Composite Concrete Pavements with Roller-Compacted Concrete

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ABSTRACT

Roller-compacted concrete (RCC) is being used to provide low-cost, low-cement-content mass concrete with marginal-quality unwashed aggregates. Tests show that pavement slabs with moderate flexural strengths can be made at these low cement factors and that high strengths should be attainable with much less cement than used in conventional concrete. Because of the low water content (no slump), shrinkage stresses in RCC pavements are to be decreased and the number of transverse contraction joints can be reduced. By topping the RCC with a thin monolithic layer of steel fiber-reinforced concrete (FRC), a durable, smooth surface with slightly improved static strength results. Tests also indicate that a fatigue life much better than conventional concrete develops, but the tests are limited. This improvement may be a result of better strength gain with maturity in the RCC or a result of the excellent fatigue properties of the fibrous concrete. By sandwiching the RCC between thin layers of FRC, an effective "structural" slab with good dimensional stability and low shrinkage can be made.

Roller-compacted concrete (RCC) has demonstrated tremendous savings in time, money, and resources when used in mass applications (1-3). It has potential for similar savings in large airfield and highway pavements, and has already been used effectively to provide pavements for log-handling facilities, port terminals, heavy-duty storage areas, and hardstands.

Recent tests indicate that RCC can be incorporated into composite paving and large slab construction with judicious use of a high-quality material such as fiber-reinforced concrete (FRC) to provide an efficient "sandwich" section. This combination can give economy, high fatigue endurance, a tough wearing surface within standard grade tolerances, minimal shrinkage and reduced jointing, reduced or eliminated corner and edge curling, and other advantages. It appears that a sizable project is necessary to realize the greatest potential in savings, and the benefits may be reduced for pavements that must be put into service soon after placement.

ROLLER-COMPACTED CONCRETE (RCC)

In simple terms, RCC can be considered as an upgraded cement-treated base (CTB) or a cement-treated base for which the engineering and material properties have been determined and are being used to advantage. After placing and curing, RCC is a concrete that can have strength properties similar to those of conventionally placed more expensive pavement mixes.

Although there are no set limits, RCC has generally been made with cement factors ranging from less than 100 to more than 500 lb of cement per yd^3 (2 to 13 percent by weight) and with maximum size aggregates ranging from 0.75 to 9 in. Fly ash or other pozzolans can be used as a substitute for a portion of the cement in RCC or as a mineral filler. Both cement factors and compressive strengths of RCC mixes have a wide range of values, but strengths can easily be the same as for conventional concrete while typically using less cement (Figures 1 and 2).

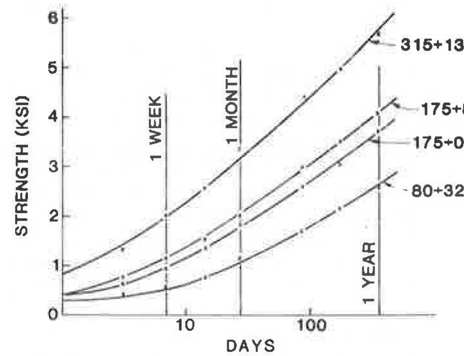

FIGURE 1 Fatigue test results.

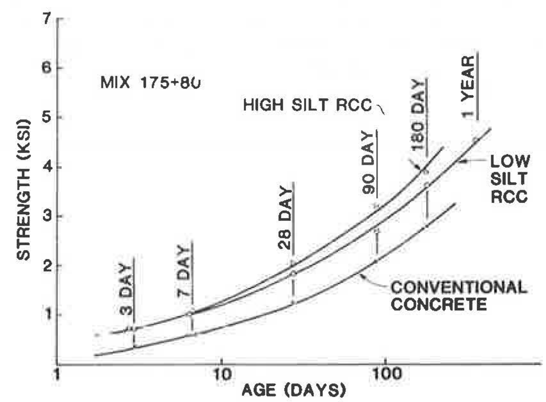

FIGURE 2 Curl results.

