# Lean-Mix Rolled Concrete for Pavement Slabs

CHUZO ITAKURA, TERUO SUGAWARA, AND TERUTOSHI KAKU
*Respectively, Professor, Assistant Professor, and Assistant, Hokkaido University, Japan*

This paper discusses the feasibility of using lean-mix concrete in pavement slabs. The cement factor was varied from 2.7 to 5.4 with properly selected aggregate gradings and with the water content held between 17 and 22 gal per cu yd. Compaction was effected with a rammer and/or a flat-wheel roller.

In design of mix proportions of portland cement concrete, workability or finishability is the basic element for determining the amount of water needed in the unit volume of concrete. From the amount of water, the amount of cement is determined for the desired strength of concrete and the water-cement ratio to resist weathering. In ordinary cases, workability is determined by the mixing operation and, especially, the compaction procedures using mechanical vibrators. If the different mixing operation and compaction procedures suitable for a drier mix and fitted to the road construction are adopted, cement content will be decreased and several troubles caused with rich mixes will be eliminated.

• IN ESTABLISHING the mix proportions of portland cement concrete, workability or finishability is a basic factor, as it determines the amount of water needed in a unit volume of concrete. From this amount of water is determined the amount of cement necessary for attaining the desired strength of the concrete and the water-cement ratio to resist weathering. In ordinary cases, workability is determined by the mixing operation and, especially, compaction procedures using mechanical vibrators. If the different mixing operation and compaction procedures suitable for drier mix fitted to the road construction are adopted, cement content will be decreased and several troubles caused by rich mixes thus will be eliminated with economic benefit.

The present research has been based on these concepts and some ideas from the technology of portland cement macadam. The aim of the present research is to determine the minimum cement content in portland cement concrete slabs compacted with a rammer and/or a road roller, instead of a vibrator.

Experimental research was made on dense- and gap-graded coarse aggregate and coarse and fine aggregate ratios to give the minimum void content in coarse and fine aggregate mixture, and the effect on the flexural and compressive strength of the concrete. But in these researches made in the laboratory, an impactor and a rammer were used as compaction equipment instead of a road roller. The data on performance and test in the field were also investigated.

### MINIMUM VOID CONTENT OF COARSE AGGREGATE

River gravel and crushed stone were used to determine the grading for minimum void content, or maximum density, of coarse aggregates. A maximum coarse aggregate size of 3⅛ in. was selected to measure the density; a 2⅜-in. size was used to observe the strength of the concrete. The coarse aggregate of No. 4 to 3⅛-in. size was screened and separated into ten groups: 2⅜ to 3⅛, 2 to 2⅜, $1\frac{9}{16}$ to 2, $1\frac{3}{16}$ to $1\frac{9}{16}$, 1 to $1\frac{3}{16}$, $\frac{13}{16}$ to 1, ⅝ to $\frac{13}{16}$, ⅜ to ⅝, $\frac{9}{32}$ to ⅜ in., and No. 4 to $\frac{9}{32}$ in. Specific gravity, unit weight and void content of each fraction of both the gravel and the crushed stone are given in Table 1. These fractions of the coarse aggregate were combined artificially to produce various gradings. The weight and specific gravity tests were made in conformance with ASTM designation C29 and 127, respectively. The void content was calculated following ASTM designation C30. The minimum void contents were obtained for both cases of gravel (Fig. 1) and crushed stone (Fig. 2). The values on the grading curves give the void contents corresponding to the curves.

*River Gravel*

The minimum void content in dense grading was 29.5 percent; its grading curve is at the upper range of the standard grading curve proposed by the Japanese Society of Civil Engineers (JCSE). On the other hand, the minimum void content in gap grading was 24.2 percent for a mix composed of 60 percent $2\frac{3}{8}$- to $3\frac{1}{8}$-in. size and 40 percent No. 4 to $\frac{3}{16}$-in. size.

*Crushed Stone*

The minimum void content in dense grading was 35.8 percent and the grading curve passes through the middle of the range of the standard grading proposed by JSCE. On the other hand, the minimum void content was 29.8 percent for a mix composed of 60 percent $2\frac{3}{8}$- to $3\frac{1}{8}$-in. size and 40 percent No. 4 to $\frac{3}{16}$-in. size as in the case of the gravel.

