded. No tests were available to compare surface texture of the two types of aggregates; however visual examination indicated that aggregates prepared from the recycled concrete had a smoother surface texture.

Mix Proportions and Workability of Concrete Mixes

In appearance, the concrete mixes made with aggregate prepared from the recycled concrete were identical to those prepared from the reference aggregate. No unusual harshness or lack of workability was noticed in the former mixes. One exploratory mix series, which has not been included in this report, contained both coarse and fine aggregate prepared from the recycled concrete. The water requirement for the mixes in this series increased sharply compared with that for the control mixes. This was particularly true when minus 100 mesh (minus 150 μm) material from the recycled concrete was included in the aggregate grading. Even when the minus 100 mesh (minus 150 μm) fraction was replaced by the corresponding fraction from natural sand, the water requirement of the mixes was generally higher than that of the control mixes.

The minus 100 mesh (minus 150 μm) fraction of the fine aggregate prepared from the recycled concrete consisted principally of hydrated cement particles. It was possible to cast 2-in. (51-mm) cubes using this material with water added. However, when demoulded after one day's normal moist-curing, the cubes disintegrated, indicating extremely low strength.

For the purposes of entraining air, dosage of the air-entraining agent required for concrete mixes made with coarse aggregate from the recycled concrete was identical to that required for the control mixes. However, when the concrete mixes were prepared with crushed limestone and fine aggregate from recycled concrete, dosage for the air entraining agent was more than twice that required for the control mixes.

Strength Characteristics

Concrete with Coarse Aggregate Prepared from Recycled Concrete

The age versus strength relationships (Fig. 5) for concrete made with the reference aggregate and for concrete made with the coarse aggregate prepared from the recycled concrete show that both compressive and flexural strengths are slightly lower for the latter than for the former. The difference in strength decreases with decreasing water:cement ratio and this generally holds true for all ages. For example, for a water:cement ratio of 0.56, the difference in the 28-day compressive strength of the two types is 285 psi (2.0 MPa); the corresponding value with a water:cement of 0.41 is 30 psi (0.21 MPa).

Concrete with Fine Aggregate Prepared from Recycled Concrete

The age versus strength relationships (Fig. 6) for concrete using the reference aggregate, and for concrete using fine aggregate prepared from the recycled concrete, once again show lower compressive and flexural strengths for the latter. Furthermore, the difference in the strength increases with decreasing water:cement ratio and this is true at all ages. For example, for a water:cement ratio of 0.67, the difference in the 28-day compressive strength of the two types is 460 psi (3.2 MPa); the corresponding value with a water:cement ratio of 0.41 is 655 psi (4.5 MPa).

Durability of Concrete Prisms Made With Reference Aggregates and Aggregates Prepared From Recycled Concrete

Durability was measured by comparing the flexural strength and pulse velocity of the test prisms after exposure to the freeze-thaw cycling with flexural strength and pulse velocity of the reference prisms at ages corresponding to the completion of freeze-thaw cycling (Tables 9 to 12).

In general, durability of the prisms from the two types of concretes was comparable. The residual flexural strength was of the same of magnitude in each case (Table 9); this was equally true of the pulse velocities. However, there some indications that the durability of concrete using crushed limestone as coarse aggregate and fine aggregate prepared from recycled concrete may be inferior to that made with coarse aggregate prepared from recycled concrete with natural sand as the fine aggregate. Further research is needed in this area.

CONCLUSIONS

1. Satisfactory concrete can be made with aggregate prepared from recycled concrete. At a higher water:cement ratio, the compressive and flexural strength of concretes made with aggregate prepared from recycled concrete are somewhat lower than the strengths of concrete made with the reference aggregate. However, mix proportions can be adjusted ot overcome this disadvantage.
2. When fine aggregate prepared from recycled concrete is used in concrete mixes, it is necessary to replace the minus 100 mesh (minus 150 μm) fraction with the corresponding fraction from natural sand to keep the water demand to a minimum.
3. The durability of concrete made with aggregates prepared from recycled concrete is comparable with that made with reference aggregate.

4. The dosage of agent required to entrain a given amount of air in concrete was identical for concretes made with the reference as well as those made with coarse aggregate prepared from recycled concrete. However, for concretes containing fine aggreages prepared from recycled concrete, the dosage required to entrain a given amount of air was double that required for the control mixes.

REFERENCES

1. Buck, A. D. Recycled Concrete, U.S. Army Engineer Waterways Experiment Station, Vicksberg, Mississippi. Miscellaneous Paper C-72-14, 19 pp. May 1972.
2. Towards the Year 2000 - A Study of Mineral Aggregates in Central Ontario. Prepared by Proctor and Redfern Limited, Toronto for the Ontario Ministry of Natural Resources, 1974. (Available from Ministry of Natural Resources, Toronto, Ontario.)

TABLE 1

Relationship Between Supply and Demand

for Mineral Aggregates in Central Ontario

(Billions of Short Tons)

	Current potential available reserves	1972 demand	2001 demand	2001 projected accumulated demand
Sand & gravel	1.9	0.033	0.102	2.0
Crushed stone	1.1	0.014	0.041	0.8
Total	3.0	0.047	0.143	2.8

TABLE 2

Amount and Percentage of Coarse and Fine Fractions
After Recycling Concrete Cylinders*

	Fraction Size	Low			Medium			High		
		lb	kg	%	lb	kg	%	lb	kg	%
Coarse fraction	+3/4 in. (19.0 mm)	40	18	3.7	158	63	.....	216	98	11.9
	-3/4 in. to +1/2 in. (-19.0 mm to + 12.5 mm)	412	187	37.7	405	184		478	217	26.5
	-1/2 in. to +3/8 in. (-12.5 mm to + 9.5 mm)	305	138	27.9	443	201		530	241	29.4
	-3/8 in. to +No.4 (-9.5 mm to + 4.75 mm)	335	152	30.7	472	214		580	263	32.2
		1092	495	100.0	1478	662	100.0	1804	819	100.0
Fine fraction	-No.4 to + No.8 (-4.75 mm to + 2.36 mm)	59	27	10.9	82	37	10.8	110	50	11.4
	-No.8 to + No.14 (-2.36 mm to + 1.40 mm)	141	64	26.2	220	100	29.0	287	130	29.8
	-No.14 to + No.30 (-1.40 mm to + 600μm)	125	57	23.2	204	93	26.9	245	111	25.4
	-No.30 to + No.50 (600μm to + 300μm)	100	45	18.5	109	49	14.4	120	54	12.5
	-No.50 to + No.100 (-300μm + 150μm)	43	19	8.1	66	30	8.7	85	39	8.8
	-No.100 (-150μm)	71	32	13.1	77	35	10.2	116	53	12.1
		539	244	100.0	758	344	100.0	963	437	100.0
Approximate Loss		2.6%			2.9%			1.6%		

