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Aggregate Gradation Effects on Cracking-Related Displacements in Concrete Pavement

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Abstract

Aggregate gradation effects on cracking-related displacements of concrete are investigated in the laboratory using the German cracking frame. Concrete workability was assessed by use of the slump and drop tests for two different concrete mixtures consisting of gap-graded and dense-graded aggregates. Shrinkage strain, cracking frame strain, and concrete strain were measured and used to compare to strength gain and creep development. The measured and calculated strains of the different aggregate gradations were compared each other. Gradation effects on strength and stress development relative to tensile cracking at saw-cut tip were also investigated. Test results revealed that the gap-graded concrete has indicated larger shrinkage and creep strains than dense-grade concrete perhaps because of its higher volume concrete of cement mortars in the mixture.

Keywords: aggregate gradation, cracking displacement, shrinkage, saw-cut tip, creep strain

1. Introduction

Gap-graded aggregates have a lower dry rodded unit weight (DRUW) and larger total volume of voids to be filled with cement mortar than concrete with dense-graded aggregates. Because of the higher mortar content (cement + water + sand) in the mixture, the concrete with gap-graded aggregates may undergo larger volumetric strain due to shrinkage. On the other hand, dense-graded aggregates have larger DRUW and more extensive surface area to make contact with the mortar. Accordingly, strength of dense-graded concrete should exceed the strength of gap-graded concrete. In this context, this paper reports preliminary results of measured effects of the aggregate gradation on the cracking-related performance of pavement concrete. Based on these backgrounds in mind, the German cracking frame was adopted in this research to evaluate the cracking-related displacements with respect to shrinkage and creep strains of gap and dense-graded aggregates in concrete mixture.

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2. The German cracking frame

A procedure to monitor gradation effects on the cracking-related strength and strain over time relative to shrinkage strain was conducted in the laboratory using the German cracking frame.[1-3)] The cracking frame (Fig. 1) accommodates a1-meter long concrete specimen. The ends of the specimen are configured by dovetails in two steel crossheads. These cross heads are connected with two steel bars to restrain longitudinal change in the distance between the crossheads. Small longitudinal deformations or strains in the steel bars are calibrated to load in order to determine the longitudinal stress applied to the frame (Fig. 2). The concrete specimen cross section at the center portion is 12.8×14.6 cm (5.05×5.75 inch) and at the ends of the dovetails is 12.8×32.9 cm (5.05×12.95 inch). It is anticipated that the cracking sensitivity of concrete can be examined within a limited geometric range by comparing test results between different concrete mixtures using the cracking frame. The cracking frame has the added advantage of providing a sufficiently large test specimen to allow for a crack inducer and instrumentation to be inserted in the concrete. The use of the

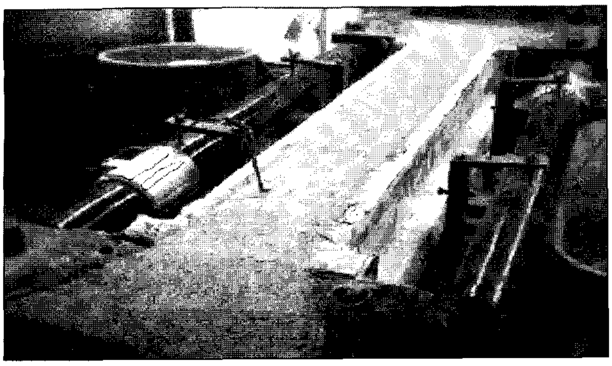


Fig. 1 German cracking frame

crack inducer ensures that the crack will indeed be controlled in the center in the specimen.

3. Laboratory test program

Cracking-related displacements with respect to shrinkage and creep strains were compared by using gap-graded and dense-graded aggregates in concrete mixtures as shown in Table 1. The concrete mixture consisted of crushed limestone as the coarse and intermediate aggregates and sand as the fine aggregate. The coarse aggregate factor (CAF) and intermediate aggregate factor (IAF), the main parameters in this study, were 0.70 and zero, and 0.45 and 0.25, respectively, while they had same cement factor (CF) of 6.0. A water cement ratio of 0.42 was used and the unit weights for gap-gradation and dense-gradation concrete were found to be 2,183 kg/m^3 (136 lb/ft^3) and 2,197 kg/m^3 (137 lb/ft^3), respectively.

