Priority Issues for Performance and Durability

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Abstract

There are many factors which influence the long-term performance of concrete pavements. They can be broadly categorised into four groups, namely thickness design, layer formats, jointing design and construction quality. Traditionally, the first two have dominated the attention of the published literature. However, in the author's experience, it is the latter two groups which dominate the performance within the first 10 to 15 years (at minimum). The key issues within these groups are joint layout (i.e. plan geometry), mix design, mixing uniformity, compaction, curing, early-age protection and joint induction. The consequence of poor construction quality is that a potentially low-maintenance asset may soon become a high-maintenance liability. Rollings (2001) has summarised all of this by stating that *"a well-built but poorly-designed pavement is likely to outperform a poorly-built but well-designed pavement"*. Too often (in the author's opinion), asset managers faced with durability problems look for exotic solutions (like corrosion protection of reinforcement) when improvements in the fundamentals of concrete construction practice (i.e. mix control, compaction and curing) would be more efficient and effective. Unfortunately, skilled craftsmen are becoming a rarer commodity and so a substantially increased training effort is needed to address the problem. This paper documents thirty years of experience to quantify the consequences of variable construction quality. It also seeks to show that the established textbook wisdom of concrete technology can be adapted in practical ways that are understood and applied by field staff.

Table 1. Nomenclature

NSW New South Wales	RTA Roads and Traffic Authority, NSW
Terms used in the paper are listed below	
American	**Australian** (1)
pavement	base (2)
base	subbase (2)
jointed plain concrete (JPCP)	plain concrete pavement (PCP) (3)
jointed reinforced concrete (JRC)(4)	jointed reinforced concrete (JRCP) (4)
subbase	select material zone (SMZ)
lean concrete base (econocrete)	lean concrete subbase (LCS)

Notes
1. Australian terminology has been adopted throughout this paper.
2. In Australia, the term "pavement" describes the combined base plus subbase (i.e. the American "pavement" plus "base").
3. Australian PCP is typically undowelled. JRC and JRCP are typically dowelled.

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Introduction

There are many components (activities) of a major paving project which will impact on the ultimate service life of the pavement, as summarised in Table 2.

Table 2. Factors which influence the performance and durability of concrete pavements

	A	B	C	D	E
	Design	**Contract documentation & management**	**Contract supervision**	**Construction quality**	**Maintenance & Latent Conditions**
1	Thickness design	Quality System (QS) documents	Enforcement of technical specifications	Support conditions (6)	Trafficking (9)
2	Joint layout design	Technical specifications	Enforcement of QS & QA requirements	Batching & mixing	Support conditions (9)
3	Format type (1)	Pavement drawings (13)	Staffing levels	Compaction	
4	Subbase type (2)	Tender assessment criteria (3)	Client standards (11)	Finishing	
5	Concrete mix design	Contractor assessment (10)	Contractor standards (11)	Curing	
6	Drainage		Supervision of subcontractors	Jointing	
7			Management priority (4)	Concrete strength (7)	
8			Testing (5)	Paving method (8)	
9			DCM & BOOT issues (12)		

Notes

1. e.g. CRCP, PCP, JRCP, SFCP
2. e.g. Lean concrete subbase, bound, cemented etc
3. e.g. price, performance history etc
4. e.g. speed, economy, quality record, environmental, OHS
5. e.g. timely, reliable and on-site
6. i.e. embankment & subgrade
7. characteristic strength, standard deviation
8. e.g. fixed-form versus slipformed
9. i.e. actual versus design
10. performance reports & prequalification rating
11. experience and/or competency standards
12. e.g. does the client want full surveillance ?
13. especially joint layout designs.

Experience (and logic) indicates that, of those which directly influence pavement performance, each exhibits a reasonably distinctive form of distress, as shown in Figure 1.

They also exhibit different time-frames for the onset of distress. For example, some jointing failures can initiate on the night of paving, but others might not emerge for 5 or 10 years.

Subgrade issues (such as differential settlement) will often initiate distress within 10 years. By contrast, a deficiency in thickness design would have to be extreme in order to initiate distress within the first 10 years.

These time-frames are represented in Figure 2.

