

AN INVESTIGATION OF THE USE OF ROLLER COMPACTED CONCRETE IN A HEAVILY-TRAFFICKED, HIGH-SPEED APPLICATION IN AUSTRALIA

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SUMMARY

This paper describes a trial of roller compacted concrete (RCC) pavement in a high-speed traffic application in Melbourne, Australia. The trial was unique because the use of RCC has been generally confined to low-speed, heavy duty applications because of the perceived difficulties in constructing it to a sufficiently high rideability standard when used as a wearing surface in high-speed applications. The construction of the pavement and problems encountered during construction are described, together with the results of acceptance testing and other tests conducted on the mix. The results of an evaluation of the characteristics of the pavement surface since 1988 are described in detail, including skid resistance, surface texture, roughness, joint and crack movement and the development of surface cracking. Changes made to the materials and construction specifications as a result of the trial, especially with respect to compressive strength, moisture content and construction techniques, are reported.

INTRODUCTION

1. A roller compacted concrete (RCC) pavement is a Portland cement-concrete pavement that is placed using construction procedures normally associated with earthworks or asphalt rather than the slipformed or formed construction techniques used for rigid concrete pavements. RCC can be considered as a construction method rather than as a new, unique material and its economic savings mainly arise from a reduction in construction costs rather than in material costs⁽¹⁾. Consequently, major pavement applications in the USA have been in low-speed, heavy duty areas.

2. Initial trials in Australia included of an overlay on a heavily-trafficked secondary road in Tasmania ⁽²⁾ and an industrial road to a power station in Queensland⁽³⁾. The Tasmanian pavement was an overlay of an existing flexible pavement and the mean roughness value of 119 c/km would be considered unacceptable in terms of accepted limits. Most of the roughness was thought to be due to poor rolling technique and the overall acceptability of the road was thought to be adequate for the industrial traffic (primarily log haulage trucks) using the road. The condition of the original road had been very poor and the use of the RCC improved the situation at minimal cost.

3. However, because of the perceived difficulties in constructing RCC to a sufficiently high rideability standard when used as a wearing surface in high-speed applications, the Victorian State Road Authority VIC ROADS trialled a 1 km

(0.6 mi) long duplication of a straight section of arterial road (Wells Road) in Melbourne, Australia. The trial, which commenced in late-1988, was carried out with the assistance of the Australian Road Research Board (ARRB) and the Cement and Concrete Association of Australia (CACA). An "all in" contract was set up providing for the construction of earthworks, drainage and pavement. The contractor appointed by VIC ROADS subsequently sub-contracted another company for the construction of the RCC portion of the pavement.

4. Full details of the initial parts of the trial are provided in Jameson *et al.*^(4,5). This paper summarises the results of the trial, including the development of the job mix, construction, the results of acceptance testing and the evaluation of the performance of the pavement - with particular reference to the surface characteristics. Amendments made to the VIC ROADS specifications as a result of the trial are also reported.

MIX DESIGN TRIALS AND DEVELOPMENT OF FINAL JOB MIX

5. An extensive series of laboratory mix design trials were conducted to assess whether proposed mixes met the specification requirements outlined in interim materials and construction specifications developed by VIC ROADS in 1988. These were largely based on the US Army Corps of Engineers⁽⁶⁾ specifications, but adapted to local conditions and materials. Of particular interest was the grading, strength and workability of the mixes⁽⁴⁾. In the process of assessing the mixes, methods were also devised for examining the influences of variables on mix parameters, for example the use of the plunger depth test to measure workability.

6. Trials were also carried out to assess the sensitivity of RCC strength and workability to changes in mix parameters (cement and moisture content), the influence of compaction on RCC strength over densities ranging from 96-100% of Modified Maximum Dry Density (MDD), the effect of delays between mixing and compaction, and whether a relationship existed between RCC strengths after one day of accelerated curing, seven days of standard curing and 28 days of standard curing.

7. The main findings were as follows:

* The compressive strength increased about by 4.5 MPa (653 psi) for every 1% increase in relative density, i.e. from about 35 MPa (5080 psi) at 96% of Modified MDD to about 53 MPa (7692 psi) at 100% of Modified MDD;

- * After 1 hour's delay between mixing and compaction the density decreased by 1%, whereas after 4 hours the decrease was 3%. Given the sensitivity of strength to density, it was apparent that RCC without set retarder needed to be compacted as soon as possible after mixing if adequate strength was to be achieved.
- * The addition of a set retarder at the recommended dose rate for concrete (0.6%) had no substantial effect on the rate at which the density decreased with delay. However, when the dose rate was increased to 1.2% of the cementitious material, the RCC could be compacted up to 2 hours after mixing without its workability being affected.
- * A 28-day strength of 40 MPa could be expected if the one-day accelerated strength reached about 25 MPa. A seven-day strength of about 30 MPa was required in order that a 28-day strength of 40 MPa could be confidently reached.

8. Following this evaluation, three mixes were submitted by the contractor to VIC ROADS for testing. Details of the final job mix selected by the contractor are as follows.

Aggregate Grading: The grading of the mix, shown in Fig. 1, was coarser than that specified; however, a preliminary field trial of the mix indicated that the mixture was reasonably workable.

Crushed Rock: The crushed rock, which formed 85% of the total aggregate, complied with the VIC ROADS' specification for Class 2A crushed rock except for grading.

Sand: The sand, which formed 15% of the total aggregate, was a "washed" product. The figure of 15% was considered to be an optimum value; less sand made the mix too unworkable, whilst the addition of more sand tended to make the final mix too fine compared to the grading envelope.

Cement: It was decided that 320 kg/m³ (20 lb/ft³) of cement was necessary in order that the specified compressive strength of 40 MPa (5805 psi) could be obtained, even though tests on cylinders had suggested that the minimum required strength could be obtained with a lower cement content. (The compressive cylinder strength of this mix was found to be 52 MPa (7547 psi). However, as will be discussed later, the in situ strengths were much lower than the cylinder strengths.)

Water: The target moisture content was 6%. The testing had suggested that higher moisture contents tended to reduce the stability of the mix and affect surface finish, whilst if the moisture content dropped below about 5.5% the strength was markedly reduced, leading to difficulties with compaction and a lack of sufficient moisture to hydrate the cement.

DESCRIPTION OF TEST SECTIONS

9. The cross-section of the test pavement is shown in Fig. 2. The total width of RCC of 7.7 m (25 ft) comprised two 3.5 m (11.5 ft) wide lanes, a 0.5 m (1.6 ft) wide outer shoulder and a 0.2 m (8 in) wide inner shoulder. Pavement thickness design was based on the fact that the pavement would be subject to traffic operating at speeds up to, and possibly in excess of, 100 km/h (60 mph). The design traffic of 1.4×10^7 commercial vehicles over a design life of 30 years was derived from local traffic counts, predicted growth rates and axle load spectra obtained from Victorian CULWAY weigh-in-motion sites.