Figure 3 shows a general band for gradations that most airfield and highway base and top courses fall into. Also shown on the same figure are the gradings of two RCC mixes. It is apparent that RCC can be made with most highway base materials. Higher strength, better density, and more efficient use of cement is probable if the aggregate contains a normally unacceptable amount of nonplastic fines. In most cases, this should consist of 4 to 11 percent of the total aggregate weight. It can be advantageous to not spend time and money washing the aggregates and maintaining a clean gradation. Additionally, it may be possible to use large aggregate material instead of the relatively small maximum

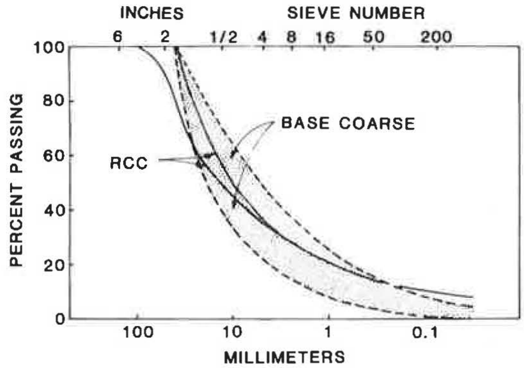

FIGURE 3 Compressive strength versus time for various RCC mixes.

aggregate sizes generally used in conventionally placed pavement concretes and base materials.

Figure 2 shows the effect of making concrete with an RCC aggregate having a typical base course gradation but with a top size of 3 in. and without removing the silt. As long as the silt and clay-size particles are relatively nonplastic, they are generally beneficial. Also shown on the same figure is the strength gain with time when the concrete is made to normal high-quality standards using conventional concrete practices; that is, aggregate manufactured to a closely controlled ideal grading, fines removed, low slump but wet-mix consistency, chemical admixtures used, and so forth. The surprising result is that this extra effort and expense resulted in significantly less strength. It also required a higher water content which, in turn, develops more shrinkage.

A major advantage in pavements of RCC's no-slump consistency is the reduced water content. Along with low cement factors, the reduced water causes theoretical drying shrinkage to be significantly less than for conventional concrete with a measured slump. An indication of what can be expected for drying shrinkage with mixes that might be used in pavements is shown in Figure 4. The figure also shows a range of strain capacities that can be expected in concrete before cracking. The lower shrinkage of RCC is obvious from this figure. In paving applications, this can directly translate into greater joint-spacing. Fewer joints and less movement in turn means lower construction costs, reduced maintenance costs, and probably less internal stress due to shrinkage.

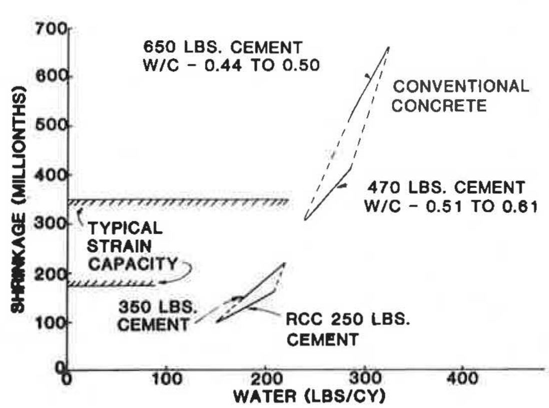

FIGURE 4 Comparison of RCC and conventional concrete strengths.

Depending on cement factor, the water-to-cement ratio (w/c) for RCC can vary considerably. When cement factors are very low, high w/c values on the order of 1.0 to 2.0 can result; yet, these mixes can have minimal shrinkage and good strengths. Conversely, because little water is used in RCC, higher cement factor mixes can have low w/c values in the range of 0.3 to 0.5.

Experience has shown that visual observation in the field can easily control and properly maintain the moisture content at a level that is just low enough to prevent the roller from sinking or pumping the mix. This is essentially the optimum moisture regardless of the resulting theoretical w/c, and it provides enough water for compaction and hydration without causing internal pore pressure during compaction because of excess water. It is important to recognize that Abram's Law (which is the basis for the long-standing emphasis on decreasing the w/c to improve quality and strength) is applicable to slumpable mixes of workable consistency--RCC is not slumpable. From a variability standpoint, theoreticians must also recognize that with low cement factor mixes, w/c ratios may vary by 0.10 throughout a workday just from changes in ambient conditions. The desire for close control of w/c ratios, which is appropriate for slumpable conventional mixes, should be greatly relaxed or ignored in properly designed lean RCC mixes.

Flexural strengths of RCC can be surprisingly high and consistent for its relatively low cement factors and no-slump consistency. Data also suggest that the long-term strengths can increase substantially. Typical flexural strengths for large beams are given in Table 1 for some RCC mixes.