Figure 1.1: Flexural fatigue failure

Figure 1.2: Jointing failure

Figure 1.3: Compaction failure

Figure 1.4: Settlement failure (over a skewed box culvert)

Figure 1. Common distress modes

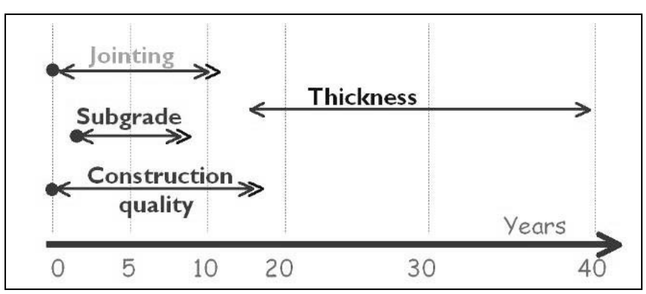


Figure 2. Typical time-frames of distress

Factors of influence on pavement performance

When studying pavement performance and premature failures, many analysts appear to focus on design and loading aspects, whilst giving little attention to the possible impact of compromises in the constructed quality.

In the author's experience, the pareto issues within the first 15 to 20 years are invariably quality-related ones, and are only rarely thickness-related.

The author's experience shows that, whilst it is possible to construct very low-maintenance concrete pavements, too often we tolerate compromised construction standards, resulting in premature distress and shortened service lives. The positive side of this is that improvement in the fundamentals is readily achievable and is certain to yield very significant benefits.

The following observations are also relevant:

(a) In the author's experience, the overwhelming majority of workers much prefer to do a good quality job than a marginal or poor one. Also;

(b) there seems to be universal agreement (at all management levels) that, in the construction field, good quality pays for itself in terms of service life, durability and life-cycle cost.

Given these attitudes, one has to question why construction standards are so often marginal or unsatisfactory. Maintenance teams understand very well the benefits of good practice, and the consequences of poor quality. They are the ones who have to repair the premature failures caused by others, and their plight is reflected in the catch-phrase *"get in, get out and stay out"*.

It is now long overdue that a similar culture be adopted in new construction; something like:

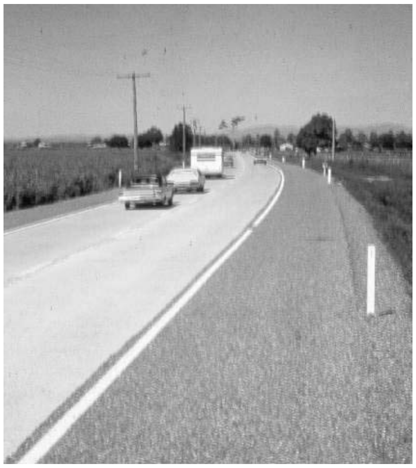
"build it for the long haul; delay the over-haul".

In NSW there are examples of concrete pavements which graphically show the value of good construction. One such example is located on the Pacific Highway 10 km north of Kempsey. There are two adjacent sections of CRCP with characteristics as follows.

Table 3. Comparison of two CRCP projects

Parameter	Stage 1	Stage 2
Construction year	1975	1985
Subgrade CBR	< 2	
Traffic (2004) (average daily, per lane)	6,000 vehicles 15% commercial	
Pavement structure	230 mm CRCP 130 mm LCS	
Paving method	fixed-formed	slipformed
Maintenance demand	Nil	Very high

As shown in Figure 3, these single carriageway pavements traverse a section of low-strength alluvial swamp and are periodically inundated by floodwaters. They share a common structural design and are subjected to exactly the same traffic.



Stage 1: CRCP constructed in 1975

Stage 2: CRCP constructed in 1985

Figure 3. Two adjacent CRCP projects

In terms of design and loading, the only difference is that Stage 1 is 10 years older. However, the difference in performance has been dramatic. Stage 1 is now 30 years old but has not suffered a single failure. By contrast, Stage 2 has required regular intensive repairs, as indicated in Figure 3 with a photograph taken at an age of 5 years.

In assessing the relevant differences, all design and traffic parameters are quickly eliminated, and the sole explanation is the significantly different standard of constructed quality. The major factors were paving practices [(2)], compaction and reinforcement cover.

The benefits of quality are readily apparent from European experience. In 1992, a delegation of American highway officials undertook a study tour of European highways (FHWA 1993). They reported that "... *European pavements are better (than American) even though European trucks are heavier and traffic volumes higher than in the US.*" One of their explanations was that "*the European emphasis is on quality and effectiveness, rather than efficiency ...*".