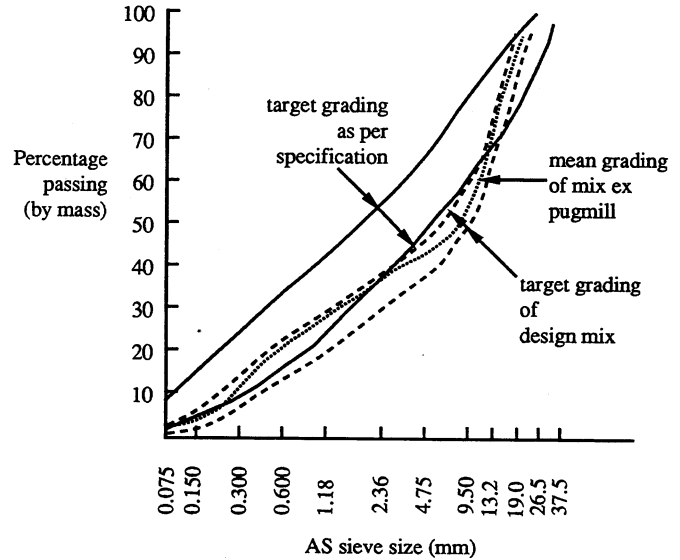


Fig. 1 - Comparison of grading envelopes of job mix and initial VIC ROADS specification with mean grading of mix ex pugmill

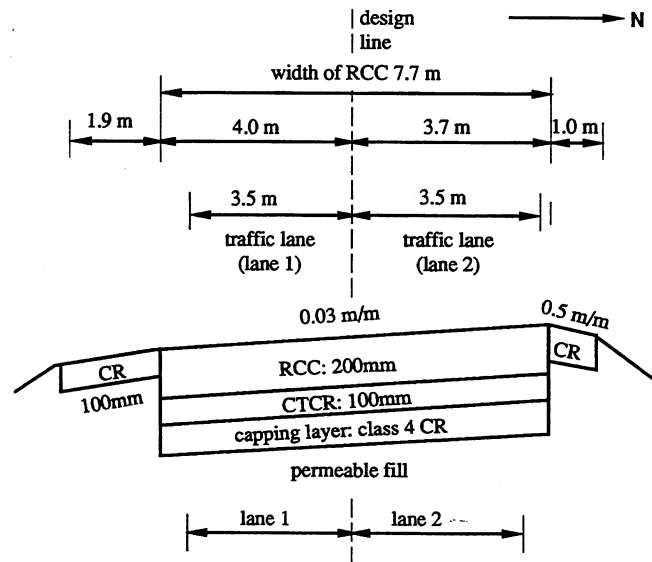


Fig. 2 - Cross-section of test pavement

10. The thickness of RCC base, derived using NAASRA⁽⁷⁾ for a flexural strength of 4.5 MPa (650 psi) and an effective design subgrade CBR of 21%, was 180 mm (7 in); 10 mm (0.4 in) was added for construction tolerances and another 10 mm because the shoulder was only 0.5 m wide (no correction is necessary if the shoulders are > 1 m (3.3 ft) wide). This corner load adjustment was similar to amendments to concrete thickness design made in the UK, the USA and the Roads and Traffic Authority, NSW at about this time. This design was checked against the fatigue criteria considerations reported by Tayabji and Halfpenny⁽⁸⁾, and a thickness of about 180-190 mm resulted. A thickness of 200 mm (8 in) was adopted in view of

the above, and the fact that the minimum recommended thickness of jointed unreinforced concrete roads is 200 mm in order to ensure effective load transfer by aggregate interlock at contraction joints.

11. The RCC base was placed on a 100 mm thick, 4% cement-treated crushed rock (CTCR) sub-base, a capping layer of Class 4 crushed rock and an imported sand subgrade. The capping layer was installed to provide a working platform for the placing of the sub-base because of stability problems of the sand subgrade in some areas.

12. Fig. 3 shows a plan view of the pavement, including the different construction methods used, and the nominal location, by chainage, of the various construction treatments adopted. The numbers on the Figure represent the "lots" used for acceptance testing, which corresponded to a day's paving.

CONSTRUCTION OF THE PAVEMENT

Material Production

13. The concrete was mixed on site using an Aran ASR 280B pugmill. The crushed rock and sand were fed into separate bins in the mixer using a rubber-tyred loader and the cement was fed directly into the pugmill from a hopper incorporated in the mixer. The water was sprayed directly into the pugmill from a supply tank incorporated in the mixer. The crushed rock, sand and cement feeds were regulated using gate controls on the mixer, whilst the rate of water supply was controlled by adjusting a tap without a flow meter. The mixer was calibrated at the commencement of each day's production in order to check the material proportions and to make allowance for any changes in the moisture content of the component materials. The final mix was loaded into tandem tipper trucks via a gohopper in order to reduce segregation whilst loading the mix and transporting it to the nearby paving site.

Construction Methods

14. In view of the VIC ROADS concerns regarding the suitability of RCC for high-speed traffic, and the possible debonding of the layers, five construction methods were trialled:

- * single 200 mm (8 in) thick layer with a dry longitudinal joint;
- * two 100 mm (4 in) thick layers with no slurry between the layers and a fresh longitudinal joint;
- * two 100 mm thick layers with slurry between the layers and a fresh longitudinal joint;
- * two 100 mm thick layers with no slurry between the layers and a dry longitudinal joint; and
- * two 100 mm thick layers with slurry between the layers and a dry longitudinal joint;

15. The order of paving was the same whether dry or fresh joints were used; however, a fresh joint signified that adjacent layers were placed within 1 hour of each other, whilst, for dry joints, at least 1 hour's delay occurred between the placement of layers. All construction was carried out "half width" because the paver used had a maximum width of only 5.5 m (18 ft).