* From MPD Report 73 - 27 (Project M1L 385)

TABLE 3

Physical Properties and Chemical Analysis of the Cement*

Description of Test	
Physical Tests General	
Time of set (Vicat Needle): Initial	1 hr 15 min
Final	4 hr 50 min
Fineness: No. 200 (passing)	97.9 %
Soundness - Autoclave	0.2 %
Physical Tests - Mortar Strength	
Compressive strength of 2-in. (51-mm) cubes	
at 3-day	2340 psi (16.1 MPa)
at 7-day	3850 psi (26.5 MPa)
at 28-day	5370 psi (37.0 MPa)
Chemical Analysis	
Insoluble residue	0.12 %
Silicon dioxide (SiO_2)	21.1 %
Aluminum oxide (Al_2O_3)	5.8 %
Ferric oxide (Fe_2O_3)	2.6 %
Calcium oxide (CaO) Total	64.1 %
Magnesium oxide (MgO)	2.9 %
Sulphur trioxide (SO_3)	2.2 %
Loss on ignition	0.34 %
Others	0.84 %

*Test results and chemical analysis supplied by the cement manufacturing company.

TABLE 4

Grading of Aggregates

Coarse Aggregate		Fine Aggregate	
Sieve Size	Cumulative Percentage Retained	Sieve Size	Cumulative Percentage Retained
3/4 in. (19 mm)	33.4	4 mesh (4.75 mm)	0.0
3/8 in. (9.5 mm)	66.6	8 mesh (2.36 mm)	10.0
4 mesh (4.75 mm)	100.0	16 mesh (1.18 mm)	32.5
		30 mesh (1.40 mm)	57.5
		50 mesh (300 μm)	80.0
		100 mesh (150 μm)	94.0
		Pan	100.0

TABLE 5

Physical Properties of Coarse and Fine Aggregates

	Aggregate Prepared from Recycled Concrete						Crushed Limestone	Natural Sand
	Coarse			Fine				
	High Strength	Medium Strength	Low Strength	High Strength	Medium Strength	Low Strength		
Specific gravity (SSD Basis)	2.53	2.53	2.50	-	2.31	2.34	2.68	2.70
Absorption, %	4.0	3.9	4.4	7.9	9.3	8.6	0.40	0.50

TABLE 6

Mix Proportions and Properties of Fresh Concrete

Mix Series	Mix No.	Type of Mix	Mix Proportions: Water:Cement (Ratio by Weight)	Mix Proportions: Aggregate:Cement (Ratio by Weight)	Properties of Fresh Concrete: Temperature °F	Temperature °C	Slump in.	Slump mm	Unit Weight lb/ft^3	Unit Weight kg/m^3	Air Content %
A	1	Control	0.69	7.77	76	24.4	2.0	50	138.0	2210	6.2
	2	C.A. prepared from recycled concrete and reference F.A.	0.69	7.92	76	24.4	2.5	60	132.0	2115	6.9
Low	3	Control	0.67	7.80	77	25.0	1.75	40	142.0	2275	5.3
Strength	4	Reference C.A. and F.A. prepared from recycled concrete	0.67	8.10	77	25.0	2.0	50	140.0	2240	3.5
B	5	Control	0.56	6.50	71	21.7	2.5	60	140.0	2240	6.1
	6	C.A. prepared from recycled concrete and reference F.A.	0.56	6.63	72	22.2	2.5	60	134.8	2160	6.3
Medium	7	Control	0.57	6.51	74	23.3	2.5	60	141.6	2270	5.9
Strength	8	Reference C.A. and F.A. prepared from recycled concrete	0.57	6.76	76	24.4	2.5	60	135.2	2165	6.0
C	9	Control	0.41	4.45	72	22.2	2.75	70	148.0	2371	4.2
	10	C.A. prepared from recycled concrete and reference F.A.	0.41	4.54	71	21.7	3.0	75	140.4	2250	4.5
High	11	Control	0.41	4.45	76	24.4	2.0	50	148.0	2370	4.9
Strength	12	Reference C.A. and F.A. prepared from recycled concrete	0.41	4.57	72	24.4	2.5	63.5	138.8	2223	4.8

TABLE 7

Density of Concrete Cylinders and Prisms at One Day

Mix Series	Mix No.	Type of Mix	Water:Cement (Ratio by Weight)	Density (Average of six test results) 6x12-in. (152x305-mm) Cylinders		3.5x4x16-in. (87x102x408-mm) Prisms	
				lb/ft^3	kg/m^3	lb/ft^3	kg/m^3
A	1	Control	0.69	141.7	2270	140.5	2250
	2	C.A. prepared from recycled concrete and reference F.A.	0.69	143.3	2296	142.9	2290
	3	Control	0.67	145.8	2335	143.1	2290
	4	Reference C.A. and F.A. prepared from recycled concrete	0.67	141.4	2265	140.0	2245
B	5	Control	0.56	141.6	2270	140.5	2250
	6	C.A. prepared from recycled concrete and reference F.A.	0.56	137.0	2195	135.5	2170
	7	Control	0.57	142.7	2285	141.9	2275
	8	Reference C.A. and F.A. prepared from recycled concrete	0.57	137.1	2195	136.4	2185
C	9	Control	0.41	148.8	2385	147.5	2365
	10	C.A. prepared from recycled concrete and reference F.A.	0.41	142.5	2280	140.9	2255
	11	Control	0.41	149.2	2390	147.9	2370
	12	Reference C.A. and F.A. prepared from recycled concrete	0.41	140.8	2250	140.1	2245