Influences on quality culture

An study of factors which act as impediments to the achievement of better overall standards indicates that combinations of the following factors often apply:

(i) "good" practice is not well defined in some areas;

[2] The biggest known issue on Stage 2 was significant mix segregation within the vibrator box during slipform paving.

(ii) specifications are often inadequate (and/or their intent is not complied with);

(iii) staff are frequently under-trained to distinguish between good & poor practices;

(iv) too often, it seems that *quality* efforts are relegated merely because of the greater emphasis being given to competing pressures such as *cost* and *time*. (i.e. "dollars and deadlines").

Conversely, there are various stakeholders who have a vested interest in high quality standards, and it is useful to identify those parties which are likely to influence the final outcome.

Figure 4 attempts to map the priorities of those parties with suggested alignments ranked according to their tendency towards a *project culture* (with a shorter-term focus) versus an *asset culture* (with a longer-term outlook).

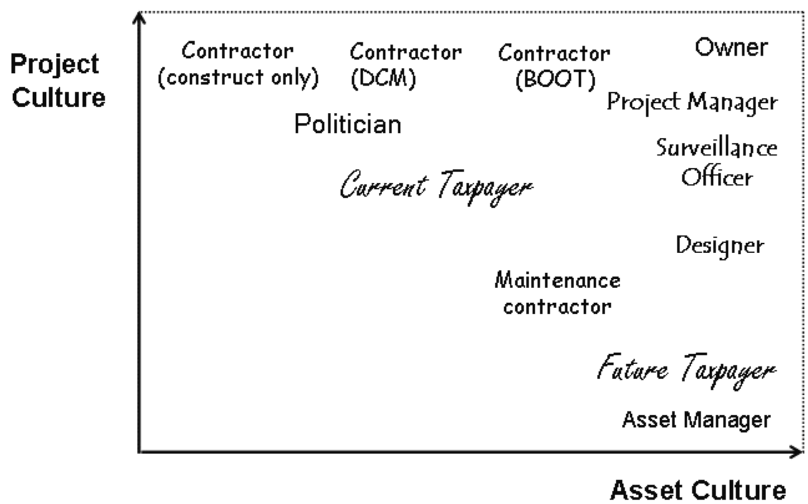


Figure 4. Mapping of Project culture versus Asset culture

Clearly, some contractors will have a relatively short-term outlook whereas an asset manager places a high priority on long-term durability. Contractors with long-term maintenance responsibilities can be expected to have different priorities, but that could depend on how long they plan to retain ownership.

A current taxpayer will be torn between the desire for economy (in order to maximise new infrastructure development) and the need to minimise maintenance. A future taxpayer (such as our children) will be critical of inheriting high maintenance liabilities rather than low maintenance assets.

The project manager is under enormous pressures from various competing interests. Figure 5 indicates the common major pressures (or key performance measures, KPM) which he/she must continually juggle. Characteristics of each KPM are summarised in Table 4.

Figure 5. The project juggler

Table 4. Typical project performance measures

KPM	Comments
Time & cost	▪ Of prime importance to all parties under the contract. ▪ Easily defined, readily measured, and constantly monitored.
EPA & OHS	▪ Mandated by legislation. ▪ Regularly audited and rigorously enforced. ▪ Large penalties apply to all parties for transgression.
Quality	▪ Definition can be vague. ▪ Application can be subjective. ▪ Consequences of compromise are poorly understood, and often won't emerge within the defects liability period. ▪ Often becomes negotiable under pressure from other KPMs. ▪ The neglected orphan, by default.
Nomenclature	KPM: key performance measure EPA: environmental protection agency regulations OHS: occupational health & safety regulations

Every party to the contract has an influence on the degree to which expediency is allowed to replace quality as the abiding ethos of our industry.

Importantly, the key group missing from the culture map (Figure 4) comprises those craftsmen who actually perform the work. Concrete has a shelf life of only a few hours and so the skill of the craftsmen is obviously critical to the constructed quality. Given that the majority of craftsmen take great pride in their work, they would seem to hold the key to future possible changes in the quality culture.

With the right training and support, it would seem possible to empower the craftsmen to do better quality work, independent of the pressures (and possible interference) from their management teams. (A cynic might even say that training is best accomplished without senior management ever needing to know about it, lest they're tempted to meddle in "managing" the associated time and costs.)