The cracking frame was instrumented to collect following data during the hardening process as:

1. Free shrinkage strain (ASTM C-157)
2. Strain of steel rods
3. Concrete strain in the cracking frame
4. Concrete temperature (top and bottom)
5. Concrete compressive strength (1, 3, and 7 days)
6. Concrete split tensile strength (Modified ASTM C-496)
7. Concrete slump (ASTM C-143)
8. Number of drops (a German DIN 1048 test standard)

Demac points were installed on the top surface of ASTM C-157 specimens. The specimens were subjected to one-dimensional drying to be representative of the drying shrinkage the frame concrete is subjected to. The cracking frame strain resulted from restraint of the free shrinkage strain and was measured by the load cells installed on the steel frame separating the bulk heads. Concrete strain was measured by vibrating wire strain gauges imbedded into the cracking frame concrete. Two thermocouples were also embeded to measure the concrete temperature at 2.54 cm (1 inch) from

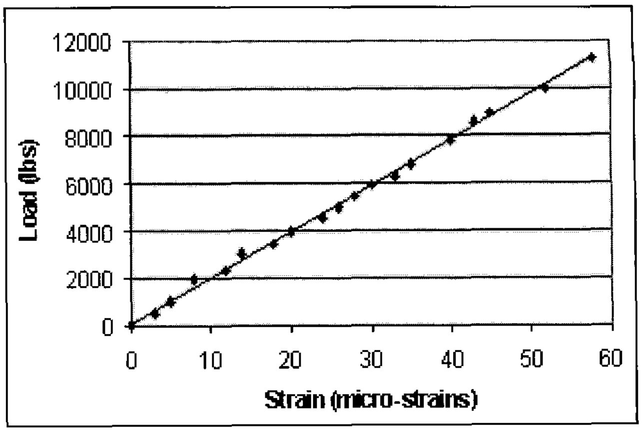


Fig. 2 Cracking frame force vs. load cell strain

Table 1 Mixture proportions in 1 m^3 (35.3 ft^3) of cracking frame concrete

	Gap-gradation	Dense-gradation
Cement	251 kg	251 kg
Fly ash	84 kg	84 kg
Coarse aggregate	1,102 kg	708 kg
Intermediate aggregate	-	424 kg
Fine aggregate	530 kg	514 kg
Water	216 kg	216 kg
Air-entraining admixture	236 mℓ	236 mℓ
w/c ratio	0.42	0.42
CAF	0.70	0.45
IAF	-	0.25
CF	6.0	6.0
Concrete unit weight	2,183 kg/m^3	2,197 kg/m^3

top and bottom surfaces. Concrete compressive strength (f_c) was measured by 15.2×30.5 cm (4×8 inch) standard cylinder specimens to monitor strength gain over time and to provide a basis for determining the degree of hydration and the modulus of elasticity. Concrete split tensile strength was also measured following the modified ASTM C-496 procedure[3-6]. Workability of concrete was measured by the slump test and characterized by the German DIN 1048 drop test method.

4. Concrete workability

Slump test and drop test were conducted immediately upon mixing the concrete[7-8]. The drop test (DIN 1048) is a German test standard that perhaps measures to some extent the mobility of concrete mixture with a slump less than 50 mm (2 inch) to serve as an indicator of whether workability is sufficient during placement of the concrete. The test is a simple measure of the number of drops taken to cause a concrete mixture in a slump cone to bulge laterally outward to a given diameter in a consistent and flowable manner. The measured slump and number of drops for each mixture are shown in Table 2. The number of drops of the concrete

Table 2 Slump and drop test result

	Gap-gradation	Dense-gradation
Slump	40 mm (1.6 inch)	40 mm (1.6 inch)
Drop	6 Drops	12 Drops

mixed with dense-graded aggregates is greater than that of open-graded aggregates although they had the same slump. The concrete mixed with dense-graded aggregates showed greater resistance to lateral movements. Apparently, the higher adhesion between aggregates and cement mortar of dense-gradation concrete hindered the concrete from bulging laterally outward.

5. Shrinkage and creep strains

During the cracking test, the concrete free shrinkage (ASTM-C157) was monitored with time (Fig. 3) along with the strain in the concrete and the steel frame. These trends are shown in the Figs. 4 and 5, respectively. The strain measured by the concrete gauge represents the net effect of shrinkage and elastic strain due to the restraint imposed by the cracking frame and if the strain in the steel frame were zero, the strain measured by this gauge would represent the creep strain in the concrete[7-8]. Otherwise, the difference between the strain measured by the gauge in the concrete and strain measured by the gauge on the steel represents the creep strain in the concrete. It is noted that the initial portion of the strain shown in Fig. 4 should not exceed the amount of free shrinkage measured from the ASTM C 157 specimen, but since it was we consequently ignored this portion in the creep strain calculation shown in Figs. 6 and 7.

As previously noted, the cracking frame strain (Fig. 5) was measured in the laboratory during the testing sequence but the load on the concrete (F_s) due to the drying shrinkage was determined using a calibration curve (Fig. 2) developed from load cell reading correlated to the strain gauge readings. Shrinkage strain (Fig. 3) was found from ASTM C-157 specimen data as was previously described. The shrinkage strain and the frame strain varied with time, as did the force in concrete. The frame strain was nearly zero until around 40 hours of concrete age. So, a significant amount of creep strain took place over 40 hours.