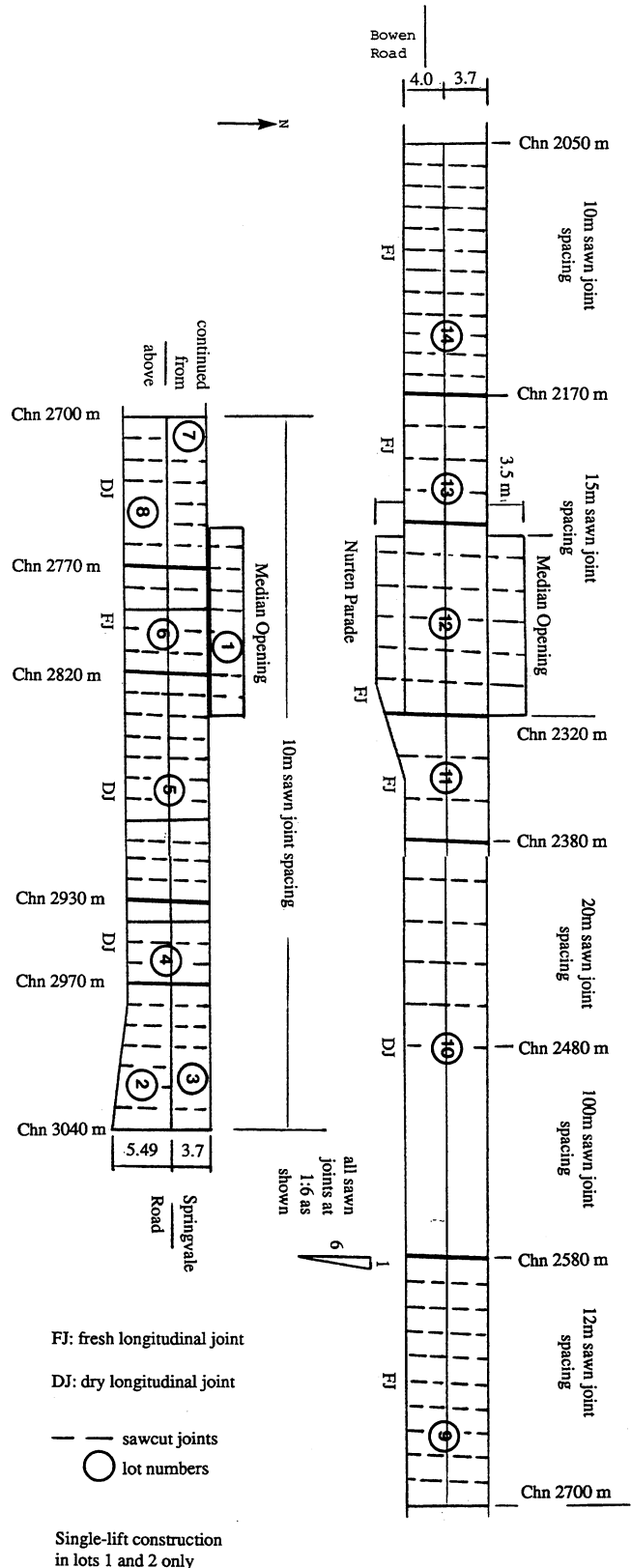


Fig. 3 - Plan view of test pavement

16. The concrete was placed using an ABG Titan 280 paver, which is a heavy duty tracked machine having a single tamping bar and vibrating plate to effect compaction. The concrete was compacted to about 80-85 per cent of MDD as it came out of the paver. Final compaction was achieved with an Ingersoll-Rand DD90 twin drum vibrating roller (9 t static load; 15-20 t in vibration) and a rubber-tyred multi-wheel roller.

17. Contraction joints were constructed at 10, 12, 15, 20 and 100 m (33, 39, 49, 66 and 328 ft) intervals in order to evaluate the most economic joint spacing (see Fig. 3). The joints, which were angled at 1:6 across the pavement to assist in load transfer, were sawcut to one-third the concrete thickness 24 hours after the placement of the concrete and temporarily sealed. Approximately 28 days later the sawcuts were widened to accommodate the permanent seal, which was either neoprene rubber or extruded silicone. The neoprene rubber was used in the joints spaced at 10 and 12 m, whilst the extruded silicone was used in the wider-spaced joints.

18. The pavement was cured with water for the specified seven days. The only source of concern was that the curing water affected the fresh concrete being laid adjacent to the areas being cured and some minor damage was caused by the truck travelling over material less than 24 hours old. The curing also affected the temperature gradient within the RCC measured using within-pavement thermocouples.

Problems Encountered During Construction

19. The main problems encountered during material production were:

- * variability in cement feed, resulting in inconsistency in cement content;
- * lack of control of water flow, resulting in variability in moisture content; and
- * contamination from the base of the sand stockpile.

With respect to transport, with half-width construction, the time taken for the empty truck to leave the work area, and the full truck to reverse onto the paver, caused frequent stopping of the paver and this resulted in a slowing of production and undoubtedly affected the final surface profile.

20. Several problems were encountered with the placement of the concrete. These can be summarised as follows.

- * The capacity of the paver was insufficient for a single 200 mm thick lift of the RCC; the paver was unable to feed the material across the full width of the screed and produce a uniformly dense mat of concrete. This resulted in an uneven profile and differential compaction of the placed material, necessitating reinstatement in some areas. The majority of the job was therefore placed in two layers. The rideability of the surface over most of Lot 2 (paved single lift) was unsatisfactory and most of it was subsequently cold planed and overlaid with asphalt to improve the riding surface.
- * The auger was not fitted with a flicker paddle to mix material inwards near the central gearbox housing and an area of low fines developed in the middle of the paver run and the concrete segregated. This resulted in the formation of a longitudinal crack in the middle of each lane over the length of most of the pavement.

- * The edge of the concrete mat broke away because it was unconfined at the edges. This was particularly noticeable with the single-layer construction.
- * The presence of segregated and dry RCC at the bottom of the layers, dropped from trucks when loading material into the paver hopper, prevented full compaction being achieved and hindered bonding of the two layers.
- * The vibrating roller could not compact right up to the previously-laid work without causing damage. A vibrating plate was used to compact the material in these locations, but full compaction could not be achieved.
- * The unsupported edge tended to "roll off" and break away under the action of the roller.
- * Variations in the moisture content of the mix hampered compaction. A dry mix is difficult to compact; a wet mix flows easily but inadequate rideability can result.

21. With respect to jointing, the sawn dry transverse joint at the end of the previous day's paving was damaged during the construction of the next section of the pavement. Problems were also encountered cutting and rolling against cold and semi-fresh longitudinal joints. The edge of the previously-laid concrete was often damaged and the integrity of fresh concrete destroyed. No problems were encountered with fresh longitudinal joints. However, the use of fresh joints resulted in more frequent transverse construction joints with the associated problems regarding paver capacity outlined above.

22. The concrete also tended to fret away from the sawn transverse construction joints, necessitating repair prior to joint sealing. The timing of the sawcutting was found to be critical, with 20 to 30 hours after placement being the optimum delay for the mild weather existing during the trial.