Expediency versus quality

The benefits of speed and economy are widely recognised and rewarded, and so they rarely need to be stated. Unfortunately, the benefits of quality receive less attention, and the consequences of poor quality usually don't become apparent until several years later, by which time they are rarely the responsibility of those who were involved in the original construction.

Miller (1992) states:

> *"Technological understanding of concrete is elementary. Its control is an art form. The most brilliant design depends for its success on the skill of the craftsmen dealing with the wet concrete."*

Rollings (2001) reinforces this in stating that *"the impact of a capable contractor with skilled and experienced superintendents and labourers on achieving good pavement performance cannot be over-emphasized"*.

Any home-owner who has endured the challenges of renovations will clearly understand that if you select the wrong builder, the best contract in the world won't keep you out of trouble. Conversely, if you select the right builder, you probably won't need a contract.

Rollings (2001) gives valuable lessons from airport pavement performance (and he could have been referring to NSW highway pavements) in stating:

> *"... our problems are almost never due to a thickness design error, but usually are human errors where we misuse our design tools and fail to deal adequately with site conditions, materials or construction processes ..."*.

> *"... we have ... concentrated our research and education on honing our thickness design sophistication ... but often neglect other aspects that are the source of most of our real problems in the field."*

> *"... a well-built but poorly-designed pavement is likely to outperform a poorly-built but well-designed pavement."*

In NSW, we are devoting greater effort to these issues through a range of actions such as the development of accreditation training programs for all staff involved in pavement construction, ranging from "*the craftsmen dealing with the wet concrete"* to the project managers and superintendents.

However, one of the major challenges is that many personnel come from structural backgrounds in multi-storey construction, and they bring with them practices and habits which, whilst being tolerated in that industry, are unacceptable in highway work. Engineers and project managers are as guilty as any other group. One of NSW's most experienced paving engineers states that most "high-rise" engineers require at least three months of re-training on pavements work before they are cured of their acquired bad habits.

Efforts to modify established practices (or "cultures") can therefore be very challenging, especially when those bad habits don't seem to be causing major problems.

During the task of designing training programs for paving staff, the author found it instructive to examine the factors of commonality and difference between various sectors of the concrete industry. The findings are briefly discussed here.

Figure 6. Highway pavements are more sensitive to compromises in quality than are structures.

Pavements appear to be far more sensitive to compromises in constructed quality than are structures, and concrete which might perform adequately in frame structures for decades could fail within five years in pavement slabs. This is largely related to the following issues:

(a) pavements perform in flexural fatigue, which is very sensitive to the concrete quality;

(b) the reinforcement which might be used in a pavement (CRCP or JRCP) is intended for crack control alone and does little or nothing to enhance the fatigue performance,[3] and;

(c) the probing and intense nature of truck loading is such that every single batch of marginal concrete will be heavily tested and exposed within a short period of service.

By comparison, high-rise concrete frame structures are heavily reinforced and exhibit substantial load distribution. It is therefore possible to bury many loads of marginal concrete throughout such a structure with little apparent compromise to its performance for several decades. The same standards used in highway construction will invariably results in distress within 5 to 10 years of trafficking.

In any case, is it valid to claim that poor practices in multi-storey construction are of little consequence? Some readers are likely to question such claims, and whether it really matters when buildings *"aren't falling down around us"*.

3 ~ with the possible exception of steel-fibre reinforcement.

To anyone with this view, the author recommends a web search using criteria such as “”concrete balconies” + corrosion”. The results provide hours of alarming reading.

Potter & Guirguis (1981) reported a survey on large (greater than three-storey residential) buildings in Australia indicating that 69% of the buildings showed some incidence of durability distress. Observation of work practices on recent multi-storey construction sites indicates that modern structures are unlikely to perform any better than those which are now demanding premature high maintenance expenditure.

The situation in the United States would seem to be similar. In 1987, a report by the National Materials Advisory Board stated that *“a problem exists with respect to inadequate durability of concrete in service, and its magnitude is great enough to merit nation action”* (NMAB 1987). Perusal of more recent literature suggests that little has changed since 1987.

In summary, therefore:

- there seems little justification for complacency about typical standards, and
- there is ample evidence that highway work warrants substantially higher standards than other industry sectors.

Uniformity, Homogeneity and Process control

Before moving on to specific construction practices, it is worth discussing the fundamental concepts of uniformity and homogeneity.