TABLE 1 Flexural Strength of RCC

Identification	Maximum Aggregate (in.)	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Age (days)	Strength (psi)
Z-100	3	100	0	90	155
Z-100	3	100	0	7	55
Z-200	3	200	0	90	275
Z-200	3	200	0	7	165
E-94F	3	94	38	90	150
W-80F	3	80	32	90	200
W-175	3	175	0	90	330
W-175F	3	175	80	90	340
W-315	3	315	135	90	500

Complementing the flexural strength of RCC is its relatively high creep rate and typically low modulus of elasticity. High static flexural strengths achieved in conventional concrete by using high cement factors can result in pavements with higher internal stresses due to both drying shrinkage and thermal cooling associated with dissipation of heat from hydration. These mixes typically also have low creep rates and a high modulus of elasticity, leading to a more brittle material with little ability to relieve internally developed stresses. Designers often are unaware that although beam strengths from unrestrained test specimens are high, the actual usable strength available in a restrained pavement to carry externally applied loads may be hundreds of psi less when subtracting out the internal stresses. With RCC, the lower modulus and higher creep rate minimize development of internal stresses that already have lower potential because of the reduced water and cement contents. Typical modulus and creep data are shown in Figure 5 for RCC and conventional concretes.

Unfortunately, RCC by itself has drawbacks if used as a paving material. These are uncertain long-

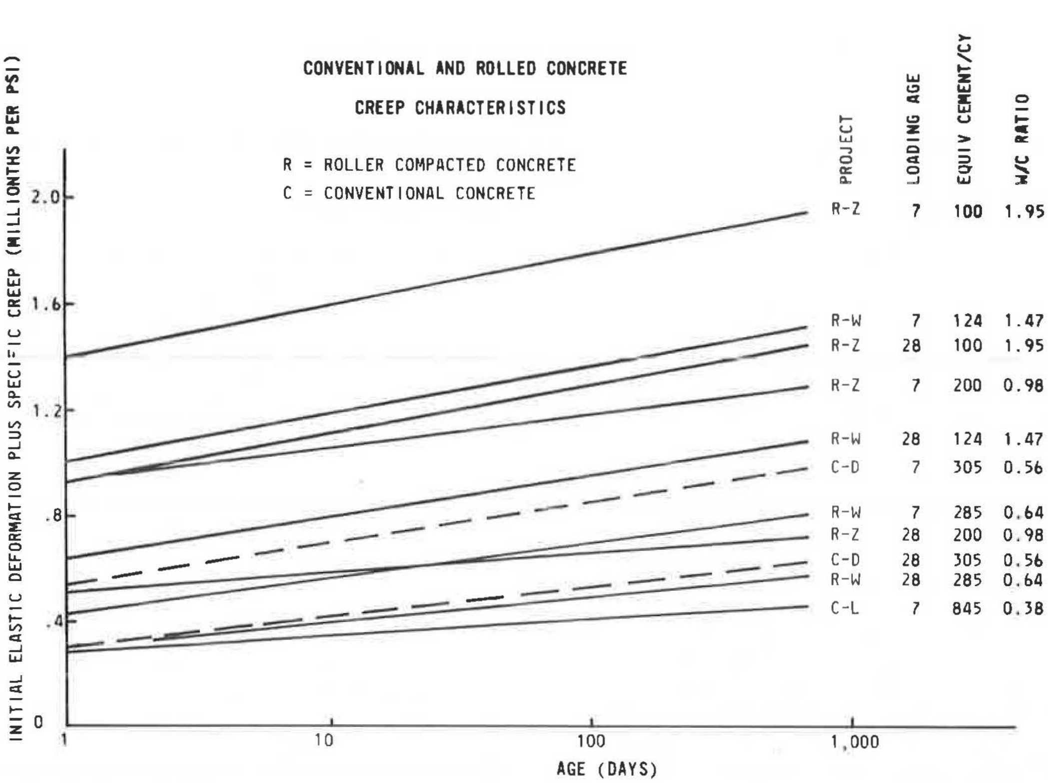

FIGURE 5 RCC and base course gradations.

term freeze-thaw durability and control of surface tolerances during high production placement. These concerns have not restricted the use of RCC for heavy-duty pavement facilities and applications such as haul roads and handling lots at port facilities or log handling yards. These concerns have, however, prevented applications of RCC to airfield pavements and highways.

Spreading and rolling equipment as well as the consistency of the mix need close attention if a flat surface is to be achieved. Without the use of a spreader box or paving machine such as is used in asphalt construction, gradual undulations of the surface of about 0.1 ft per 10 ft can be expected. With laser-controlled blades on spreading equipment, quite accurate control can be achieved before rolling, but even then, roller marks and dips where the roller reverses can be expected.