TABLE 8

Summary of Compressive Strength Test Results at Various Ages

Mix Series	Mix No.	Type of Mix	Water:Cement (Ratio by weight)	Compressive Strength of 6x12-in. (152x305-mm) Cylinders					
				7-Day		28-Day		91-Day	
				psi	MPa	psi	MPa	psi	MPa
A	1	Control	0.69	2035	14.0	2555	17.6	2600	17.9
	2	C.A. prepared from recycled concrete and reference F.A.	0.69	1310	9.0	1986	13.6	2030	13.9
	3	Control	0.67	2360	16.2	2840	19.5	3265	22.4
	4	Reference C.A. and F.A. prepared from recycled concrete	0.67	1855	12.7	2380	16.3	2605	17.9
B	5	Control	0.56	2585	17.6	3190	21.9	3340	22.9
	6	C.A. prepared from recycled concrete and reference F.A.	0.56	2330	16.0	2905	20.0	3015	20.7
	7	Control	0.57	-	-	2950	20.3	3255	22.4
	8	Reference C.A. and F.A. prepared from recycled concrete	0.57	-	-	2470	17.0	2595	17.8
C	9	Control	0.41	4525	31.1	4730	32.5	5160	35.4
	10	C.A. prepared from recycled concrete and reference F.A.	0.41	4140	28.4	4700	32.3	5440	37.4
	11	Control	0.41	4635	31.8	5270	36.2	5920	40.7
	12	Reference C.A. and F.A. prepared from recycled concrete	0.41	3780	26.0	4615	31.7	4905	33.7

TABLE 9

Summary of Flexural Strength Test Results

Series No.	Mix No.	Type of Mix	Water:Cement (Ratio by Weight)	Flexural Strength *								
				Moist-Cured Prisms				Prisms alter Exposure to Freeze-Thaw Cycling				Residual Strength, per cent
				After 14 days		At age Corresponding to the end of Freeze -thaw Cycling		No. of Freeze-thaw Cycles	Age at end of Freeze-thaw cycling, days	Strength		
				psi	MPa	psi	MPa			psi	MPa	
A	1	Control	0.69	645	4.4	745	5.1	760	100	675	4.6	90.6
	2	C.A. prepared from recycled concrete and reference R.A.	0.69	540	3.7	595	4.1	760	100	545	3.8	91.6
	3	Control	0.67	715	4.9	780	5.4	684	93	725	4.9	92.9
	4	Reference C.A., and F.A. prepared from recycled concrete	0.67	655	4.5	760	5.2	684	93	655	4.6	86.2
B	5	Control	0.56	840	5.8	825	5.7	603	82	770	5.3	93.3
	6	C.A. prepared from recycled concrete and reference F.A.	0.56	675	4.7	670	4.6	603	82	745	5.1	111.2
	7	Control	0.57	730	5.0	800	5.5	603	82	760	5.2	95.0
	8	Reference C.A., and F.A. prepared from recycled concrete	0.57	620	4.3	680	4.7	603	82	670	4.7	98.5
C	9	Control	0.41	940	6.5	1095	7.5	750	96	1040	7.2	95.0
	10	C.A. prepared from recycled concrete and reference F.A.	0.41	970	6.7	1000	6.9	750	96	970	6.7	97.0
	11	Control	0.41	995	6.9	1200	8.3	750	100	1105	7.7	92.1
	12	Reference C.A., and F.A. prepared from recycled concrete	0.41	800	5.5	1050	7.2	750	93	860	5.9	81.9

*Each result is a mean of tests on two prisms, with testing being done at third point loading.

TABLE 10

Changes in Pulse Velocity of Test Prisms During Freeze-Thaw Cycling - Series A

Mix Series	Mix No.	Type of Mix	Water: Cement (Ratio by Weight)	Pulse Velocity of Test Prisms after Exposure to Freeze-Thaw Cyclings*														Pulse Velocity of Reference Prisms at age Corresponding to end of Freeze-thaw Test		Per Cent Change
				V_0^{+}		V_{130}^{++}		V_{154}		V_{344}		V_{429}		V_{684}^{**}		V_{757}^{**}				
				ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	
A	1	Control	0.69	14,524	4,427	-	-	14,245	4,341	14,461	4,408	-	-	-	-	14,430	4,398	14,856	4,528	+3.0
	2	C.A. prepared from recycled concrete and reference F.A.	0.69	12,989	3,959	-	-	12,784	3,897	13,040	3,975	-	-	-	-	13,085	3,988	13,495	4,113	+3.1
	3	Control	0.67	14,733	4,490	14,692	4,478	-	-	-	-	14,749	4,495	14,744	4,503	-	-	15,142	4,613	+2.7
	4	Reference C.A. and F.A. prepared from recycled concrete	0.67	14,042	4,280	13,831	4,216	-	-	-	-	13,903	4,238	13,940	4,249	-	-	14,005	4,269	+0.7

* Each result is a mean of tests on two prisms; + V_0 means pulse velocity at zero freeze-thaw cycling,
** End of freeze-thaw test ++V_{130} means pulse velocity at end of 130 freeze-thaw cycles and so on.

TABLE 11

Changes in Pulse Velocity of Test Prisms During Freeze-Thaw Cycling - Series B

Mix Series	Mix No.	Type of Mix	Water:Cement (Ratio by Weight)	Pulse Velocity of Test Prisms After Exposure to Freeze-Thaw Cycling*								Pulse Velocity of Reference Prisms at age Corresponding to end of Freeze-thaw Cycling		Per Cent Change
				V_o^{+}		V_{126}^{++}		V_{414}		V_{595} **				
				ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	
B	5	Control	0.56	14,540	4,431	14,774	4,503	14,815	4,516	14,700	4,481	14,903	4,542	+1.4
	6	C.A. prepared from recycled concrete and reference F.A.	0.56	13,387	4,080	13,717	4,181	13,732	4,185	13,682	4,170	14,109	4,300	+3.1
	7	Control	0.57	15,100	4,602	14,998	4,571	14,898	4,541	14,782	4,506	15,225	4,640	+3.0
	8	Reference C.A., and F.A. prepared from recycled concrete	0.57	13,788	4,203	13,940	4,249	13,724	4,183	13,605	4,147	14,124	4,305	+3.8

* Each result is a mean of tests on two prisms; + V_o means pulse velocity at zero freeze-thaw cycling,
** End of freeze-thaw test ++ V_{126} means pulse velocity at end of 126 freeze-thaw cycles and so on.