Analysis of the restraint provided in the cracking frame suggests that the creep strain can be found from the following relation[3]:

$$\varepsilon_{crp} = \varepsilon_v - \varepsilon_e - \left[\frac{F_s}{E_c A_c}\right] = \varepsilon_{conc} - \varepsilon_e \qquad (1)$$

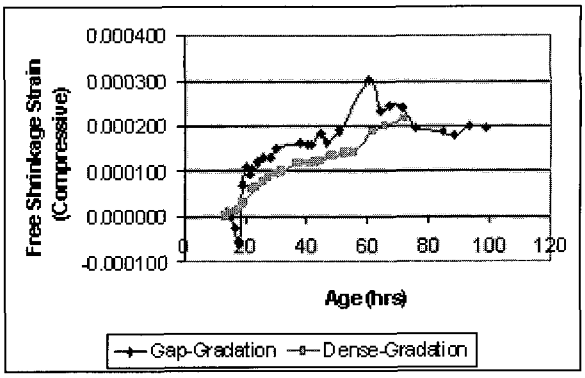


Fig. 3 Free Shrinkage Strain

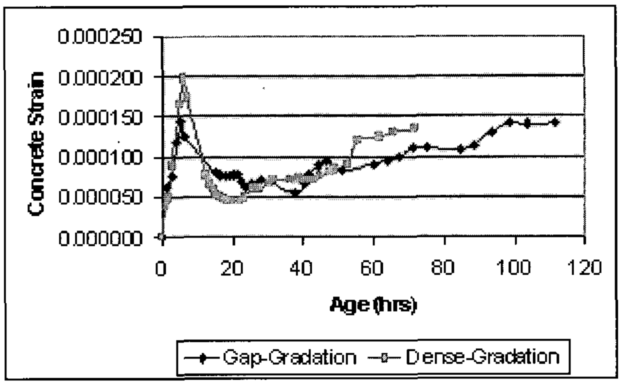


Fig. 4 Concrete Strain

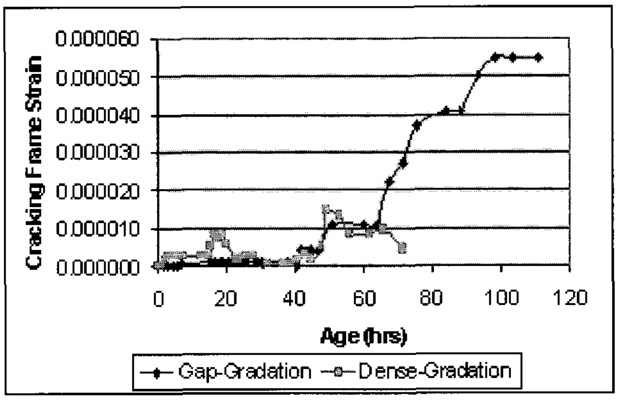


Fig. 5 Cracking Frame Strain

where

ε_{crp} = creep strain

ε_v = shrinkage strain (ASTM C-157)

ε_e = frame strain

ε_{conc} = concrete strain

F_s = force in concrete (F)

E_c = modulus of elasticity of concrete (F/L^{-2})

A_c = specimen cross sectional area (L^2)