Durability of RCC in freeze-thaw environments can correctly be described as anything from excellent to terrible, depending on which data are used. When subjected to rapid freeze-thaw conditions while saturated (such as in the ASTM C666 test), RCC deteriorates rapidly. Also, when large blocks of RCC containing 200 lb of cement per yd^3 were subjected to alternating freezing and thawing concurrent with wetting and drying in a salt water tidal zone, they disintegrated.

On the other hand, RCC tested in environments simulating freezing and thawing from typical frost action and intermittent rain (surface damp but not thoroughly saturated conditions) with subfreezing internal temperatures to depths of 0.25 and 1 in., showed that it could withstand 1,000 cycles of freezing and thawing with only minimal loss to less than 1 in. deep. Also, large slabs of RCC left exposed for years in the natural environment near Portland, Oregon, have shown excellent performance. The slabs have rough irregular horizontal surfaces that puddle water. The area gets many cycles of freezing and thawing, but few hard and continuous freezing periods. The slabs show no apparent change from their condition when first placed outside. Even more notable is the excellent performance of hundreds of thousands of square yards of unprotected RCC pavements used in various log handling and shipping terminal facilities around the area of Vancouver, British Columbia, Canada. Most of these pavements have been in service for about 1 to 5 yr.

RCC pavements can be given the close surface tolerances and the durability desired by topping them with a thin layer of conventional concrete placed with conventional equipment. The idea is similar to the concept used for toppings of bridge decks or "super flat" industrial floors. The practicality of doing this on a large scale for miles of pavement has been investigated. Concrete paving equipment to accomplish this is used in highway or airfield construction and is currently available with only minor modifications. On a smaller scale, a demonstration project conducted without paving machines has shown excellent results for more confined and specialized flooring applications.

A variety of topping materials could be used ranging from latex-modified concrete, to dense concrete (Iowa system), to fiber-reinforced concrete. The topping mix needs to have minimal shrinkage and good bond as well as "finishability" and durability. It should also closely approximate most of the hardened physical properties of the RCC.

Bond can be achieved relatively easily for several reasons. The RCC surface will not be smooth, but will have a substantial roughness when examined closely. Also, because there should be little or no excess free moisture in the RCC mix, bleeding and the resulting problem of laitance at the surface is generally nonexistent or insignificant. Consequently, expensive and time-consuming surface-cleaning and abrading is not necessary. In most cases, the topping mix is expected to consist of a thin (1 to 2 in.) layer of relatively high-strength high-

cement factor concrete with corresponding high paste and mortar. This combination lends itself automatically to good bond.

Because the RCC has minimal shrinkage and the topping will be bonded to it, a similar low value of shrinkage should be designed into the surface mixture. This can be accomplished with high-range water reducers, latex modifiers, no-slump dense mixes, or vacuum dewatering.

FIBER-REINFORCED CONCRETE

Fiber-reinforced concrete (FRC) is ideally suited for pavement because of its high static flexural strengths and, more important, because of its improved fatigue performance. Unfortunately, it is expensive unless a reduction in design thickness is achieved, and it may develop other concerns in thin pavement sections.

There are hundreds of publications concerning FRC, but perhaps the best overview is the American Concrete Institute's state-of-the-art report (4). Airfield pavement thicknesses of about 5 to 10 in. are achievable with FRC as compared to about 8 to 20 in. for conventional concrete.

When taking into account the static strength and rate of strength gain for paving concrete and then subtracting the loss of strength for service conditions (fatigue and less than ideal cure), the usable working stress can be plotted (5). Figure 6 shows the results of this type of analysis for an actual airfield paving project that compared conventional concrete to fibrous concrete. The graph clearly shows that under the fatigue of service conditions, conventional concrete continually loses load-carrying capacity with time whereas fibrous concrete improves with time after a slight initial reduction at the start of its service life. The FRC is simply gaining strength with maturity faster than it is losing it because of fatigue.

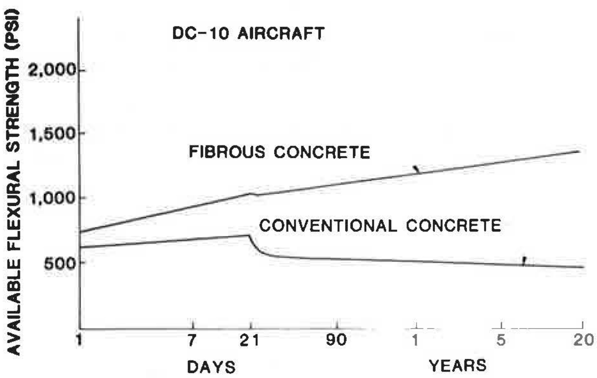

FIGURE 6 Shrinkage and strain capacity for RCC and conventional concrete.