As may be expected, the larger the

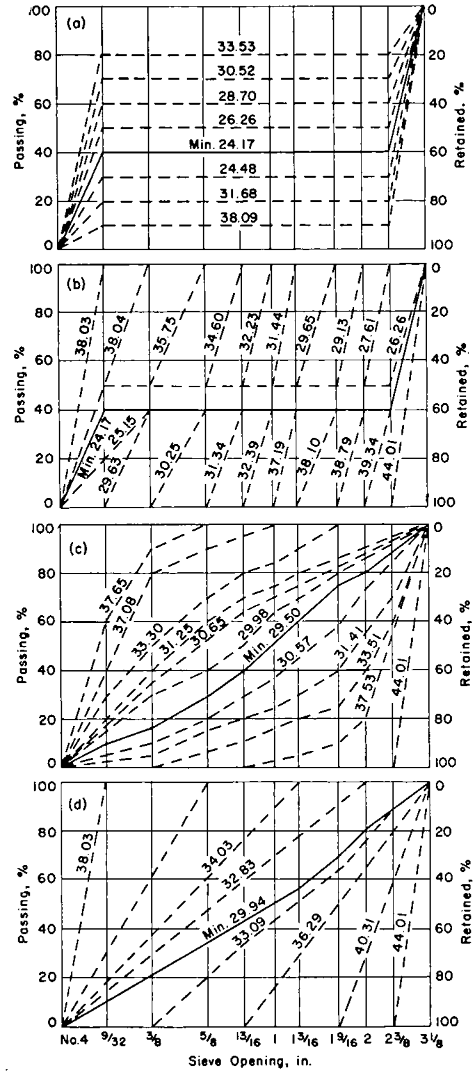


**Figure 1. Void percentage of gap-graded gravel (a and b) and dense-graded gravel (c and d).**

TABLE 1

SPECIFIC GRAVITY, DENSITY, AND VOID CONTENT OF GRAVEL AND CRUSHED STONE

| Particle Size (in.) | Gravel | | | Crushed Stone | | |
|---|---|---|---|---|---|---|
| | Sp. Gr. | Density (lb/cu ft) | Voids (%) | Gr. Sp. | Density (lb/cu ft) | Voids (%) |
| $> 2\frac{3}{8}$ | 2.67 | 93.3 | 44.01 | 2.65 | 89.2 | 46.08 |
| $2-2\frac{3}{8}$ | 2.66 | 97.8 | 41.39 | 2.59 | 84.1 | 47.99 |
| $1\frac{9}{16}-2$ | 2.66 | 99.0 | 40.38 | 2.60 | 86.6 | 46.62 |
| $1\frac{3}{16}-1\frac{9}{16}$ | 2.65 | 100.5 | 39.25 | 2.60 | 89.2 | 44.18 |
| $1-1\frac{3}{16}$ | 2.65 | 101.5 | 38.64 | 2.59 | 92.7 | 42.66 |
| $\frac{13}{16}-1$ | 2.64 | 102.3 | 37.92 | 2.62 | 92.2 | 43.59 |
| $\frac{5}{8}-\frac{13}{16}$ | 2.64 | 102.3 | 37.88 | 2.63 | 90.7 | 44.71 |
| $\frac{3}{8}-\frac{5}{8}$ | 2.63 | 101.6 | 38.06 | 2.61 | 87.4 | 46.36 |
| $\frac{9}{32}-\frac{3}{8}$ | 2.62 | 100.6 | 38.47 | 2.60 | 85.3 | 47.42 |
| No. $4-\frac{9}{32}$ | 2.59 | 100.2 | 38.03 | 2.51 | 70.0 | 48.93 |

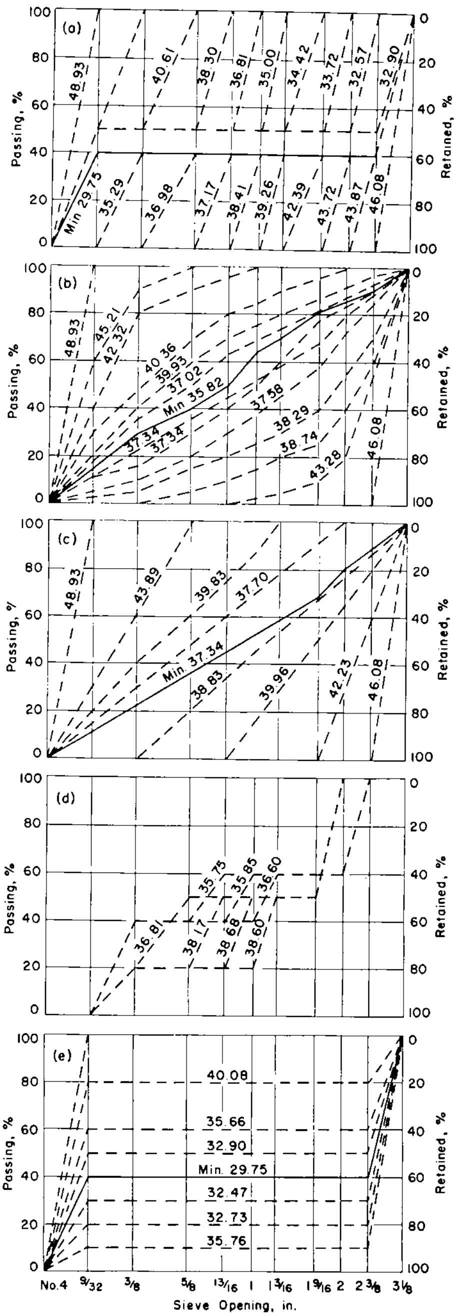


**Figure 2. Void percentage of gap-graded crushed stone (a, d and e) and dense-graded crushed stone (b and c).**

aggregate the smaller is the void content. But a similar relation between the void content and the composition of the fractions of dense- and gap-graded aggregates will also be brought about with smaller sizes of aggregates.