TABLE 12

Changes in Pulse Velocity of Test Prisms During Freeze-Thaw Cycling - Series C

Mix Series	Mix No.	Type of Mix	Water:Cement (Ratio by Weight)	Pulse Velocity of Test Prisms After Exposure to Freeze-Thaw Cycling*										Pulse Velocity of Reference Prisms at age Corresponding to end of Freeze-thaw Cycling		Per Cent Change
				V_o +		V_{100} ++		V_{300}		V_{500}		V_{750} **				
				ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	ft/sec	m/sec	
C	9	Control	0.41	16,084	4,902	15,817	4,821	15,939	4,858	-	-	15,900	4,846	16,688	5,086	+5.0
	10	C.A. prepared from recycled concrete and reference F.A.	0.41	14,998	4,571	14,709	4,483	14,749	4,495	-	-	14,766	4,501	15,530	4,733	+5.2
	11	Control	0.41	15,949	4,861	15,817	4,821	-	-	15,789	4,812	15,943	4,859	16,633	5,070	+4.3
	12	Reference C.A. and F.A. prepared from recycled concrete	0.41	15,126	4,610	14,881	4,536	-	-	14,898	4,541	15,023	4,579	15,446	4,708	+2.8

* Each result is a mean of two test prisms; + V_o means pulse velocity at zero freeze-thaw cycling,
** End of freeze-thaw cycling ++ V_{100} means pulse velocity at end of 100 freeze-thaw cycles and so on.

TABLE 13

Within-Batch Standard Deviations and Coefficients of Variation for Compressive Strength Test Results at Various Ages

Series No.	Mix No.	7 Days					28 Days					91 Days				
		Compressive Strength+		S.D.*		C.V.**	Compressive Strength		S.D.		C.V.	Compressive Strength		S.D.		C.V.
		psi	MPa	psi	Mpa	%	psi	MPa	psi	MPa	%	psi	MPa	psi	MPa	%
A	1	2035	14.0	190	1.3	9.3	2555	17.6	58	0.4	2.2	2600	17.9	15	0.1	0.5
	2	1310	9.0	7	0.04	0.5	1985	13.6	88	0.6	0.4	2030	13.9	30	0.2	1.4
	3	2360	16.2	37	0.2	1.5	2840	19.5	30	0.2	1.0	3265	22.4	112	0.8	3.4
	4	1855	12.7	35	0.2	7.8	2380	16.3	25	0.2	1.0	2605	17.9	68	0.5	2.6
B	5	2585	17.6	40	0.3	1.5	3190	21.9	233	1.6	7.3	3340	22.9	75	0.5	2.2
	6	2330	16.0	25	0.2	1.0	2905	20.0	30	0.2	1.0	3015	20.7	23	0.15	0.7
	7	-	-	-	-	-	2950	20.3	37	0.3	1.2	3255	22.4	13	0.1	0.3
	8	-	-	-	-	-	2470	17.0	25	0.2	1.0	2595	17.8	145	0.9	5.5
C	9	4525	31.1	42.4	0.3	0.9	4730	32.5	685	4.7	14.4	5160	35.4	-	-	-
	10	4140	28.4	12.7	0.1	0.3	4700	32.3	53	0.4	1.7	5440	37.4	37	0.3	0.6
	11	4635	31.8	50.0	0.3	1.0	5270	36.2	12	0.1	0.2	5920	40.7	163	1.1	2.7
	12	3780	26.0	262	1.8	6.9	4615	31.7	140	0.9	3.0	4905	33.7	296	2.0	6.0

+ Each strength value is average of tests on two 6x12-in. (151x30S-mm) cylinders.
* Standard Deviation
** Coefficient of Variation.

TABLE 14

Within-Batch Standard Deviation and Coefficient of Variation for Flexural Strength Test Results at Various Ages

Series No.	Mix No.	14 Days					82 Days					96 ± 4 Days				
		Flexural+ Strength		S.D.*		C.V.**	Flexural+ Strength		S.D.		C.V.	Flexural+ Strength		S.D.		C.V.
		psi	MPa	psi	MPa	%	psi	MPa	psi	MPa	%	psi	MPa	psi	MPa	%
A	1	645	4.4	88	0.6	13.6	-	-	-	-	-	745	5.1	21	0.1	2.8
	2	540	3.7	2	0.01	0.4	-	-	-	-	-	595	4.1	11	0.1	1.7
	3	715	4.9	73	0.5	10.2	-	-	-	-	-	780	5.4	27	0.2	3.4
	4	655	4.5	12	0.1	1.8	-	-	-	-	-	760	5.2	45	0.3	5.9
B	5	840	5.8	69	0.5	8.2	825	5.7	45	0.3	5.5	-	-	-	-	-
	6	675	4.7	13	0.1	1.9	680	4.6	27	0.2	4.1	-	-	-	-	-
	7	730	5.0	6	0.04	0.8	800	5.5	52	0.4	6.4	-	-	-	-	-
	8	620	4.3	28	0.2	4.5	680	4.7	60	0.4	8.8	-	-	-	-	-
C	9	940	6.5	28	0.2	2.9	-	-	-	-	-	1095	7.5	56	0.4	5.1
	10	970	6.7	42	0.3	4.4	-	-	-	-	-	1000	6.9	91	0.6	9.1
	11	995	6.9	40	0.3	4.0	-	-	-	-	-	1200	8.3	21	0.1	1.8
	12	800	5.5	88	0.6	11.0	-	-	-	-	-	1050	7.2	74	0.5	7.1

* Standard Deviation
** Coefficient of Variation
\+ Each strength value is average of tests on two 3.5x4x16-in. (89x102x408-mm) prisms.