RESULTS OF TESTING DURING MANUFACTURE OF RCC

Grading

23. The contractor nominated a grading coarser than that specified and had difficulties in keeping within the nominated envelope, especially in the 0.425-0.300 mm range, where the grading was generally finer than the approved grading envelope, but closer to the original VIC ROADS specification.

Cement and Moisture Content

24. Fig. 4 compares the cement and moisture contents of 34 samples of the mix taken from the pugmill with the specification. Only 15 of the 34 samples tested were within the tolerances for both moisture content (target of $6.0 \pm 0.5\%$) and cement content (nominated by the contractor as 13%, with VIC ROADS tolerances of $\pm 2.0\%$, -0.5% from this level). The contractor's control over moisture content was unrefined, resulting in widely varying results, even during a day's production.

25. The cement contents ranged between 11% and >17%, with fluctuations of 3% common during a day's production.

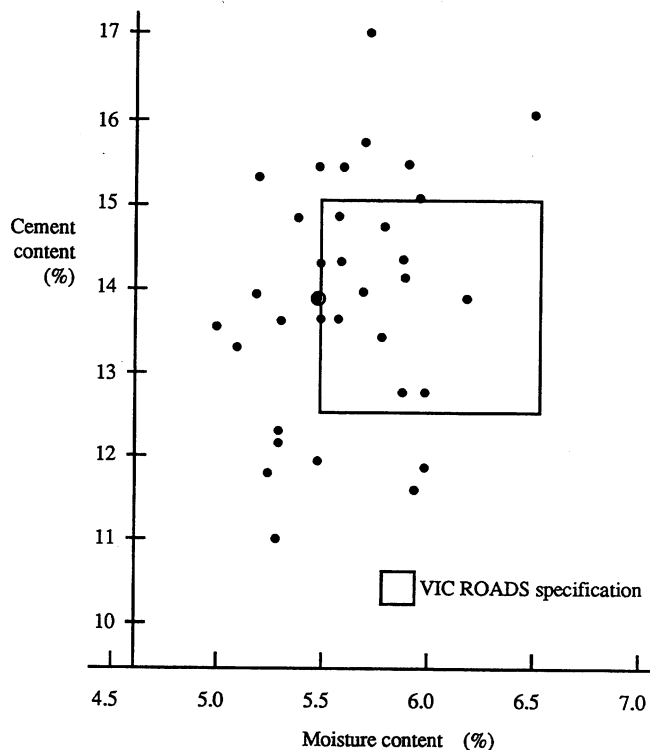


Fig. 4 - Comparison of cement and moisture contents of mix ex pugmill with VIC ROADS specification

Whilst the control on cement feed was generally good, settlement in the hopper overnight resulted in bulking in the cement and this made it difficult to control the flow rate at the commencement of each day's production. It is also necessary to keep the hopper topped up, because the fresh cement, when delivered, is aerated and hence it flows more easily than the cement stored in the hopper.

Compressive Strength

26. Cylinders for compressive strength testing were cast using material from the paver hopper and compacted to 98% of Modified MDD in order to be consistent with the testing carried out during the mix assessment and the specification requirements. The mean compressive strength after 28 days was 47.3 MPa (6865 psi), well above the specified mean value of 40 MPa (5805 psi), and on all days the mean cylinder strength exceeded the 40 MPa criterion. The mean strengths after one and seven days were about 80 and 90% respectively of the 28-day strengths.

27. Regression equations were generated relating moisture content and compressive strength after one, seven and 28 days and the compressive strengths at a moisture content of 6% were 36.8, 44.0 and 48.9 MPa respectively and a 1% variation in moisture content resulted in a 12.5 MPa change in strength. Regression equations were also generated relating compressive strength, moisture content and relative compaction in order to assess if the latter two variables had a statistically significant affect on the compressive strength. Moisture content was a significant factor in all three cases, but relative compaction was not significant within the range tested. This was probably due to

the fact that the range of relative densities was small (95.4-99.0%), as the aim was to compact to 98% Modified MDD. The results suggest that testing after one day's accelerated curing is not a very reliable indicator of the 28-day strength, because the variation in strength with changing moisture content is not as pronounced as at seven or 28 days.

28. In view of the effect of changing moisture content on compressive strength, VIC ROADS retained the minimum 28 day compressive strength as 40 MPa in their revised specification but stipulated that the test be carried out at 0.5% dry of OMC rather than at OMC, because this is closer to the moisture content at which RCC is typically placed.

Flexural Strength

29. Flexural strength testing was conducted on 22 beams cast on site with a vibrating hammer and also on five beams cut from the pavement in Lot 2. The age of the cast beams at testing varied between 31 and 40 days (average 35 days). The mean flexural strength of the cast samples at 98% MDD and a mean moisture content of 5.9% was 5.6 MPa (813 psi) (standard deviation of 0.5 MPa (73 psi)), compared to the mean 28-day compressive strength of 47.3 MPa (6865 psi). The mean flexural strength of the five beams cut from Lot 2 (single lift) was 5.5 MPa (standard deviation 0.7 MPa), but if one low value (4.4 MPa) is ignored, then the mean value was 5.8 MPa (standard deviation 0.3 MPa).

30. In concrete pavement thickness design, the typical relationship used for converting 28 day compressive strength (C_{28}) results to 90 day flexural strength (F_{90}) is⁽⁷⁾:

$$F_{90} = K(C_{28})^{0.5}$$

An examination of the flexural strengths of the beams cast at the site suggested that, at 98% of MDD, the flexural strength was about 5.6 MPa. For a mean value of F_{28} of 5.6 MPa, and a mean value of C_{28} of 47.3 MPa, the value of K , assuming an exponent value of 0.5, is 0.81. Assuming that $F_{90} = 1.1(F_{28})$, then the relationship between F_{90} and C_{28} at Wells Road therefore is:

$$F_{90} = 0.89(C_{28})^{0.5}$$

31. If a mix is approved with a mean 28 day compressive strength of 40 MPa, then the characteristic compressive strength ($x - 1.38(SD)$) of cores taken from the pavement, assuming a coefficient of variation of 15%⁽¹⁾, would be 31.7 MPa. The corresponding characteristic flexural strength for thickness design, using the above equation, would therefore be 5.0 MPa, compared to the flexural strength value of 4.5 MPa used in the Wells Road pavement thickness design.

32. The data suggest that it may be possible to lower the mean compressive strength, and hence the acceptance criterion, by about 5 MPa and still achieve an in situ characteristic flexural strength of 4.5 MPa.

RESULTS OF TESTING OF RCC CORES

Acceptance Testing

Core Length

33. The specification provided for the job to be accepted at full payment, reduced payment or rejected based on the mean

difference between the design and constructed thickness. For example, when the thickness was 10 mm below the design level, 85% of the scheduled rate would be paid for that section of the works.