### MINIMUM VOID CONTENT OF COARSE AND FINE AGGREGATE MIXTURE

The coarse aggregates used were the dense-graded gravel and the gap-graded crushed stone giving the previously noted minimum void content. The fine aggregate used was a dense-graded beach sand. The properties of the sand are given in Table 2; its grading is shown in Figure 3. The coarse and fine aggregates were mixed in five different ratios (CA/FA)—namely, 2.0, 2.5, 3.0, 3.5, and 4.0—and the void content for each mix determined (Table 3). The minimum void content was 20.9 percent in the dense-graded gravel at CA/FA=2.5, and 12.7 percent in the gap-graded crushed stone at CA/FA=3.5. From experience with field tests at the job sites hereinafter mentioned, it was revealed that the conditions of field performance were fairly good with CA/FA=2.5 to 3.0. Therefore, the value of CA/FA=3.5 is not considered too large.

### STRENGTH OF CONCRETE COMPACTED WITH IMPACTOR

Based on the foregoing results, beam specimens were prepared and strength tests were made, at various values of CA/FA and cement content, using the dense-graded gravel and the gap-graded crushed stone and compaction with an impactor.

#### *Materials*

The cement used was Asano portland cement. The properties of the coarse and fine aggregates are given in Table 2.

#### *Mix Proportions*

The cement contents used were 235, 303, 337, 421, and 506 lb per cu yd. The values of CA/FA were 2, 2.5, 3.0, 3.5, and 4.0. For the gravel concrete and the crushed stone concrete water use amounted to 17.2 and 22.4 gal per cu yd,

TABLE 2
PROPERTIES OF COARSE AND FINE AGGREGATES

| Item | Source | Grading | Sp. Gr. | Absorp. (%) | Fine Mod. | Voids (%) |
|---|---|---|---|---|---|---|
| Gravel | Mukawa River mouth | Dense | 2.67 | 2.18 | 7.87 | 30.5 |
| Crushed stone | Ishikari River | Gap | 2.61 | 1.14 | 7.80 | 29.8 |
| Sand | Nishikioka Beach | Dense | 2.74 | 0.50 | 2.75 | 33.0 |

respectively. These water factors were determined from preliminary compaction tests to gain almost the same compactibility and finishability for the two kinds of concrete.

*Preparation of Specimens*

The concrete was mixed in a 2-cu ft tilting mixer. The size of the specimens was 6- by 6- by 24-in. Compaction was performed with an impactor (The American Wayer Co., Type D-25) for about 6 min per specimen. After molding, the specimens were cured in a water bath at 68±0.4 F, and 28-day strength was observed. The modulus of rupture and the compressive strength were measured according to ASTM designation C78 and C116, respectively. Static and dynamic moduli of elasticity were also observed.

*Tests Results*

Relations between the values of CA/FA, the cement content, the modulus of rupture, and the compressive strength of the concrete specimens are shown in Figures 4 and 5.

*Dense-Graded Gravel Concrete.* For concrete made with the dense-graded gravel the maximum values of the modulus of rupture and compressive strength were gained at CA/FA=3.5 for every cement content. It was revealed that the desired strength was obtained for pavement slabs when the cement content was 337 to 421 lb per cu yd. The modulus of rupture was about 571 to 914 psi and the compressive strength was about 3,200 to 3,860 psi. When 506 lb of cement was used per cubic yard of concrete, these values reached 986 and 4,430 psi. It also was noticed that the selection of the CA/FA ratio is quite important in such a lean-mix concrete. Because the surface texture of such concrete is rough, it is advisable to add a wearing course to improve riding quality.

*Gap-Graded Crushed Stone Concrete.* For the concrete made with gap-graded crushed stone aggregate the general tendency was similar to the dense-graded gravel concrete and the maximum strength was obtained at CA/FA=2.5. The absolute values were lower than those of the dense-graded gravel concrete. This is due to the fact that the compaction was quite difficult with the impactor in the case of the crushed stone, due to its angularity, and the water-cement ratio was larger than that of the gravel concrete.

*Cement Content* vs *Concrete Strength.* Relations between the cement content and the modulus of rupture and compressive strength of concrete specimens are shown in Figures 6 and 7. It is com-

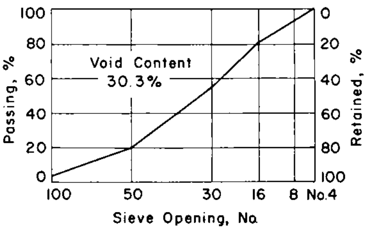


**Figure 3. Grading curve of fine aggregate.**

TABLE 3
VOID CONTENT FOR VARIOUS COARSE AGGREGATE/FINE AGGREGATE RATIOS

| CA/FA Ratio | Voids (%) Dense-Graded Gravel-Sand Mixture | Voids (%) Gap-Graded Stone-Sand Mixture |
|---|---|---|
| 2.0 | 17.3 | 25.5 |
| 2.5 | 14.8 | 20.9 |
| 3.0 | 13.1 | 22.5 |
| 3.5 | 12.7 | 23.6 |
| 4.0 | 13.8 | 22.9 |