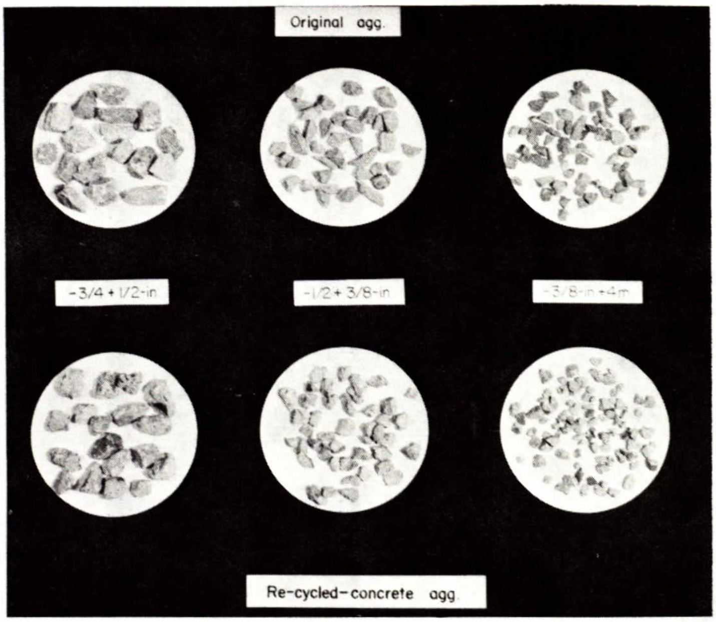


Figure 1 - A comparison of particle shape and surface texture of fractions of crushed limestone and coarse aggregates prepared from recycled concrete.

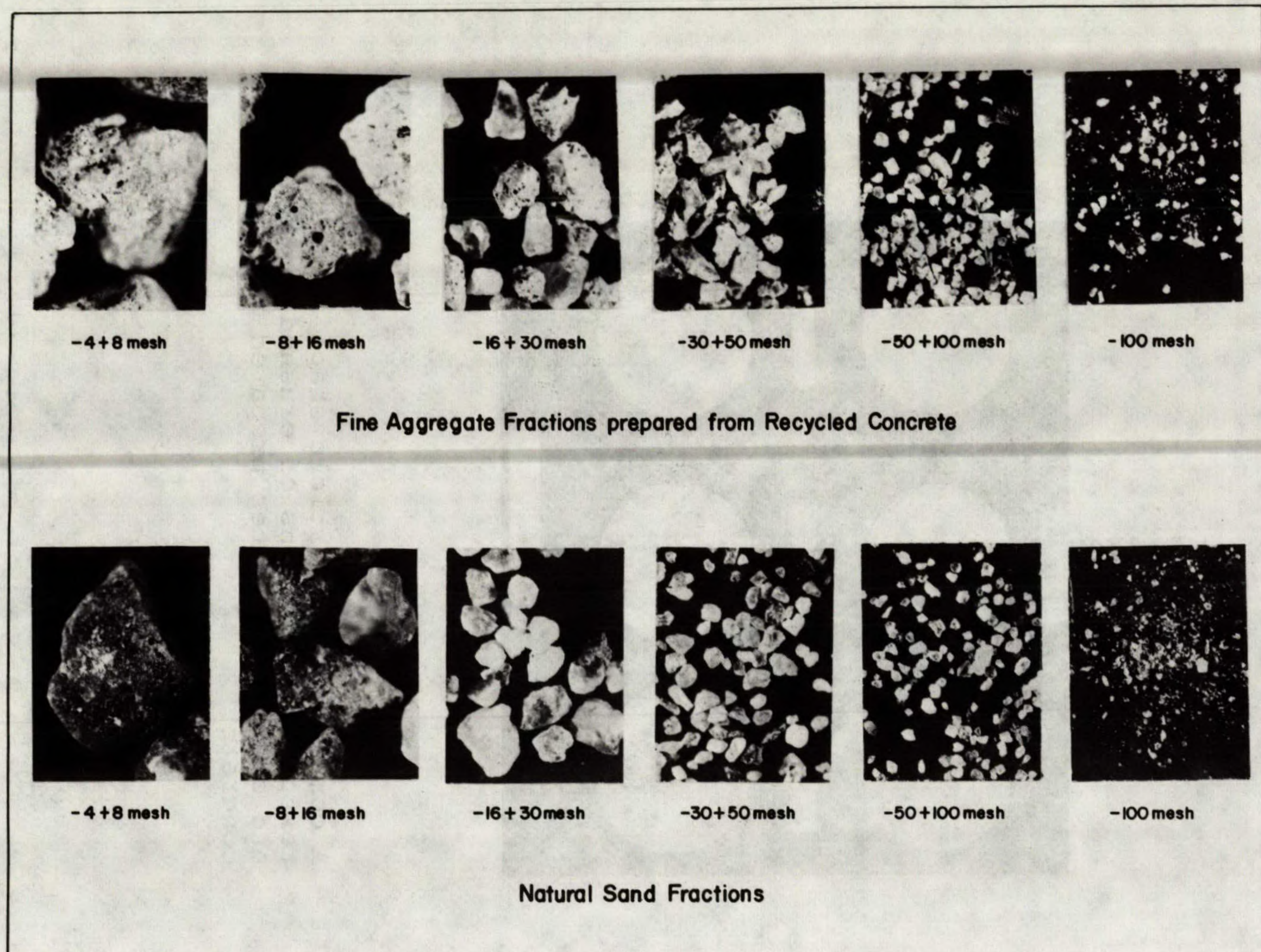
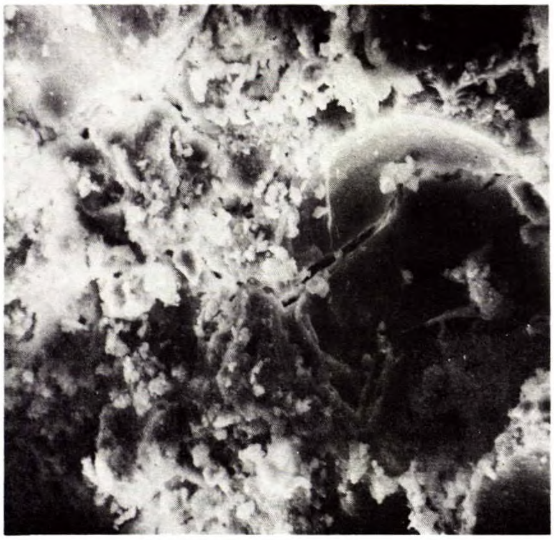


Figure 2 - Photomicrographs showing particle shape and surface texture of natural sand and fine aggregate fractions prepared from recycled concrete. Approximate magnification 13 x



Aggregate prepared from recycled concrete x625

Natural crushed limestone x625

Figure 3 - SEM photomicrographs of minus 3/4 in. plus 1/2 in. (minus 19.0 mm plus 12.7 mm) aggregate fraction.