The major emphasis of the specification is to achieve:

- the required quality in the Works, and
- an assurance of consistency at that quality level.

The concept of uniformity is basic to the application of quality efforts and to quality assurance procedures. Surprisingly, however, it appears to be poorly understood and too rarely applied.

Compactive rolling of earthworks provides a simple demonstration, as per Figure 7.The diagram represents random unsystematic rolling patterns within a defined Lot. We will assume that:

(a) insitu density testing has been carried out at a sampling frequency and at locations (as marked) which were selected in accordance with accepted statistical procedures, and;

(b) that all tests within the Lot yielded conforming results.

Figure 7. Unsystematic rolling of earthworks

The question is: "in view of the conforming test results, should this Lot be deemed *conforming* ?

The answer is clearly "no". The process is unsystematic and hence the resulting product cannot possibly be homogeneous, and this is the most fundamental requirement of any product under a quality system such as the ISO 9000 series.

In brief:

- the product was nonconforming before any testing was initiated, and
- the actual test results are irrelevant to the issue of conformance;
- this project theoretically has two problems, viz a product nonconformance and a quality system nonconformance.

In an example like this using roller compaction, few people will dispute the disposition.

However, if we switch to the issue of internal vibration of concrete, different interpretations seem to apply. Personal observations and persistent anecdotal evidence indicates that this is exactly the way much of the concrete is placed around the World every day (with the likely exception of slipform paving), and few clients seem to raise objections.

Figure 8 is used to demonstrate the point with a hypothetical comparison between slipform and fixed-form (manual) paving.[4]

Case 1 represents compaction patterns which could be expected in slipform paving. Whilst there will be some degree of lateral variability in compaction levels, it will nevertheless be systematic, and appropriate density testing will provide a high

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4 This is not to suggest that all slipforming is systematic or that all fixed-form paving is unsystematic. The author has seen slipforming that was far less systematic than good fixed-form paving. However, it would seem axiomatic that fixed-form paving is more prone to the vagaries of different crews and individual craftsmen.

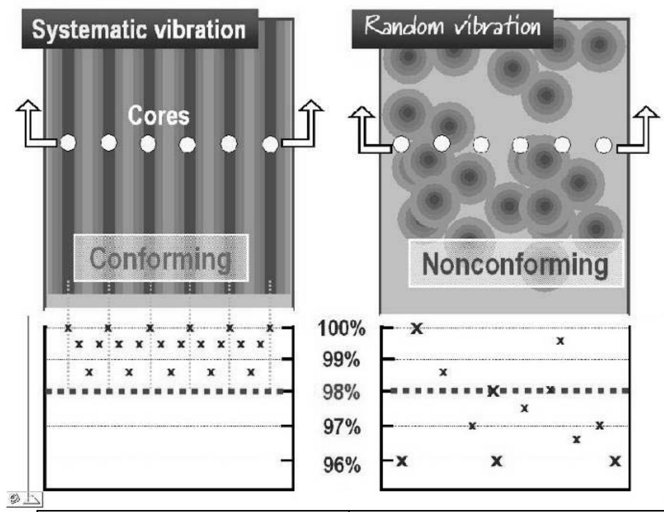
degree of assurance regarding its acceptability, assuming all vibrators are working and that paver travel speed is controlled.

Case 2 represents an example of fixed-form paving where the vibrators are inserted in a random, unsystematic pattern (and probably also for varying durations).

The differences are summarised in the lower section of Figure 8.

In essence, Case 2 involves an unsystematic process, and the results will be highly variable. In basic terms, unsystematic processes are essentially random number generators, and conventional statistical acceptance procedures become invalid.

Stated another way, the concrete in Case 2 is nonconforming at the time of paving. It will not magically become conforming upon the production of "conforming" test results, it will not become conforming at 28 days, and under a DCM contract (for example) it will not become conforming even if it survives without failure for the duration of the maintenance period.



	Case 1: compaction in slipform paving	**Case 2:** random compaction in fixed-form paving
Process	systematic	unsystematic
End product	predictable	unpredictable
Statistical testing	valid	futile, invalid
Outcome	conforming (likely)	nonconforming

Figure 8: Comparison of systematic and random vibration techniques.