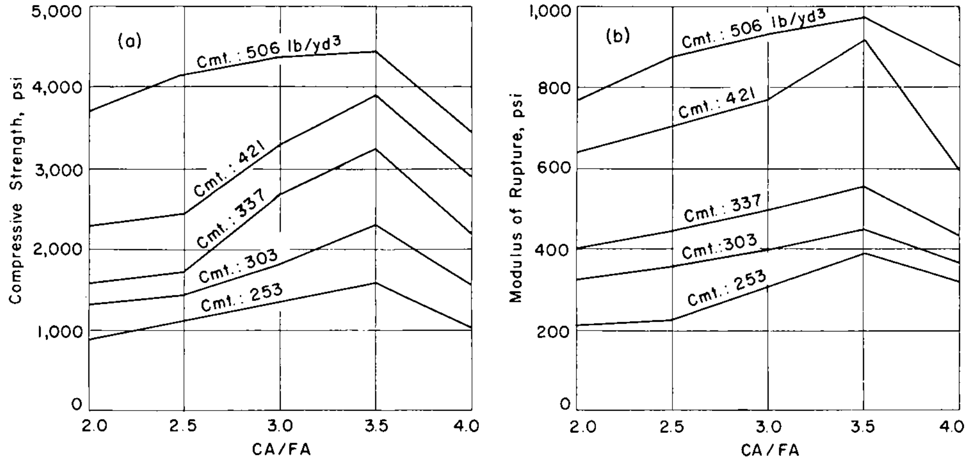


**Figure 4. Relation between CA/FA and (a) 28-day compressive strength and (b) 28-day modulus of rupture; dense-graded gravel concrete.**

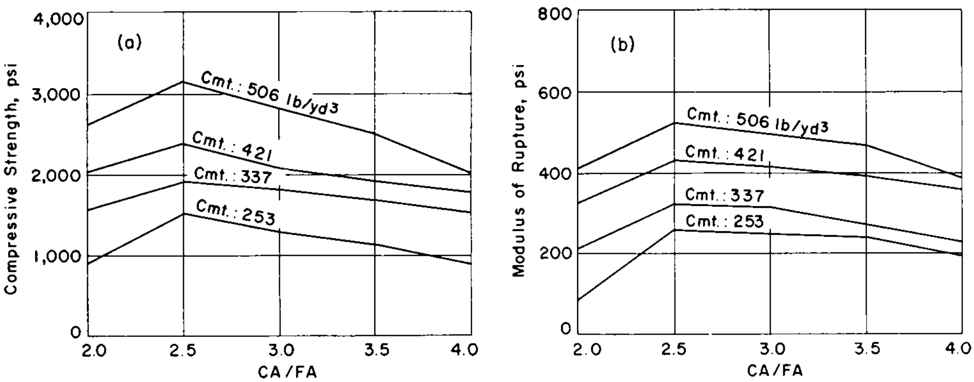


**Figure 5. Relation between CA/FA and (a) 28-day compressive strength and (b) 28-day modulus of rupture; gap-graded crushed stone concrete.**

mon knowledge that the strength of the concrete varies inversely as the water-cement ratio. In Figures 6 and 7, it is evident that enough compaction could not be obtained in the crushed stone concrete with the impactor. Moreover, the quality of the crushed stone itself was poorer than the gravel, as shown in Table 2. The abrasion test result using a Deval abrasion machine was 8.03 percent.

*Density of Concrete Specimens.* The density of the specimens molded by the previously described procedure was 158.5 to 161.6 lb per cu ft for the gravel concrete and 144.1 to 154.1 lb per cu ft for the crushed stone concrete.

The modulus of elasticity of the concrete specimens was low, those at 28 days being as follows:

| Modulus Type | Coarse Aggregate | Modulus Value (psi × $10^6$) |
|---|---|---|
| Static | Dense-graded gravel | 3.6 to 6.3 |
| | Gap-graded stone | 3.5 to 5.0 |
| Dynamic | Dense-graded gravel | 4.3 to 7.4 |
| | Gap-graded stone | 1.5 to 2.8 |

## STRENGTH OF CONCRETE COMPACTED WITH RAMMER

### *Materials*

Asano portland cement was used. The properties of the fine and coarse aggre-

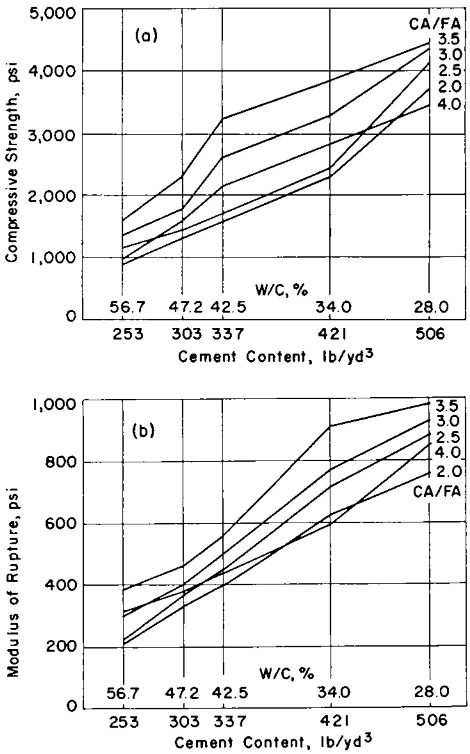


**Figure 6. Relation between W/C, cement content, and (a) 28-day compressive strength and (b) 28-day modulus of rupture; dense-graded gravel concrete.**

gates used are given in Table 4. The grading of the sand was within a range of the standard of JSCE, as in Figure 3. Both dense- and gap-graded gravels were used, the maximum gravel size being 2⅜ in. The minimum void content of the dense-graded gravel was 31.3 percent, as shown in Figure 8. In the gap grading, the particle size distribution was 40 percent No. 4 to ⅜ in. and 60 percent 1$\frac{9}{16}$ to 2 in., giving a minimum void content of 26.0 percent, as shown in Figure 9.