However, this example does not take into account curl and shrinkage stresses due to drying and dissipation of internal heat. These should be included in the analysis for both fiber and conventional concrete. Without special provisions such as high-range water reducers or cooled mixes, the fiber material typically uses high water and cement contents and will have higher internal shrinkage stresses. Depending on thickness, it may or may not have higher adiabatic thermal stresses than the thicker but lower cement factor conventional mix.

Because of the thinner pavement sections achieved with FRC, corner curling and related stresses are of more concern than with deeper conventional pavements (6). This can limit the benefits of FRC when used by itself in a full pavement thickness.

From an engineering standpoint, FRC has improved fatigue endurance, higher flexural and tensile strength, greater strain capacity and crack resistance, high toughness and energy absorbing properties, and extraordinary resistance to damage by impact. With proper entrained air and mix proportioning, it has excellent resistance to freeze-thaw and wet-dry damage.

In pavement applications, steel fibers are typically used, but because they are discrete and non-connected elements, they have not shown the internal corrosion problems of conventionally reinforced concrete in salted environments.

From a practical standpoint, conventional equipment can be used to mix and place FRC in thick or thin pavements and slab sections. The typical close surface tolerance controls desired in highway, industrial floor, and airfield pavements can be achieved.

FRC mixes normally have fairly high cement factors and higher sand contents, and often use smaller maximum size aggregates. These characteristics make them well-suited for latex modifiers, high-range water reducers, and placement in thin sections.

RCC PAVEMENTS WITH FRC

When used in combination, FRC and RCC complement each other and can provide a remarkable paving material. FRC is an ideal topping for RCC slabs and can also be used with them to create a "sandwich panel" pavement.

A series of tests was conducted to establish whether the RCC and FRC could be placed with compatibly; to determine the hardened physical properties

FATIGUE TEST RESULTS

BEAM	CEMENT + ASH (LBS/CY)	% STATIC STRENGTH* (UPPER TO LOWER LOAD)	CYCLES TO FAILURE
2"	585+249		
9"	315+135	10% - 80%	455,700
2"	585+249		
2"	902+0		
9"	175+0	92% - 100%	100
2"	902+0		
2"	585+249		
9"	315+135	10% - 80%	1,076,820
2"	902+0		
9"	175+0	10% - 80%	615,170

* BASED ON 28 DAY STRENGTH. ACTUAL AGE AT THE TIME OF FAILURE FOR EACH TEST WAS GREATER. STORAGE AFTER 28 DAYS WAS COOL AND DRY CONDITIONS.

FIGURE 7 Conventional and roller-compacted concrete creep characteristics.

of deep pavement sections made with the FRC as a topping and with RCC sandwiched between FRC layers; and to obtain an indication of what the long-term performance of the composite material might be in service. The dimensions of the sections and the cement factors used for the RCC and FRC mixes are shown in Figures 7-10. The beams were a nominal 4 ft long and were obtained by sawing them out of slabs made with different design sections, as shown in Figures 11-13.

Aggregates and mix designs for the RCC were identical to those used in more than 400,000 yd^3 of RCC placement on the Willow Creek Project (1). Although that work was for a dam, the contractor was an experienced road builder, and the method of mixing, placing, spreading, and compacting used paving procedures. In essence, the dam consists of 12-in. pavement slabs stacked on top of each other. A dual-drum low-profile pavement plant mixed the material, scrapers and bottom dumps hauled it, a bulldozer spread it, and a vibratory roller compacted it. The in-place cost of the RCC was approximately $19 to $20 per yd^3.