Quality system documents typically contain requirements as follows:

> *"A lot shall consist of a continuous portion of homogeneous and/or representative material or end product produced under essentially constant conditions. Discrete portions of a lot which are visually non-homogeneous and/or non-representative shall be excluded from the lot …".*

Under these rules, the concrete in Case 2 should theoretically be partitioned into multiple small homogeneous lots, each of which requires discrete testing and assessment. However, given that it would be impossible to identify areas of homogeneity, such a disposition would be unacceptable, and the work should obviously be rejected.

Faced with a challenge such as this, some contractors will automatically engage a so-called "expert" to assess the concrete's *fitness-for-purpose*. Given that most specifications require *conformance* rather than *fitness*, the concept of accepting a product which is *"nonconforming but fit"* would seem an illogical and unnecessary concession. Notwithstanding, it appears to have become a fashionable concept and so it is worth considering the superintendent's options.

Given that the engaged expert was unlikely to have been present on site during the work, there appears no possible way in which he/she is able to vouch that the processes were systematic, and hence they have no grounds for certifying the homogeneity of the end product. If the surveillance staff possess archived video footage demonstrating unsystematic practices then it would seem that the expert has few options short of proposing a re-write of the fundamental theories of statistical acceptance.

As stated above, the enforcement of this fundamental concept would make life much easier for a lot of surveillance teams, and would dramatically improve the quality and performance of concrete pavements (and structures). Most importantly, if applied during the initial paving trial, it could potentially save the contractor a substantial amount of waste and expense by enforcing a review of his unsystematic procedures.

The discussion so far has centred on vibration in manual paving. This, in itself, is significant because in any major paving project there is a substantial amount of manual placement at areas such as end-of-day joints, at bridge approaches, at ramp junctions, and on bridge decks.

However, the same principles apply to many other aspects of both slipform and manual paving, and a few examples are given in Table 5.

Figure 9 provides demonstration of a case where the paving operation was "unsystematic" in some regard(s). There is an obvious area where the concrete appears to have been unusually wet at the time of texturing. This was no doubt apparent at the time of paving and should have led to a review of the production and paving operations.

Quality system documents usually cater for the issue of work which is visually non-homogeneous.

Table 5. Common systematic processes

Activity	Issues
concrete mixing	▪ is the batching systematic ? ▪ is the mixing time adequate and consistent ? ▪ is the workability (slump) consistent ? ▪ if retempering is allowed, is remixing adequate ?
compaction in slipform paving	▪ are vibrator spacings appropriate ? ▪ are all vibrators working reliably ? ▪ are all vibrators working at consistent frequency and amplitude ? ▪ is paver speed being monitored and controlled ?
compaction in manual paving	▪ is the insertion grid appropriate ? ▪ are insertion spacings appropriate ? ▪ are durations satisfactory ? ▪ is withdrawal slow enough ? ▪ is the operation of the vibrating screed systematic ?

Figure 9.1. Non-uniform concrete

Figure 9.1. Close up of non-uniformity.

Figure 9. Localised non-homogeneous concrete

The implications of the preceding discussion (based on the author's experience) is that much of the concrete which is routinely placed every day (in all sorts of applications) is unsystematic and hence is nonconforming. Under typical quality system documents, the superintendent possesses clearly defined obligations in response to a quality system nonconformance, and the contractor should be required immediately to review the paving operations.

ISO 9001:2000 : Quality management systems - Requirements

Request to be Unlocked

Details

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Abstract

ISO 9001:2000 specifies requirements for a quality management system where an organization

1. needs to demonstrate its ability to consistently provide product that meets customer and applicable regulatory requirements, and
2. aims to enhance customer satisfaction through the effective application of the system, including processes for continual improvement of the system and the assurance of conformity to customer and applicable regulatory requirements.

All requirements of this International Standard are generic and are intended to be applicable to all organizations, regardless of type, size and product provided.

Figure 10. ISO 9001 documents provide ample support for surveillance staff in pursuing uniform product from systematic processes.

Engineering variables of pavement performance.

Figure 11 shows indicative relationships between pavement life (in fatigue) and a number of key variables.

The significant difference between the two curves appears to be related to the load-damage relationship. AASHTO's 4th power law is far lower than PCA's, and its apparent insensitivity to compaction/strength appears inconsistent with observed performance.