*Mix Proportions*

The cement content was 253, 337, and 421 lb per cu yd. For both mixes 17.2 gal of water was used per cubic yard. Therefore, the water-cement ratios were 6.38, 4.79, and 3.87 gal water per sack of cement, respectively. The CA/FA ratios were 2.0, 2.5, 3.0, 3.5, and 4.0.

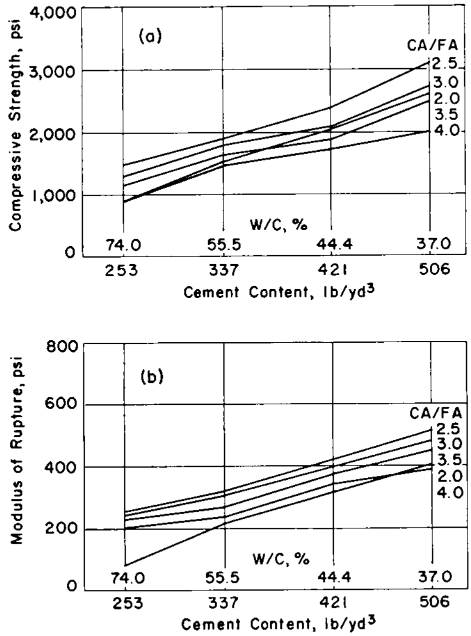


**Figure 7. Relation between W/C, cement content, and (a) 28-day compressive strength and (b) 28-day modulus of rupture; gap-graded crushed stone concrete.**

*Preparation of Specimens*

The specimens were of the same size as in the previous tests. Two 33.5- by 76.8- by 6-in. abutments were made of concrete, and each abutment was so separated with form boards that 8 specimens could be cast at a time. The materials were mixed in a 2-cu ft tilting mixer, and the mixture was poured between the separation boards. The compaction was performed with 4 drops of a rammer[1] on the same area. Consistency of the concrete was measured with a DIN 1048 consistency meter. The amount of penetration by the meter was ¼ to $\frac{5}{16}$ in. for the concrete containing 253 and 337 lb of cement per cubic yard and $\frac{5}{16}$ to ⅜ in. for the concrete containing 421 lb of cement per cubic yard. After 48-hr moist curing in place, the specimens were removed from the abutments and cured in a water bath at the standard

[1] The Tanaka Dokō-Ki Co., capacity of oil tank 0.476 gal, height 3.6 ft, weight 176 lb, ram height 12 to 14 in., number of blows 50 to 60 times per minute, diameter of tamping foot 9$\frac{7}{16}$ in.

TABLE 4
PROPERTIES OF COARSE AND FINE AGGREGATES

| Aggregate | Source | Sp. Gr. | Fine. Mod. | Density (lb/cu ft) | Absorp. (%) | Deval Abras. (%) | Max. Size |
|---|---|---|---|---|---|---|---|
| Coarse | Toyohira R. gravel | 2.62 | 7.50 | 108.3 | 3.19 | 3.4 | 2 ⅜ in. |
| Fine | Nishikioka Beach sand | 2.67 | 2.45 | 116.1 | 1.21 | — | No. 4 |

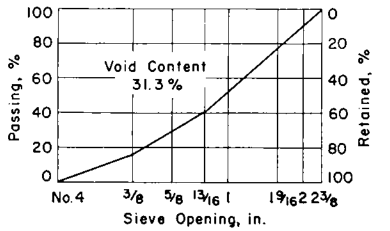


**Figure 8. Grading curve of dense-graded gravel.**

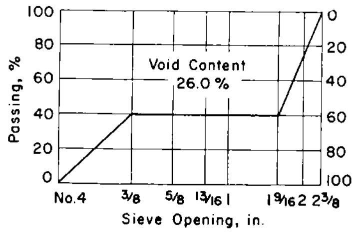


**Figure 9. Grading curve of gap-graded gravel.**

temperature. The weights and strengths of the specimens were measured after 7 days and after 28 days.

## *Test Results*

Table 5 gives the modulus of rupture and the compressive strength of the concrete specimens at 28 days. From the investigations, the following conclusions are clear:

At each cement content in the unit volume of concrete, the maximum strength was obtained at CA/FA=3.5 with dense- as well as gap-graded coarse aggregate (Figs. 10 and 11).

Generally, the specimens made with the dense-graded gravel had higher strength than those with gap-graded aggregates, especially in modulus of rupture. The ratio of the modulus of rupture of gap-graded gravel concrete to dense-graded gravel concrete was 0.8 to 0.9, except in case of CA/FA=3.5 and 4 at cement content (Cmt) of 253 lb per cu yd and CA/FA=3.5 at cement content of 337 lb per cu yd. The ratio of the com-