Aggregate prepared from recycled concrete x625

Natural crushed limestone x625

Figure 4 - SEM photomicrographs of minus 1/2 in. plus 3/8 in. (minus 12.7 mm plus 9.5 mm) aggregate fraction.

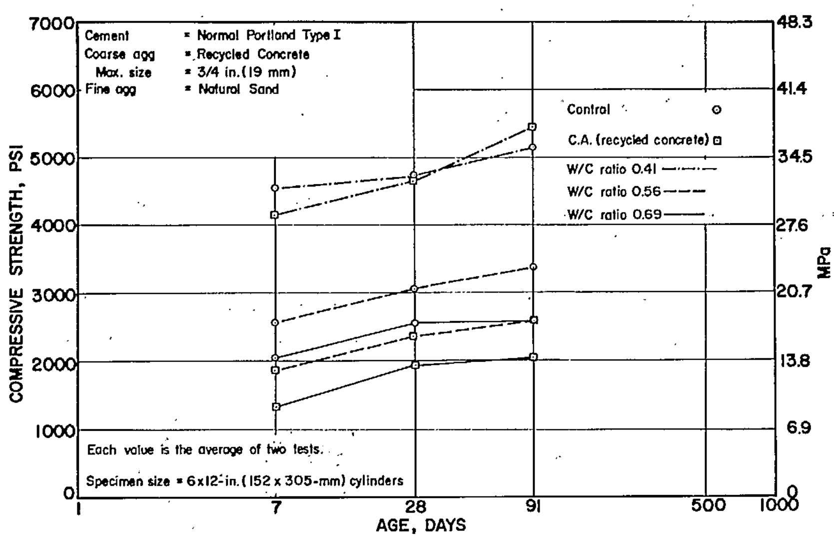


Figure 5 - Relationship between age versus compressive strength for the control mix and for concrete mix made with coarse aggregate prepared from recycled concrete.

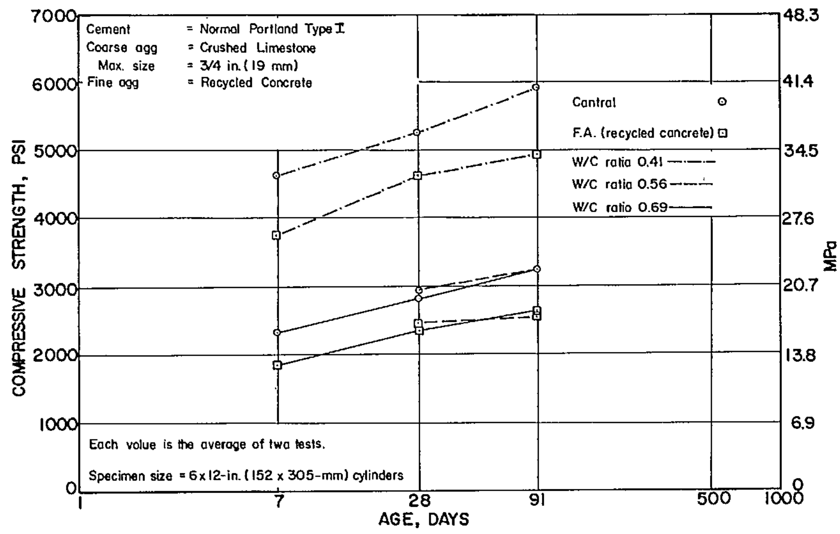


Figure 6 - Relationship between age versus compressive strength for the control mix and for concrete mix made with fine aggregate prepared from recycled concrete.

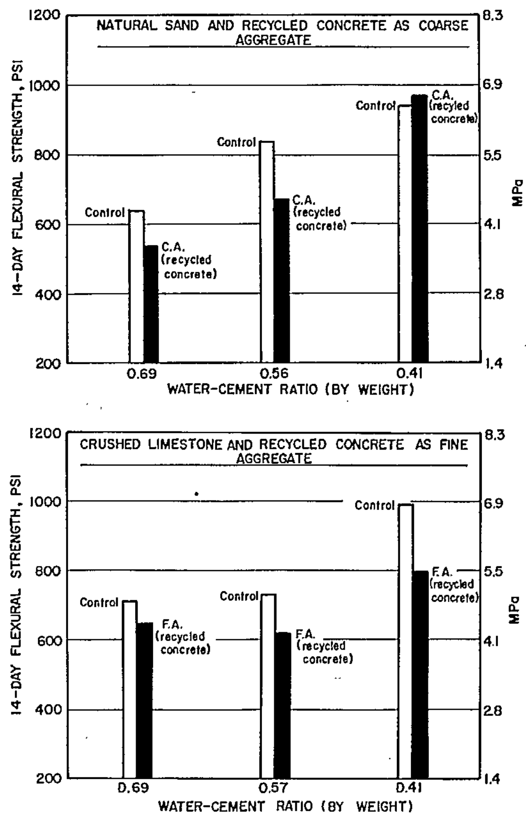


Figure 7 - Bar charts for 14-day flexural strength of prisms made from the control mix and for concretes made with aggregate prepared from recycled concrete.

(a) Control mix and mix with natural sand and recycled concrete as C.A.

(b) Control mix and mix with crushed limestone and recycled concrete as F.A.

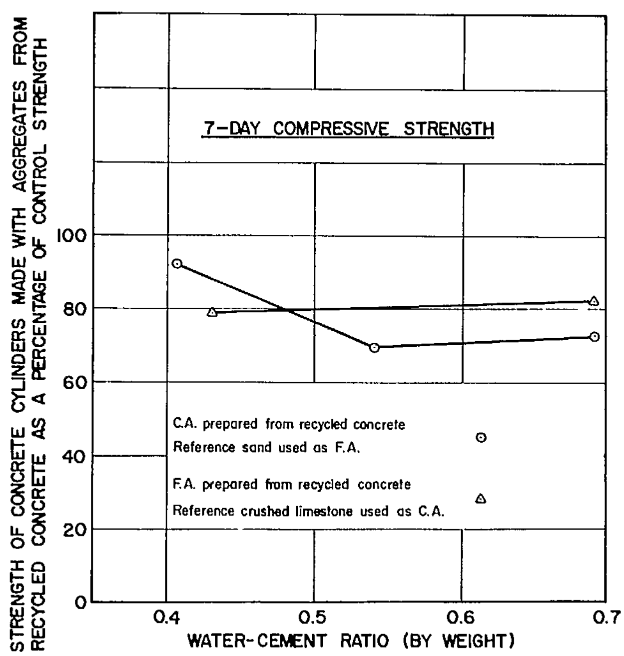


Figure 8 - Relationship between water-cement ratio and 7-day compressive strength of concrete made with aggregates prepared from recycled concrete as a percentage of control strength.