34. The results, given in *Table 1*, show that the specification was not fully met, in terms of payment, in only one of the 14 lots (Lot 1), viz. a mean departure greater than 5 mm (0.2 in) less than the required thickness. However, although the mean thicknesses were satisfactory, the high scatter in the results (typical standard deviation of 15 mm (0.6 in)) resulted in a substantial proportion of the pavement being more than 10 mm (0.4 in) below the design thickness.

35. As a result of this testing, VIC ROADS revised their specification in terms of a characteristic thickness departure. On the basis of the revised specification, three lots would have been rejected, seven lots accepted at full payment and four lots accepted at a reduced rate.

36. The CTCR sub-base was placed with a grader which spread the material after it was dumped from trucks and it is probable that some of the variation in thickness of the RCC was due to a variation in surface levels on the surface of the sub-base. It would be more desirable for the CTCR to be placed with a paver.

Core Strength

37. The cores were laboratory cured and tested after 28 days and the results used to calculate characteristic strength. Lots were accepted or rejected according to a similar payment scheme adopted for thickness.

38. Only two of the lots tested met full payment requirements (*Table 1*). Some of the low results were due to the location of the sample sites being biased towards the longitudinal construction joint between the two lanes and the edges. The compaction was lower near the longitudinal construction joints because of a lack of edge support in the cases when the adjacent lane had not yet been constructed.

39. Another factor influencing the low strengths was that the densities achieved in the second week were about 3% lower than those in the first week, corresponding to a decrease in strength of about 12 MPa (1742 psi).

40. The 28-day cylinder and core strengths were compared with the corresponding saturated surface dry density and it was found that, for a given density, the cylinder strengths were 10-15 MPa higher than the core strengths, i.e. about 30% and 20% lower for the two-layer and single-layer construction respectively. This difference may have been influenced by the fact that the cores were cured in the field for the first seven days, whereas the cylinders were cured in the laboratory. Both the cores and the cylinders were cured in the laboratory for the remainder of the curing period.

41. It may not be appropriate to test for compressive strength of a "composite" core consisting of two separate layers, because the stresses induced at the interface of the two layers produce a failure mode different to that induced in a single layer.

42. As a result of the lower strengths and densities achieved near the longitudinal joint and the edges, it is considered that, in future works:

Table 1
Variation in Length and Compressive Strength of RCC Cores

Lot No.	Core Length (mm)			Compressive Strength (MPa)			
	Mean	Std Dev.	Mean Dep.	Mean	Std Dev.	Sample Size	Char.* Strength
1	187.6	12.1	-12.4	39.0	6.8	10	29.7
2	213.9	13.9	13.9	38.7	1.0	10	37.3
3	213.7	19.3	13.7	39.7	5.8	10	31.7
4	205.1	13.2	5.1	44.6	7.6	6	33.3
5A	206.6	18.2	6.6)	40.3	3.0	6	35.8
5B	207.8	12.6	7.8)				
6A	210.4	11.7	10.4)	55.0	9.6	3	****
6B	207.4	6.8	7.4)				
7A	220.6	3.9	20.6)	40.7	2.9	3	****
7B	222.3	1.7	22.3)				
8	212.3	9.8	12.3	32.3	9.5	7	18.6
9	199.8	14.5	-0.2	29.5	12.2	7	11.9
10	200.9	12.5	0.9	23.8	4.5	6	17.1
11	205.3	16.0	5.3	29.0	11.5	9	12.9
12	219.5	21.2	19.5	25.4	6.0	10	17.1
13	197.5	16.9	-2.5	32.0	10.7	9	17.0
14	200.6	11.5	0.6	35.6	6.2	10	27.0

* Characteristic strength = $\bar{x} - 1.38 \text{ SD}$.

**** Most cores fell apart and could not be tested. Compressive strength values pertain to lots 5, 6 and 7, rather than lots 5A, 6A, 7A, etc.

- (a) at least 0.5 m (1.6 ft) wide RCC shoulders should be provided on both sides of the pavement unless there is an edge to compact against; and
- (b) paving should be conducted full width wherever possible provided high delivery rates of the RCC can be assured.

Density

43. Although not an acceptance criterion in the specification, both the contractor and VIC ROADS carried out extensive density testing as a means of gaining an appreciation of how well the material was being placed. VIC ROADS carried out testing using a nuclear density gauge after 24 hours and seven days with the gauge at both 150 and 200 mm in backscatter mode at a range of offsets (generally about 0.5-3.0 m) from the pavement centreline.

44. The compaction levels were generally high, with characteristic relative compactions (CRC) exceeding 100%, except in Lot 2 (one of the two single lift sections) where the CRC was about 3% lower. During the second week's paving, the CRCs determined from the cores were about 3-4% lower than in the first week, except in Lot 14. Nevertheless, the compaction of all lots exceeded 98% except at longitudinal joints and edges. Generally the lowest compactions occurred within 0.5 m of the longitudinal joint and the compaction was lower near dry joints rather than fresh joints. The lack of strength along the joint is a cause for concern given the proximity of this joint to the wheelpaths.

45. The overall mean relative compaction obtained with the nuclear gauge on the single-lift Lot 2 at 150 and 200 mm was 99.7% per cent; as the relative compaction of the top 150 mm was 100.8%, that in the bottom 50 mm was estimated to be 96.4%, a difference of 4.4%. In the two-lift construction, the density for 200 mm testing was on average only 0.3% higher than that for 150 mm testing, suggesting that uniform compaction was achieved for the two-lift construction.

Core Separation

46. For a multiple-lift construction to be structurally successful, sufficient bond must be achieved between lifts in order that they behave monolithically. Cores taken from the pavement were often found to have separated at the interface between the lifts, the rates of separation varying from 0 to 80%. The cores taken from sections without slurry or grout between the lifts separated at rates of 80, 80 and 30% for times between placement of 2, 1 and 1.5 hours respectively. The separation rates of cores removed from sites that had grout were 0% (Lots 13 and 14), 10% (Lots 12 and 13), 30% (Lot 9), 40% (Lots 4 and 10) and 60% (Lot 5). Some of these cores were, however, removed with a hand-held coring device which had a higher separation rate than the truck-mounted system used later.

PERFORMANCE OF RCC SINCE CONSTRUCTION

47. In order to evaluate the suitability of the surface of the RCC for high-speed traffic applications, skid resistance, surface texture, the development of surface cracking, crack and slab movement and roughness were monitored after construction and monitoring of roughness, crack development and skid resistance has continued since construction.

Surface Texture

48. The texture of the surface was variable, due to ravelling in the first few months of trafficking, which was in part due to inadequate compaction of the RCC when a layer was compacted without a confining edge. Nevertheless, the ravelled areas have good texture for a high-speed road, whereas the intact areas have a low macrotexture.