TABLE 5
28-DAY CRUSHING STRENGTH OF CONCRETE SPECIMENS

| Cement Content (lb/cu yd) | W/C Ratio (%) | CA/FA | FA / (CA + FA) [a] | 28-Day Crushing Strength (psi): Dense Grading: Mod. of Rupture, $\sigma_b$ | Comp. Strength, $\sigma_c$ | $\sigma_c/\sigma_b$ | Gap Grading: Mod. of Rupture, $\sigma'_b$ | Comp. Strength, $\sigma'_c$ | $\sigma'_c/\sigma'_b$ | Strength Ratio: $\sigma'_b/\sigma_b$ | $\sigma'_c/\sigma_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 253 | 56.7 | 2.0 | 32.9 | 244 | 1706 | 7.0 | 184 | 1010 | 5.5 | 0.8 | 0.6 |
| | | 2.5 | 28.2 | 319 | 1878 | 5.9 | 241 | 1208 | 5.0 | 0.8 | 0.6 |
| | | 3.0 | 24.7 | 399 | 2076 | 5.2 | 368 | 1365 | 3.7 | 0.9 | 0.7 |
| | | 3.5 | 21.9 | 472 | 3428 | 7.3 | 592 | 2901 | 4.9 | 1.3 | 0.8 |
| | | 4.0 | 19.7 | 426 | 2844 | 6.7 | 436 | 2532 | 5.8 | 1.0 | 0.9 |
| 337 | 42.5 | 2.0 | 32.9 | 547 | 2631 | 4.8 | 425 | 2375 | 5.6 | 0.8 | 0.9 |
| | | 2.5 | 28.2 | 597 | 3001 | 5.0 | 447 | 2560 | 5.7 | 0.8 | 0.9 |
| | | 3.0 | 24.7 | 614 | 3044 | 5.0 | 490 | 2759 | 5.6 | 0.8 | 0.9 |
| | | 3.5 | 21.9 | 725 | 4551 | 6.3 | 737 | 4879 | 6.6 | 1.0 | 1.1 |
| | | 4.0 | 19.7 | 665 | 3883 | 5.8 | 562 | 3840 | 6.8 | 0.8 | 1.0 |
| 421 | 34.0 | 2.0 | 32.9 | 651 | 3271 | 5.1 | 606 | 3172 | 5.2 | 0.9 | 1.0 |
| | | 2.5 | 28.2 | 739 | 3612 | 4.9 | 645 | 3997 | 6.2 | 0.9 | 1.1 |
| | | 3.0 | 24.7 | 835 | 3811 | 4.6 | 675 | 4551 | 6.7 | 0.8 | 1.2 |
| | | 3.5 | 21.9 | 866 | 5163 | 6.0 | 782 | 5361 | 6.9 | 0.9 | 1.0 |
| | | 4.0 | 19.7 | 728 | 4594 | 6.3 | 652 | 4537 | 7.0 | 0.9 | 1.0 |

[a] Absolute.

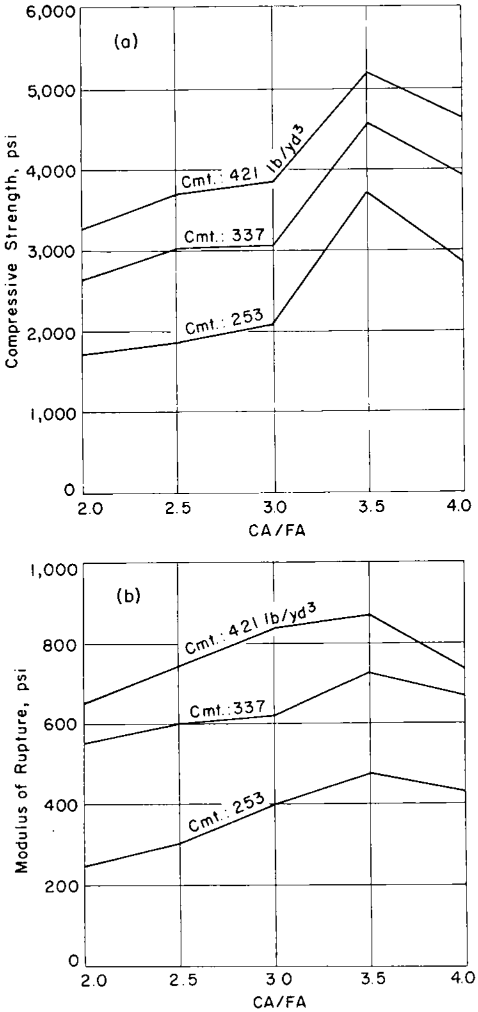


**Figure 10. Relation between CA/FA and (a) 28-day compressive strength and (b) 28-day modulus of rupture; dense-graded gravel concrete.**

pressive strength of gap-graded gravel concrete to dense-graded gravel concrete was small in leaner mix and large in richer mix (namely, 0.6 to 0.9 at Cmt=253, 0.9 to 1.1 at Cmt=337, and 1.0 to 1.2 at Cmt=421).

The relation between Cmt and strength of concrete specimens made of dense- and gap-graded aggregates is illustrated in Figures 12 and 13, respectively. More than the required value (737 psi) of modulus of rupture could be obtained at Cmt=337 and CA/FA=3.5.

The ratio of compressive strength to modulus of rupture was 3.7 to 5.8 at Cmt=253, 5.6 to 6.8 at Cmt=337, and 5.2 to 7.0 at Cmt=421.

Concrete specimens compacted with the rammer reached a higher strength than those compacted with the impactor. The ratio of the modulus of rupture of two different specimens compacted with the rammer and the impactor was 1.2 to 1.4, and that of the compressive strength was 1.5 to 1.8.