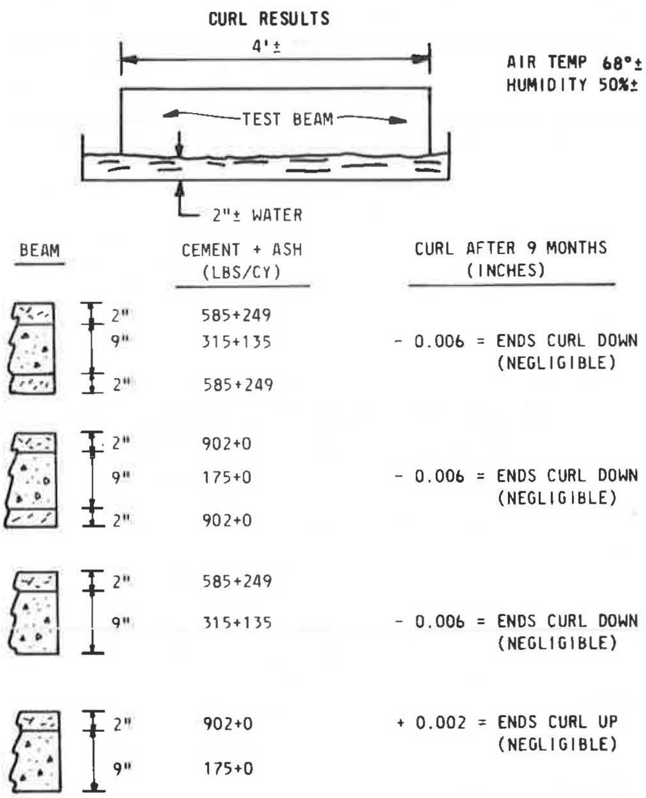

FIGURE 8 Usable design stresses in an airfield pavement.

The RCC aggregate quality, grading, and production are discussed by Schrader (1) and Schrader and McKinnon (3). The aggregate basically consisted of 70 percent basalt from a quarry; the basalt was crushed simultaneously with the silty sandy gravel overburden composing the other 30 percent of the aggregate. The RCC mixes used both 3-in. maximum size aggregate (mix 175+0) and 1.5-in. maximum size aggregate (mix 315+135). There was no washing of the aggregate. It would not have met normal road base criteria and would not have begun to approach normal conventional concrete aggregate specifications. Typically, the total aggregate contained about 8 percent material passing the No. 200 sieve. When separated into two piles on the 0.75-in. sieve, approximately 17 percent of the 0.75 minus product passed the No. 200 sieve.

The FRC aggregate was manufactured by processing and washing of the RCC aggregate so that it had a maximum size of 0.5 in. and a typical conventional concrete gradation. It is generally prudent to use the same basic aggregate source or similar materials for both the FRC and RCC so that thermal and elastic similarity is achieved.

From a materials standpoint, the test slabs and beams were designed by:

1. Using the previously established RCC mixes and their required water content for compaction by vibratory rolling;
2. Assuming that a w/c of 0.26 provided adequate water to hydrate the cement;
3. Determining the quantity of water added to the RCC that was above the amount necessary for cement hydration;
4. Establishing topping mix proportions (in this case, fiber-reinforced concrete) using enough water to hydrate the cement at a w/c of 0.26 and provide

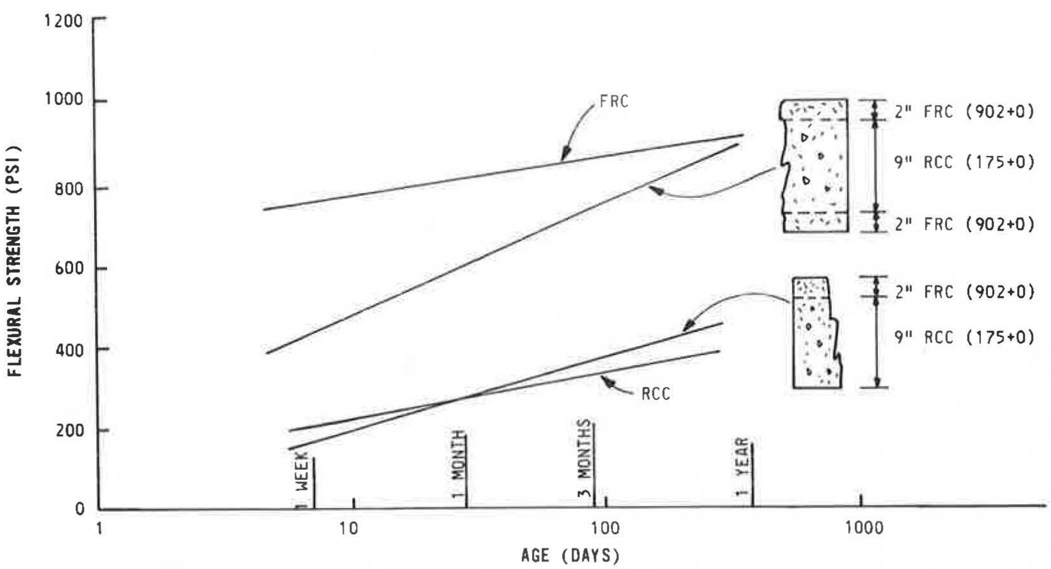

FIGURE 9 Static flexural strengths of RCC-FRC composite pavement (no fly ash).