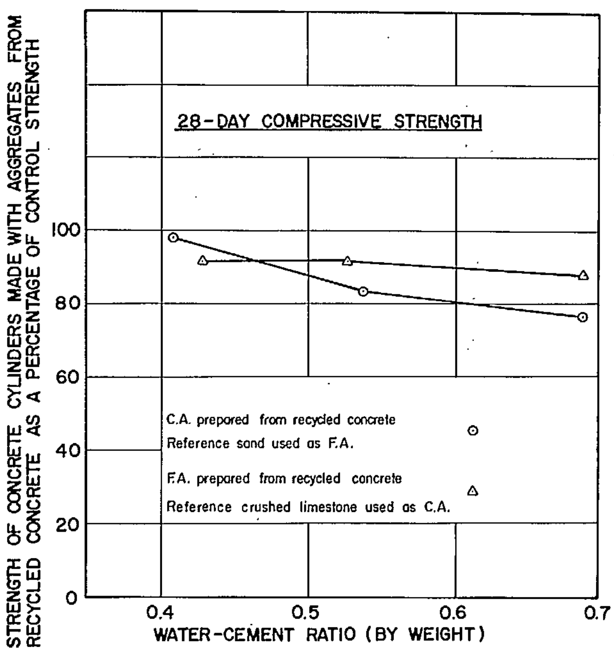


Figure 9 - Relationship between water-cement ratio and 28-day compressive strength of concrete made with aggregate prepared from recycled concrete as a percentage of control strength.

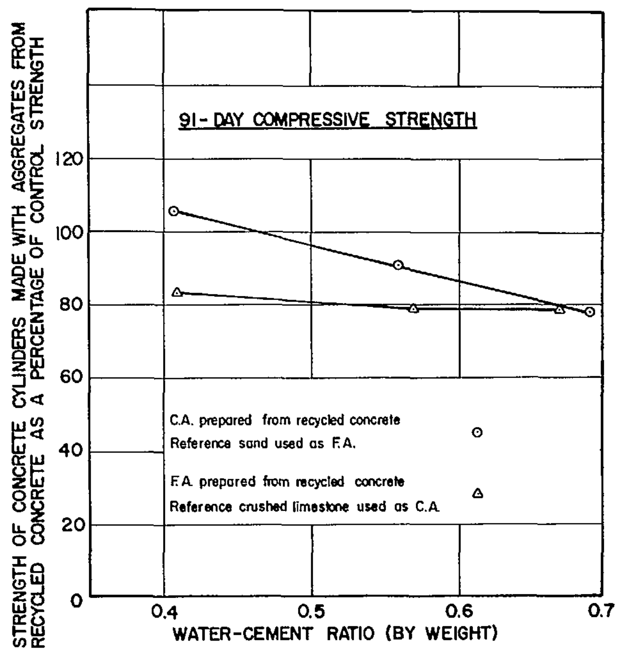


Figure 10 - Relationship between water-cement ratio and 91-day compressive strength of concrete made with aggregate prepared from recycled concrete as a percentage of control strength.

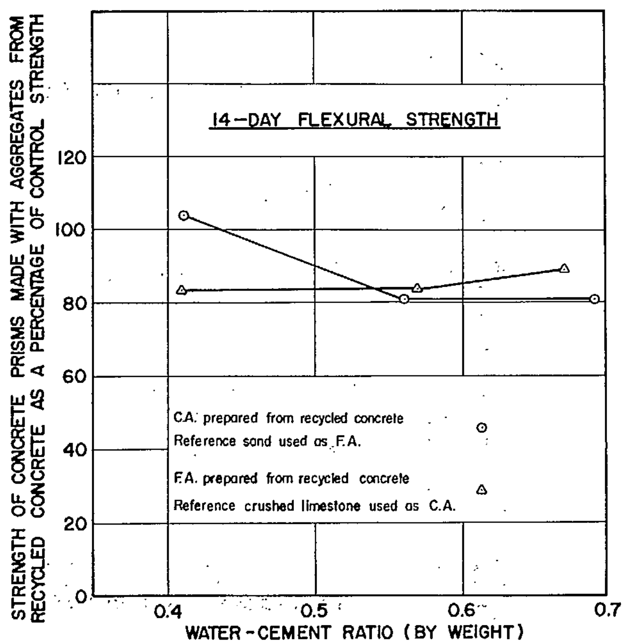


Figure 11 - Relationship between water-cement ratio and 14-day flexural strength of concrete made with aggregate prepared from recycled concrete as a percentage of control strength.