*Density of Concrete Specimens.* The

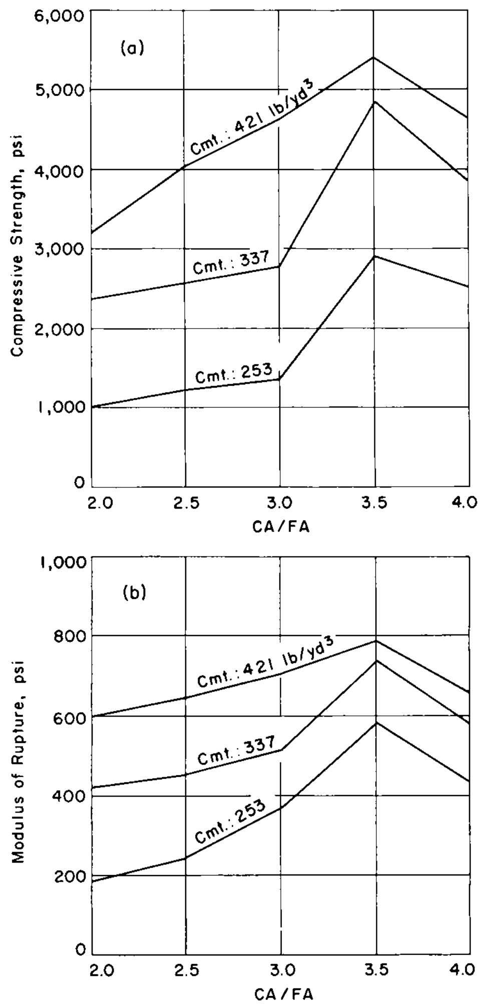


**Figure 11. Relation between CA/FA and (a) 28-day compressive strength and (b) 28-day modulus of rupture; gap-graded gravel concrete.**

density of the concrete specimens molded with the rammer was 150 to 156 lb per cu ft.

## FIELD INVESTIGATION

Using the laboratory test data as the basis for design, actual pavements and base courses were constructed by this method in Hokkaido, Japan, as follows:

### *Freight Yard, Wakkanai Station, Japanese National Railway*

The pavement constructed had an area of 12,880 sq ft and a thickness of 8 in.

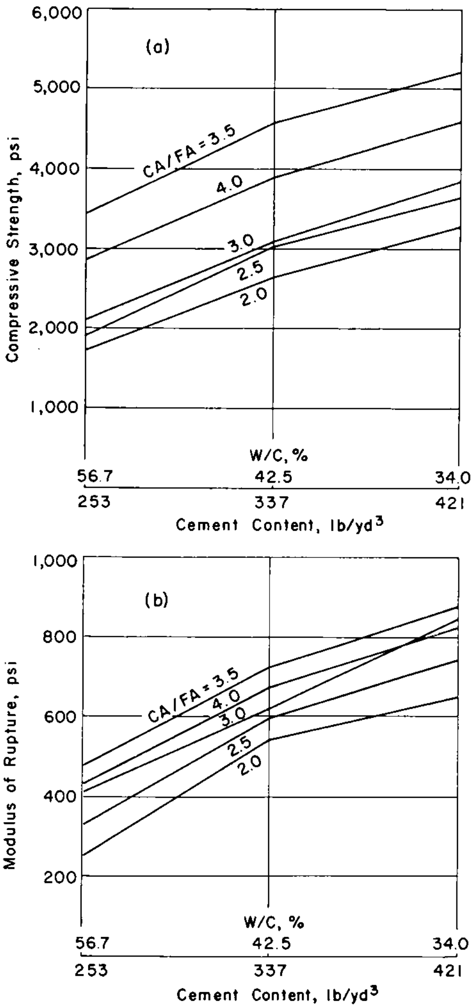


**Figure 12. Relation between W/C, cement content, and (a) 28-day compressive strength and (b) 28-day modulus of rupture; dense-graded gravel concrete.**

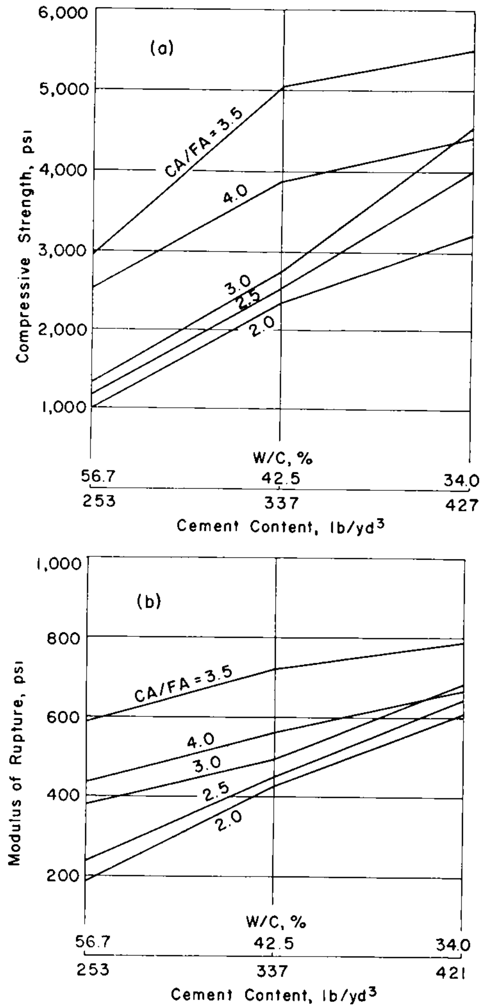


**Figure 13. Relation between W/C, cement content, and (a) 28-day compressive strength and (b) 28-day modulus of rupture; gap-graded gravel concrete.**

The coarse aggregate used was dense-graded Embetsu River gravel with a maximum size of 2⅜ in. The fine aggregate was dense-graded Embetsu River sand. The CA/FA ratio was about 2.5. The amount of portland cement was 354 lb per cu yd; the water-cement ratio was about 4.73 to 4.84 gal of water per sack of cement.