Skid Resistance

49. Skid resistance levels were measured with the VIC ROADS' SCRIM in November 1988, just prior to the pavement being opened to traffic, in April 1989, i.e. about five months after trafficking commenced, and in September 1992, almost four years after the pavement was opened to traffic. Testing was conducted in both wheelpaths of both lanes, at 50 km/h (30 mph) in November 1988, at 50 and 80 km/h (50 mph) in April 1989, and at 50 km/h in September 1992.

50. The results of the testing are summarised in *Table 2*. Considering the 50 km/h data first, it can be seen that, in the first five months of trafficking, the sideways force coefficient (SFC) values dropped by about 15%, with the most pronounced decreases being in the outer wheelpath of lane 1 (the slow lane) and the outer wheelpath of lane 2. Whilst only about 3% of the readings in these wheelpaths were below 40 in November 1988, this figure had increased to about 20 per cent by April 1989. These changes in skid resistance may be partially due to seasonal or day-to-day variations.

51. As the surface texture was generally variable, there was concern that the skid resistance may drop with increasing speed, and so testing at 80 km/h was conducted in April 1989. The skid resistance in the outer wheelpath of lane 1 at 80 km/h was about 16% lower than at 50 km/h, and 65% of the readings were below 40 and 4% below 30. The skid resistance dropped by about 3 points in the inner wheelpath of lane 1 and in both wheelpaths of lane 2 and overall about 30% of the values were below 40 at this speed.

52. By September 1992 the SFC had increased to close to their original values and, in two wheelpaths) increased to values in excess of 60. The standard deviations had decreased to about half their original values, suggesting that the surface had become less variable after four years of trafficking.

Development of Surface Cracking

53. Four surveys have been conducted to monitor the development of surface cracking. The first survey was conducted in December 1988, about two months after the RCC pavement was installed, whilst the latest was conducted in February 1992, more than three years later. The location and extent of all observed cracking was mapped onto a plan of the pavement.

54. *Fig. 5* shows the development of cracking in the lot where the transverse joint spacing was 100 m, these being typical of the behaviour observed. The main features of the cracking are as follows.

- (a) The longitudinal cracking along the length of the middle of each lane which developed shortly after construction. As already discussed, this was probably caused by the segregation of the mix near the central auger bearing housing of the paver.

Table 2
Skid Resistance of RCC Surface Measured with SCRIM

Nominal Speed (km/h)	SFC Value	RCC				Asphalt			
		Lane 1		Lane 2		Lane 1		Lane 2	
		OWP	IWP	OWP	IWP	OWP	IWP	OWP	IWP
November 1988									
50	mean	55.5	61.5	55.5	55.4				
	std dev.	8.6	10.5	10.2	7.7				
	n	170							
April 1989									
50	mean	44.8	54.7	45.1	53.1	53.1	62.9	51.2	62.7
	std dev.	6.2	9.7	6.6	7.8	5.1	4.9	3.4	6.0
	n	186							
80	mean	37.7	51.1	42.8	50.1	45.9	60.3	54.1	61.8
	std dev.	5.9	9.3	7.1	7.6	6.2	4.0	3.4	4.9
	n	187							
	% <40	65	12	31	8	14	0	0	0
September 1992									
50	mean	60.1	59.0	53.8	62.0				
	std dev.	4.0	3.9	5.2	4.3				
	n	186							

n = sample size.

- (b) Reflection cracking along the pavement centreline, at the transverse sawcut joints and at the transverse construction joint in the section overlaid with asphalt (50 mm thick). This occurred about six months after the overlay was constructed.
- (c) Transverse cracking developed at approximately 3-4 m intervals in most sections where the spacing of the sawcut joints was 10 m, and also in the section with sawcut spacings of 12 m. This cracking, which developed under trafficking, probably resulted from the lack of bonding between the two 100 mm (4 in) thick layers and the presence of the longitudinal crack in the middle of each lane, which effectively resulted in the formation of long, narrow slabs. A similar pattern occurred in the sections with sawcut spacings of 20 m (66 ft) and 100 m (328 ft) (e.g. Fig. 5), but some of this cracking is shrinkage cracking rather than structural cracking because it occurred prior to trafficking.
- (d) No transverse cracking occurred between joints in the last section of the job constructed during the first twelve months of trafficking and there was no longitudinal centreline cracking between the lanes as it was a fresh joint. However, longitudinal cracking occurred along the middle of each lane.
- (e) As already mentioned, the sawn dry transverse joint at the end of the previous day's paving was damaged during the construction of the next section of the pavement. Problems were also encountered cutting and rolling against cold and semi-fresh longitudinal joints.

Joint and Crack Movement

55. Prior to trafficking, four transverse sawcut joints were assessed for traffic-activated movement in October and December 1988 using a crack displacement transducer⁽⁹⁾. The transducer is mounted across the crack and displacements, if any, are measured as the edge of the rear wheels of a rigid truck travelling at a speed of about 1 m/s passes within about 300 mm of it. No significant movement was detected in the horizontal direction (typically <20 micrometre) and no movement was detected in the vertical direction.

56. A further evaluation was conducted in December 1988 at three locations where cracking had occurred after construction. Once again, no movement was detected and it was concluded that, at the locations tested, the pavement, although cracked, was behaving as a continuous surface at the time of testing.

57. A third survey was conducted in February 1989 at transverse joints at locations where partial deflection gauges were also installed. Almost all of the total movement consisted of the shear component, i.e. the slabs on each side of the joint moving "along" each other. There was only a small relative vertical component of movement, i.e. both slabs moved downwards, but by almost equal amounts.

Slab Displacement Near Transverse Joints

58. Partial deflection gauges (PDG) were installed at three locations near transverse joints in February 1989 in order to assess, and quantify, the suspected debonding of the RCC

layers. The gauges were installed to depths of approximately 150 mm, i.e. nominally in the middle of the lower RCC layer. Displacements were measured when the dual wheels of a rigid truck loaded to 80 kN on the rear axle passed near the gauges. The data indicated Lot 5 (two lifts with grout, four hours between placement) lost bond between the lifts, Lot 7 (two lifts without grout, one hour between placement) maintained bond and Lot 9 (two lifts with grout, 1.5 hours between placement) lost bond. The displacements between the layers under each axle were very similar, indicating a lack of slab support, because the rear axle was loaded to 80 kN and the steer axle to about 55 kN. This finding is similar to that obtained when the de-bonding behaviour of cement-treated layers was evaluated at the Accelerated Loading Facility (ALF) site at Beerburrum, Queensland⁽¹⁰⁾.