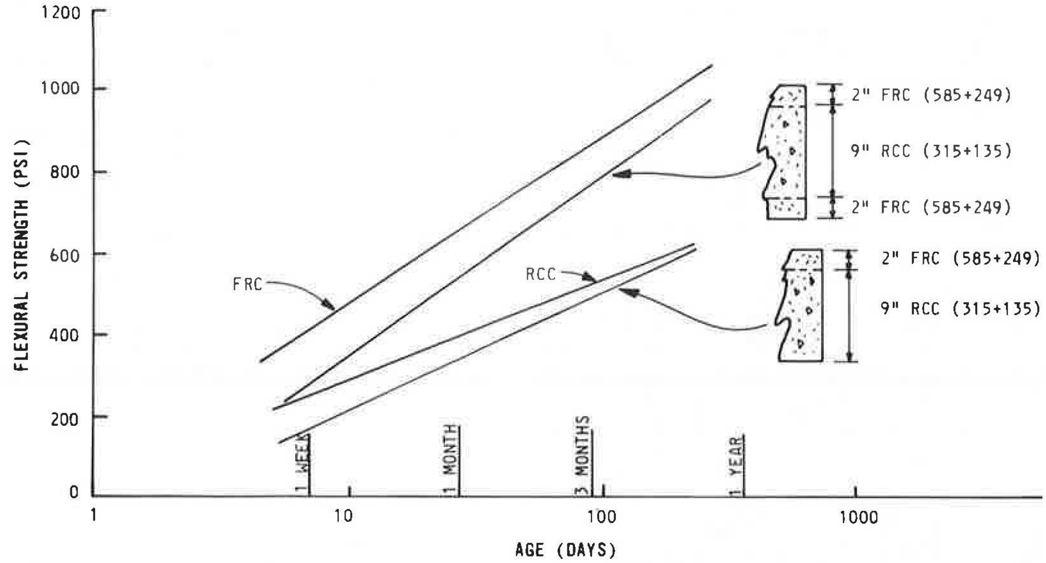

FIGURE 10 Static flexural strengths of RCC-FRC composite pavement (fly ash).

FIGURE 11 RCC topped with FRC (close up view).

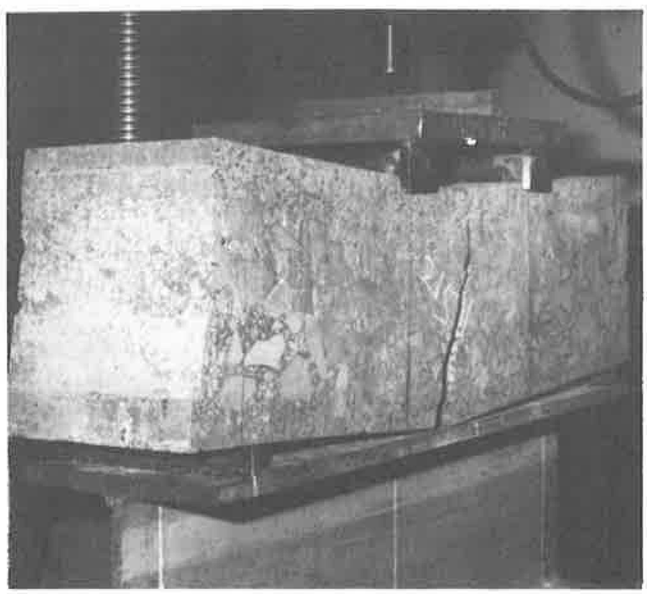

FIGURE 12 RCC topped with FRC (long view).

the same amount of total excess water per cubic yard as found for the RCC mix; and

5. Using a high-range water reducer and air entraining additive to provide approximately 5 percent entrained air and a workable topping mix with a slump that allowed it to be placed with conventional equipment.

The slabs were constructed in a manner that simulated an anticipated practical large-scale construction schedule for the system. A vibratory roller compacted the RCC and the FRC was placed with a vibrating screed. The RCC had been compacted for about 4 hr when the top lift of FRC was placed. No cleaning, bonding, or special treatment was performed except for keeping the lift surface damp as would be accomplished with a standard water truck during construction. In practice, the FRC could be placed immediately after rolling the RCC or probably as late as 6 hr, depending on temperature.