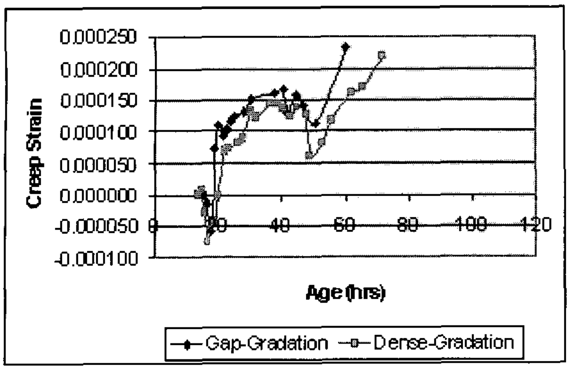


Fig. 6 Creep Strain Calculated by Equation

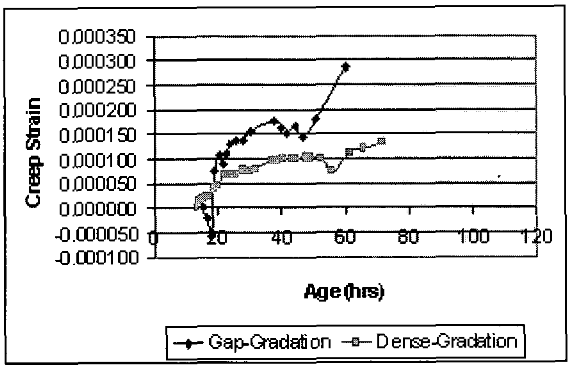
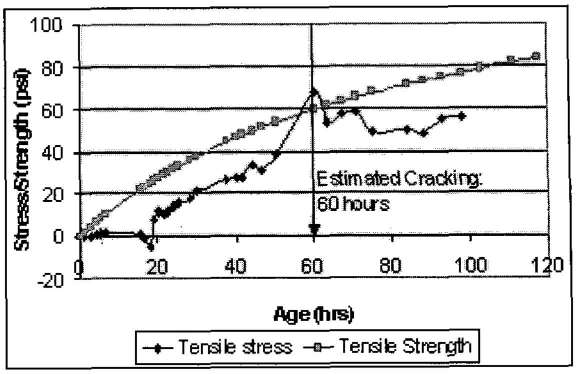
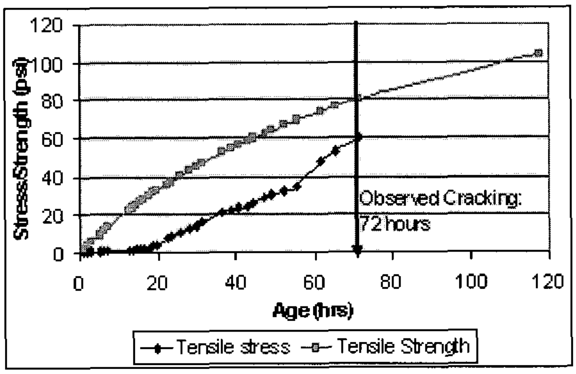


Fig. 7 Net Difference between Concrete Strain and Cracking Frame Strain



(a) Gap-Gradation



(b) Dense-Gradation

Fig. 8 Stress and Strength Development

The accumulative creep curves determined by equation (1) are shown in Fig. 6. The total creep strain of concrete mixed with gap-graded aggregates appears to be larger than the dense-gradation concrete. The accumulative creep curves determined by net difference between concrete strain and cracking frame strain with time are shown in Fig. 7.

6. Cracking at the saw-cut notch

The time of crack formation in the cracking frame concrete mixed with gap-graded aggregates was not accurately observed while the crack formed in the dense-gradation concrete at 69 hours. The time of cracking was estimated between 55-65 hours. The cracks run through the full depth of the test specimen. The laboratory strength gain with time for both gradations can be seen from Fig. 8.

To determine the strength development of the concrete over time, compressive strength tests were conducted at an age of 1, 3, and 7days. Using specially prepared fracture specimens following a modified ASTM C-496 procedure,[6] the fracture parameters (K_{If} and c_f) of the concrete were found and used to determine the cracking strength over time based on the use of fracture mechanics. The tensile strength (f_t) at the tip of the notch was determined using equation:

$$f_c = \frac{K_{If} c_n}{\sqrt{g'(\alpha)c_f + g(\alpha)h}} \qquad (2)$$

where

$g'(\alpha)$ and $g(\alpha)$ are slab geometry factors

K_{If} = stress intensity factor ($F/L^{-2}\,L^{-1/2}$)

c_f = process zone length (L)

c_n = arbitrarily defined constant

h = slab thickness (L)

Tensile stress of the concrete was calculated based on the restraint of shrinkage and thermal strains. Comparing to gap-gradation concrete, higher tensile strength and lower tensile stress were developed in the concrete specimen mixed with dense-graded aggregates as shown in Fig. 8. The estimated time of cracking of gap-gradation concrete coincide with the calculated cracking time as shown in Fig. 8 (a). However, the calculated tensile stress of dense-gradation concrete did not exceed the concrete strength at the time of the observed cracking.

The results shown in this paper indicate the shrinkage measurement methodology needs to be improved because of the differences in the readings between the demac and the vibrating wire gauges previously noted.

7. Conclusions

Cracking-related displacements of concrete with respect to aggregate gradation effects are under investigation in the laboratory using the German cracking frame. The concrete mixed with gap-grade aggregates had 0.7 of CAF while the concrete with dense-aggregate had 0.45 of CAF and 0.25 of IAF. The gap-graded concrete has indicated larger shrinkage and creep strains than dense-gradation concrete perhaps because of its higher volume content of cement mortars in the mixture. Because of the larger shrinkage strain, higher restraint tensile stress was developed in the gap-gradation concrete. Lower level of tensile strength of gap-gradation concrete was developed due to its higher cement content and more extensive surface area of aggregates to be contacted to the mortar. As the result, crack was formed in the concrete mixed with gap-graded aggregates earlier than the concrete mixed with dense-graded aggregates.

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