Roughness of RCC Surface

59. Three surveys of the profile of the RCC surface have been conducted with the ARRB Laser Profilometer since construction. The Profilometer measures the longitudinal profile in both wheelpaths and mid-way between the wheelpaths and the data are analysed using a "quarter-car simulator" to produce roughness values in terms of the International Roughness Index (IRI). These values can in turn be related to NAASRA roughness in counts/km.

60. Table 3 summarises the results obtained from the three surveys. Suggested roughness tolerances for new pavements are as follows:

1-60	: acceptable
61-80	: provisionally acceptable
81-120	: unacceptable
>120	: exceeds tolerable limit

Lots 2 and 3 had initial roughness values over 200 counts/km and had to be overlaid with asphalt (hence the lower values in Runs 2 and 3). Of the other 10 lots, only Lot 10 would be (just) acceptable on the basis of the above tolerances, Lots 9 and 13 would be provisionally acceptable, and all the other lots would be unacceptable, including Lot 11, which exceeded the tolerable limit.

61. It is also clear from the results that the roughness along the pavement was very variable, with high coefficients of variation (CV) in each lane. The dramatic increase in roughness in Lot 4 between 1990 and 1991 also suggests that this section eventually lost bond even though a grout had been installed between the lifts.

62. Generally the values were an improvement on that achieved on both the Tasmanian pavement, where the average roughness was about 119 counts/km, and the trial sections on the Queensland pavement, where the mean values were 114 and 144 counts/km. The mean roughness of the final pavement in Queensland was lower, being 79 counts/km, which indicated the relationship between construction experience and roughness. Even with this improvement, however, the roughness value barely made the provisionally acceptable range.

FOLLOW-UP TRIAL

63. In January 1990 a second trial was undertaken in an access road along Brew Road, Tynong, near Melbourne, using the revised specifications and construction practices to attempts to improve on the Wells Road pavement. The pavement was 7 m wide, and the RCC base, 200 mm thick, was constructed in two 100 mm thick layers on 120 mm of a 3% CTCR sub-base and a clay subgrade of design CBR 5%. The sub-base was placed by grader and surfaced with a 5 mm aggregate seal to

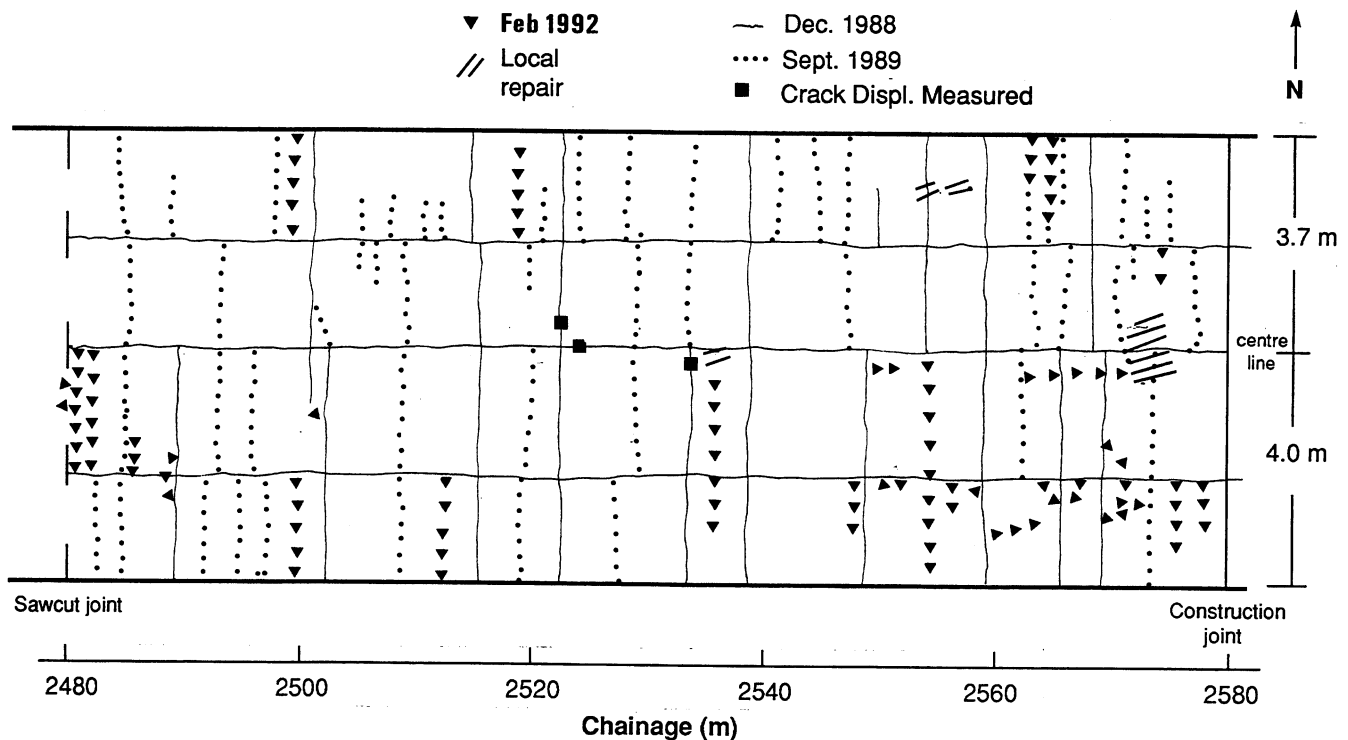


Fig. 5 - Crack development in lot having transverse joint spacing of 100 m

Table 3
Summary of Roughness Surveys

Lot No.	Chainage (m)	No. of Lifts/ Grout?	Time Between Lifts (h)	Length (m)	NAASRA Roughness (counts/km)											
					Run 1				Run 2				Run 3			
					$\bar{x}$	SD	CV	n	$\bar{x}$	SD	CV	n	$\bar{x}$	SD	CV	n
2	2970-3040	1		70	277.6	143.1	52	12	53.6	14.4	27	18	53.2	6.3	6	12
3			1.5													
4	2930-2970	2/yes	48	40	85.2	26.8	32	6	90.4	24.8	27	6	115.0	39.1	34	15
5	2820-2930	2/yes	4	110	89.7	34.7	39	20	90.0	25.3	28	30	94.9	30.4	32	50
6	2770-2820	2/no	2	50	83.9	25.5	30	8	86.2	18.1	21	12	82.7	21.5	26	20
7,8	2700-2770	2/no	1-1.5	70	94.0	38.1	41	12	84.3	27.6	33	18	95.2	40.2	42	30
9	2580-2700	2/yes	1.5-4	120	64.4	18.5	29	22	66.0	18.8	29	36	63.6	19.8	31	55
10(a)	2480-2580	2/yes	19-25	100	60.8	19.9	33	18	63.7	14.6	33	30	63.7	13.4	21	45
10(b)	2380-2480			100	60.9	14.3	23	18	58.1	7.3	13	30	57.5	15.2	26	45
11	2320-2380	2/yes	12-52	60	160.7	65.2	41	10	142.9	24.1	17	18	149.6	59.5	40	25
12	2230-2320	2/yes	18-65	90	87.5	32.5	37	16	85.4	26.1	31	24	89.7	33.3	37	40
13	2170-2230	2/yes	21-42	60	74.1	54.5	74	10	58.9	17.0	29	12	65.9	36.5	55	25
14	2050-2170	2/yes	7-18	120					57.1	8.4	15	30	62.1	20.8	33	55