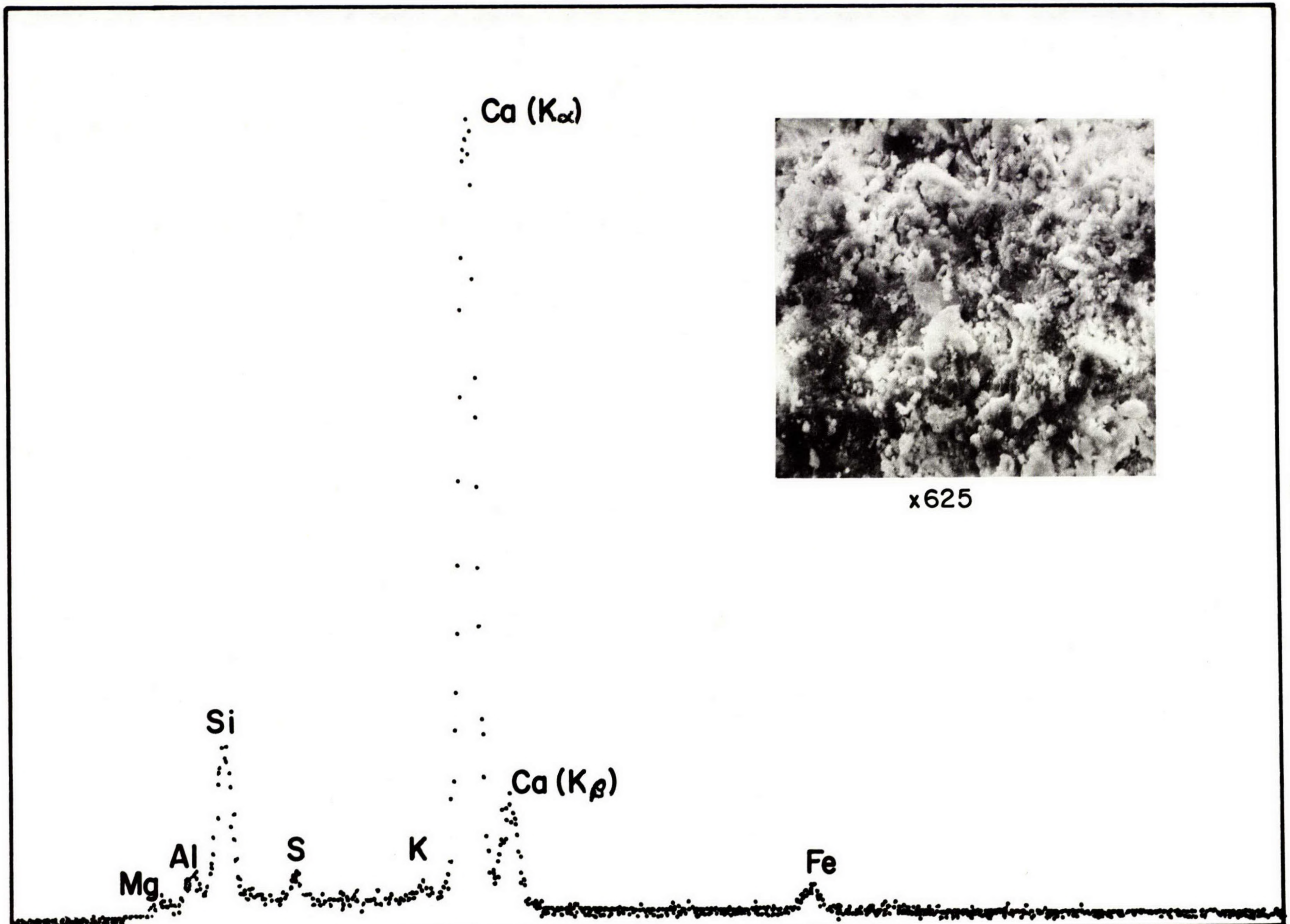


Figure 12 - SEM photomicrograph of a coarse aggregate particle prepared from recycled concrete, together with the qualitative X-ray fluorescence analysis.

CANMET PUBLICATIONS

Recent CANMET publications presently available or soon to be released through Printing and Publishing, Supply and Services, Canada (addresses on inside front cover), or from CANMET Publication Office, 555 Booth Street, Ottawa, Ontario K1A 0G1

CANMET Reports:

76-4 The Preparation of Mica Cylinders for the Measurement of Thermal Conductivity; by F. G. McDonald and V. V. Mirkovich;
Catalogue No. M38-13/76-4; Price: $0.50 Canada, $0.60 other countries.

76-5 Tungsten Ores Ct-1, BH-1, and TLG-1: Their Characterization and Preparation for Use as Certified Reference Materials; by G. H. Faye, W. S. Bowman and R. Sutarno;
Catalogue No. M38-13/76-5; Price: $1.00 Canada, $1.20 other countries.

76-6 On the Determination of the Lattice Type and Unit Cell Parameters of a Crystal Using Electron Diffraction; by K. S. Milliken;
Catalogue No. M38-13/76-6; Price: $0.50 Canada, $0.60 other countries.

76-7 Catalogue and Index of CANMET Scientific and Technical Papers Published in or Submitted to Periodicals and Presentations, 1967-1973; by Technology Information Division;
Catalogue No. M38-13/76-7; Price: $2.00 Canada, $2.40 other countries.

76-8 Comparison of Pull-Out Strength of Concrete with Compressive Strength of Cylinders and Cores, Pulse Velocity and Rebound Number; by V. M. Malhotra and G. Carette;
Catalogue No. M38-13/76-8; Price: $1.00 Canada, $1.20 other countries.

76-9 Catalysts for Hydrocracking and Refining Heavy Oils and Tars Part 3: The Effect of Presulphiding Conditions on Catalyst Performance; by M. Ternan and M. J. Whalley;
Catalogue No. M38-13/76-9; Price: $1.00 Canada, $1.20 other countries.

76-10 Recent Advances in Copper Electrowinning; by D. J. MacKinnon and V. I. Lakshman;
Catalogue No. M38-13/76-10; Price: $1.00 Canada, $1.20 other countries.

76-11 The Determination of Radium 226 in Uranium Ores and Mill Products by Alpha Energy Spectrometry; by J. B. Zimmerman and V. C. Armstrong;
Catalogue No. M38-13/76-11; Price: $1.00 Canada, $1.20 other countries.

76-12 Lightweight Aggregates for Structural Concrete; by H. S. Wilson;
Catalogue No. M38-13/76-12; Price: $3.75 Canada, $4.50 other countries.

76-13 Development of a Sirconia Electrolyte for Use in a Steel-Making Oxygen Probe; by T. A. Wheat;
Catalogue No. M38-13/76-13; Price: $5.00 Canada, $6.00 other countries.

76-15 Competing Reactions in Hydrotreating Coker Distillates from Athabasca Bitumen on Unpromoted and Promoted Catalysts; by R. Ranganathan, M. Ternan and B. I. Parsons;
Catalogue No. M38-13/76-15; Price: $0.50 Canada, $0.60 other countries.

76-16 A Digest of Environmental Regulations Pertinent to Open Pit Mining in Canada (Current at April 1975); by Dames and Moore, Toronto;
Catalogue No. M38-13/76-16; Price: $1.75 Canada, $2.10 other countries.