The sandwich panel section with top and bottom lifts of FRC requires an additional pass of the vibrating screed to place it. Paving equipment already exists that has demonstrated excellent ability to place thin FRC sections in a production situation. Because of the high-range, water-reducing admixture, a suitable initial slump with a desired rapid rate of slump loss can easily be achieved. The interlocking effect of the fibers and the rapid slump loss (without affecting the final set time) allows dumping and spreading of the FRC over the RCC during a practical working time from about 0.5-5.5 hr after placing. This time can be adjusted with the admixture chemistry.

The sequence and timing for the different concrete mixes dictates a moving series of two or three paving operations. The same mix plant could make

FIGURE 13 RCC sandwiched between FRC.

both the RCC and FRC mixes, although in anticipated high production application, two separate plants may be necessary just to provide the material quantities. Discussions with equipment manufacturers indicate that modifications to existing paving equipment to combine the operations into an efficient single pass system handling both mixes is feasible.

A major part of the test program was concerned with potential delamination of the two mixes. This never occurred nor was it possible to force a delamination. The pavement section acted as a composite monolithic mass. Testing included flexural bending to ultimate failure, fatigue testing at a high range of loading, and long-term curl tests with the bottom of the slabs maintained in ponded water while the top dried.

Figures 5 and 6 show results of static flexure tests for the different composite paving sections and for the individual mixes. Simply topping to RCC with FRC logically did little or nothing to improve flexural strengths. However, when bending is in the opposite direction (not tested), such as would occur at the cantilevered edges and corners of pavements, a major increase in load-carrying capacity similar to that shown for the sandwich panel section could be expected. The sandwich panels showed a marked improvement in static flexural strength--almost to the point of achieving as much strength at later ages as could be expected if the expensive FRC were placed to the full depth. In reality, if it were placed in a very deep section, high internal thermal stresses due to the high cement factor may have made the usable strength of an all-FRC pavement less than that of the sandwich section.

The fatigue results shown in Figure 7 are limited, but they point toward very good fatigue endurance properties beyond those of conventional concrete pavements. Additional testing to better define the improvement and to identify whether it is the result of the FRC or if RCC by itself has good fatigue endurance should be pursued.

The curl test results shown in Figure 8 indicate no movement of any significance. The measured curl was less than 0.007 in. over a span of 4 ft in all cases and probably was within the accuracy of the test. For comparison, it is not unusual to have conventional pavement slabs curl 0.125 to 0.250 in. Occasionally, curl as much as 0.500 to 0.750 in. has been recorded. It should be noted that these values are for spans 3 to 10 times as great as those tested and involve temperature changes as well as moisture differences. The deep section and low cement factors of FRC/RCC pavements of similar spans should provide the stiffness and material properties that result in negligible field curl even at the greater spans.

CONCLUSIONS

RCC can provide an economical and rapidly placed pavement. The drawbacks to its use in airfield and highway applications can be overcome by judicious use of an integral high-strength specialized concrete such as FRC. Aggregate materials typically used for base support under a pavement can be made to less stringent requirements, mixed with a relatively small amount of cement, and used to produce a structural RCC section. A very efficient sandwich panel pavement can also be constructed with RCC and FRC, but it appears that its practicality is limited to heavy-duty pavements, large projects, and jobs having inherently poor subgrade support that would otherwise require a deep section or expensive upgrading of the subgrade.

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REFERENCES

1. E.K. Schrader. World's First All-Rollcrete Dam. Civil Engineering, American Society of Civil Engineers, April 1982, pp. 45-48.
2. E.K. Schrader. Roller Compacted Concrete. The Military Engineer, Society of American Military Engineers, Vol. 69, No. 451, Sept.-Oct. 1977, pp. 314-317.
3. E.K. Schrader and R. McKinnon. Construction and Initial Operation of Willow Creek Dam. Concrete International Design and Construction, American Concrete Institute, Detroit, Mich., June 1984.
4. American Concrete Institute. State-of-the-Art Report on Fiber Reinforced Concrete. Concrete International Design and Construction, Detroit, Mich., May 1982, pp. 9-30.
5. E.K. Schrader. Design Methods for Pavements with Special Concretes. Proc., 1982 International Symposium on Fiber-Reinforced Concrete, American Concrete Institute, Detroit, Mich., 1983.
6. E.K. Schrader and D.R. Lankard. Inspection and Analysis of Curl in Steel Fiber Reinforced Concrete Airfield Pavements. Bekaert Steel Wire Corporation, Irving, Tex., April 1983.