Run 1: 13/10/1988 One Profilometer run in both lanes.
Data for Lots 2 & 3 prior to asphalt overlay.
No data taken on Lot 14.

Run 2: 30/08/1990 Three Profilometer runs in both lanes.
Data are mean of the 3 runs, averaged over 20 m lengths.

Run 3: 22/08/1991 Three Profilometer runs over Lane 1; two runs over Lane 2.
Data are mean of the runs, averaged over 10 m lengths.

establish uniform texture and thus adequate friction between the RCC base and the sub-base for crack initiation at joints. Transverse contraction joint spacing was constant at 10 m.

64. Other differences between this trial and the Wells Road trial were that some flyash (64 kg/m³) was included in the mix, the pavement was constructed full width, and flicker plates were fitted to the spreading auger. In one section a cement slurry consisting of three parts cement to four parts water was applied at an approximate rate of 1.4 kg/cement/m².

65. The contractor was not experienced in this type of construction and some technical problems occurred that affected the quality of the final product. The main findings of the trial were as follows.

* Despite the pugmill having a more sophisticated water metering system than at Wells Road, moisture contents varied between 5.3 and 6.1%. This probably contributed to the variable surface texture and shape as evidenced by bony and ravelled areas and areas where roller marks were apparent. The field densities measured from cores were, however, satisfactory.

* The average cement content was 16% with values ranging from 14.5 to 18.3%, compared to the target value of

14%. This range was less than that at Wells Road; however, improvement is needed in the methods to produce a more accurate and consistent additive rate.

* Difficulties were encountered in achieving smooth, well-compacted construction joints. At the cessation of paving the fresh material was not promptly cut back and preparation of the joint when paving resumed was time-consuming and affected the finish obtained.

* Transverse contraction joints were sawn about 18-24 hours after placement and several unplanned cracks developed. The temperature during construction was higher (30-35°C) than at Wells Road and earlier sawcutting (say 6-10 hours) would have been desirable. Considerable spalling occurred and the cuts were not as uniform as at Wells Road.

* The 28 day compressive strengths varied between 19 and 41 MPa, with characteristic values of 29, 21 and 19 MPa. When adjusted to account for the field densities they increased to 36, 39 and 28 MPa, compared to the specified adjusted characteristic strength of 35 MPa.

* Core thicknesses varied between 180 and 200 mm, whilst characteristic thicknesses were 189 and 206 mm. The

automatic sensor controlling the screed level required constant attention and the stringline was not always taut.

* Ten cores were taken from the pavement where the slurry had been applied and only four exhibited any bonding between the layers.

* Roughness was measured after four months of trafficking and the overall mean of 134 counts/km was greater than the overall value for Wells Road (84 counts/km) (see para. 60) and closer to the terminal value of 150 counts/km suggested by NAASRA⁽⁷⁾. The poor rideability reflects the frequent interruption in paving and the fluctuations in screed levels.

SUMMARY AND CONCLUSIONS

66. This paper has described a trial of roller compacted concrete (RCC) pavement for high-speed traffic conducted in Melbourne, Australia, since 1988. The trial was unique because the use of RCC has been generally confined to low-speed, heavy duty applications because of the perceived difficulties in constructing it to a sufficiently high rideability standard when constructed as a wearing surface in high-speed applications.

67. Several difficulties were encountered in constructing the pavement, mainly brought about by the need to construct in half widths, constructing in a single 200 mm thick layer, and variation in the mix. It was recommended that full-width construction be used in future works and this was adopted by VIC ROADS in their revised specification and in the follow-up trial at Brews Road. More development is required in the methods of constructing dry joints and in achieving a good bond between layers.

68. The average 28-day compressive strength of the job mix was 47 MPa when cylinders were tested in the laboratory, well above the specified minimum value of 40 MPa. Subsequent testing of cores removed from the pavement, however, revealed that the compressive strength at similar density was about 30% lower than the cylinder strength for two-layer construction, and about 20% lower for single-layer construction.

69. The properties of the RCC mix were very sensitive to changes in moisture content, with workability, strength, density, surface texture and rideability all being affected. The moisture content of the mix during construction needs to be closely monitored and maintained within very tight limits because a 0.5% variation in moisture content resulted in about a 6 MPa variation in compressive strength. As a result, VIC ROADS revised their specification and it is now stipulated that testing be conducted at 0.5% dry of OMC rather than at OMC because the former is the lower tolerance limit for moisture content. Fluctuations still occurred, however, in the follow-up trial at Brew Road.

70. A 1% reduction in density caused approximately a 5 MPa reduction in strength. There was variation between the gauge densities measured in situ and those determined from cores at Wells Road. Much closer agreement was achieved at Brew Road.

71. The results of joint and slab movement and roughness surveys support the commonly used rule-of-thumb that bonding occurs if placement of RCC lifts occurs within one hour of each other, although obviously mix characteristics also influenced this. Some good results were achieved with grout between lifts as demonstrated by the good core recovery rates in several lots at Wells Road, but the deflection measurements on Lots 5 and 9 and the increase in roughness in Lot 4 indicated a loss of bond

and raises the issue as to whether the bond can be maintained over time and under traffic. Ten cores were taken from the Brew Road pavement where slurry had been applied and only four exhibited any bonding between the layers.

72. Techniques for achieving full bond for bonded overlays of conventional concrete pavements have been developed and are widely in use. This suggests that full bonding of RCC lifts can also be achieved; however, the results to date suggest that more work is needed before multiple-lift RCC construction can be assured of achieving full bond by any method rather than the rapid placement of one lift on another (normally within one hour of each other).

73. The work described in this paper suggests that the state-of-the-art of RCC construction cannot reliably provide a pavement as smooth as conventional pavement construction techniques. Consequently, the use of RCC is probably best suited to low-speed applications or as a base layer with an asphalt wearing surface.

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