The concrete was mixed in a tilting mixer, then compacted in one layer with an 8-ton macadam roller. Each strip was 11.6 ft wide, with expansion joints spaced at 66 ft and two dummy joints provided between expansion joints. The surface of the pavement was treated with asphalt emulsion of about 48 percent and stone chips. The consistency of the fresh concrete as measured with a DIN 1048 consistency meter was $1\frac{3}{16}$ to $1\frac{5}{16}$ in., and that on the pavement after rolling was $\frac{13}{16}$ to $\frac{29}{32}$ in. Concrete density was 155.4 to 157.9 lb per cu ft. Average modulus of rupture of the concrete specimens made and cured for 90 days at the job site was 786 psi.

*Freight Yard, Fukagawa Station, Japanese National Railway*

Area of the 8-in. thick pavement in this case was 14,811 sq ft. Coarse aggregate consisted of dense-graded gravel from the Ishikari River with $1\frac{3}{4}$-in. maximum size. Fine aggregate was dense-graded Ishikari River sand. Coarse aggregate-to-fine aggregate ratio, cement content, method of mixing, details of expansion joints and dummy joints, and the surface treatment, were almost the same as for the preceding job. Compaction was in two layers by means of a 10-ton macadam roller. The amount of penetration with the DIN 1048 consistency meter was about $\frac{3}{8}$ in. after rolling. Concrete density was 157.2 lb per cu ft. The average modulus of rupture of the specimens after 28 days was 621 psi; the average compressive strength was 4,760 psi. The average modulus of rupture of the specimens after 90 days was 860 psi.

*Base Course, National Road No. 36*

The base course of a section of National Road No. 36 was constructed by the same method. The 1-mi long section was 23.1 ft wide, for an area of about 1,134,000 sq ft. The thickness was 8 in., and the base course concrete was rolled in three layers with an 8-ton macadam roller. The concrete slab was cured with water-sprayed straw mat during the first three days, then 48 percent asphalt emulsion was sprayed over the surface for final curing. The base concrete slab was covered with a $2\frac{3}{8}$-in. thick surface course of bituminous concrete. The asphalt emulsion sprayed over the base concrete slab for curing became a suitable primer for the bituminous concrete surface course. In this case, mixing was performed with a twin-shaft pugmill specially made for the purpose and the mix was transported about 0.7 mi in covered trucks from the mixing plant to the job site.

In these field jobs, grading of aggregates was not controlled as strictly as in the laboratory tests. Nevertheless, the data from the field job tests showed good agreement with the laboratory tests on concrete compacted with a rammer, and the pavements are in good condition and have served satisfactorily over a period of four years.

## SUMMARY


1. The maximum density of coarse aggregates by the test conforming to ASTM designation C29, C127, and C30 was obtained at the gap grading. The void content in gravel was about 5 percentage points less than in crushed stone. The minimum void content in the gap-graded gravel was 24.2 percent for the maximum size of $3\frac{1}{8}$ in.

2. The coarse aggregate-to-fine aggregate ratio was 3.5 in gravel and 2.5 in crushed stone. When dense-graded gravel and sand were mixed, the minimum void content was 12.7 percent.

3. The bonding power between crushed stone particles was low for such a lean-mix concrete. Strength and bond depend on compaction and density, as well as water content and CA/FA ratio. When crushed stone is used, greater compaction may be needed.

4. Within the cement content range of 253 to 506 lb per cu yd, the maximum strength was obtained at the mixing proportion to gain the maximum density of fine and coarse aggregate mixture. At every CA/FA value, the strength of the concrete was nearly proportional to the cement content, provided the water content was kept constant.

5. Modulus of rupture and compressive strength of dense-graded gravel con-

crete with cement contents of 337 to 421 lb per cu yd and compacted with a rammer or a road roller were nearly equal to those of ordinary concrete containing 506 to 590 lb of cement per cubic yard. In the case of gap-graded gravel concrete, the cement content will be reduced to 253 to 303 lb per cu yd.

6. The difference in strength between the gap-graded gravel concrete and dense-graded gravel concrete was larger in the leaner mix and became smaller in the richer mix.

7. The density of concrete compacted with a rammer or a road roller was 1.05 to 1.10 times that of ordinary concrete, and was 158.5 to 161.6 lb per cu ft.

8. The strength of concrete compacted with the rammer was higher than that compacted with an impactor. The ratio of the modulus of rupture and compressive strength by the two methods of compaction was 1.2 to 1.4 and 1.5 to 1.8, respectively.

9. The ratio of the compressive strength and modulus of rupture of concrete compacted with the rammer was between 5 and 6.

10. There was good correlation between the laboratory and the field jobs, even though field grading of aggregates was not strictly controlled.

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