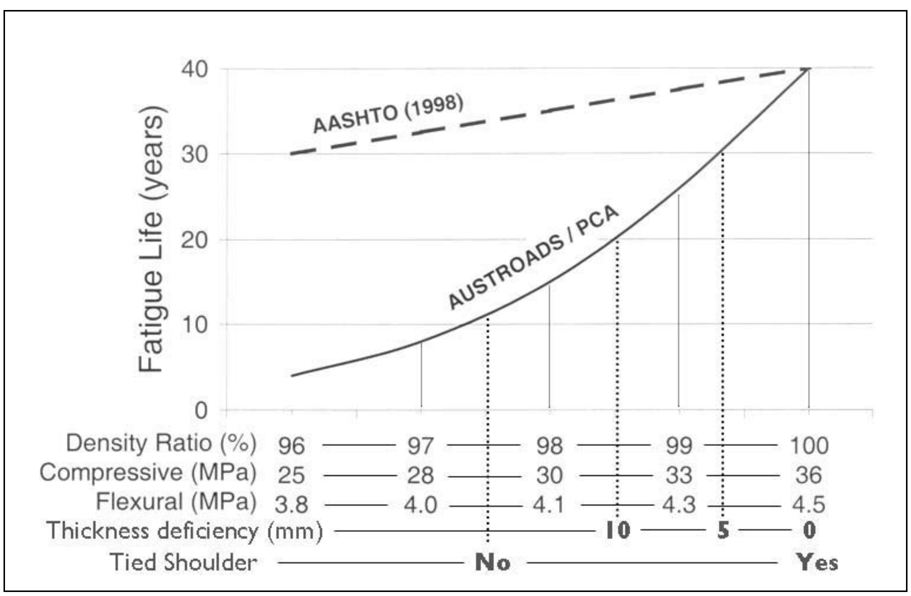

Figure 11. Key parameters of pavement fatigue life

The curves are provided merely to show indicative relationships. The x-axis values have been derived by applying the typical density-strength relationship of 6% compressive strength loss (and 4% flexural strength loss) for each 1% increase in air content. The curves have been derived by inputting the flexural strength values into the appropriate design model.

The lower-most value (tied shoulder) relates to load transfer at longitudinal joints and edges, as calculated from the Portland Cement Association (PCA) model. Rollings (2001) provides a relevant graphic example on an airfield project where edge loading led to failure soon after construction.

The Austroads/PCA curve indicates that a 1% reduction in density ratio theoretically causes a 10 to 15-year loss in fatigue life. To counter this would require a flexural strength increase of 4% (or compressive strength increase of about 6%). In a typical paving mix, this would require an increase in cement content of about 15 kg/m^3.[(5)]

Figure 11 also supports the following comments:

(a) in view of the emphasis which is typically placed on the achievement of the specified thickness, equal emphasis is warranted on insitu density;

(b) the loss of integrity of tiebars (due to under-design or pull-out failure) clearly has a dramatic impact on fatigue life, similar in magnitude to a relative density of 97.5%;

(c) in the author's experience, a relative density of 97.5% is difficult to achieve consistently without a concerted effort on the part of the paving team. NSW experience shows that paving speeds in excess of 1.5 m/min give an increased risk of nonconformance.

(d) a small increase in thickness (i.e. a construction tolerance) gives a high benefit/cost ratio (as long as the constructed quality is good.

When considered in conjunction with the various distress mechanisms shown in Figure 1, it follows that;

(e) if the constructed quality is poor, then increased thickness will give little benefit (because the distress mechanisms are different, and it would require an unrealistic thickness increase to influence that fact);

(f) in jointed pavements, thickness design and slab geometry are inseparable components, whereas many thickness designers delegate the responsibility for slab geometry to others.

In summary, thickness and quality are not inter-changeable. Both are necessary for the achievement of good long-term performance.

Clear support for these statements can be found in a number of major projects world-wide where failure has occurred during the contract period, long before the pavement was opened to public traffic. In such cases, failure occurred independent of thickness and prior to significant trafficking, as a consequence of issues such as poor constructed quality and inappropriate slab geometry. Several cases have occurred in

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[5] This is quoted merely for indicative purposes because (in the author's opinion) an increased cement content is a poor subsititute for good compaction.

NSW, Rollings (2001) reported examples in airfield pavements, and others are known in other parts of the world.[6]

Correlation between cast specimens and insitu properties

Specification typically seek to distinguish between controls relating to:

(i) the quality of materials as supplied to site
(as reflected in cylinder/beam/cube properties), and;

(ii) the processes used to incorporate those materials into the Works
(as reflected by insitu test results such as core properties).

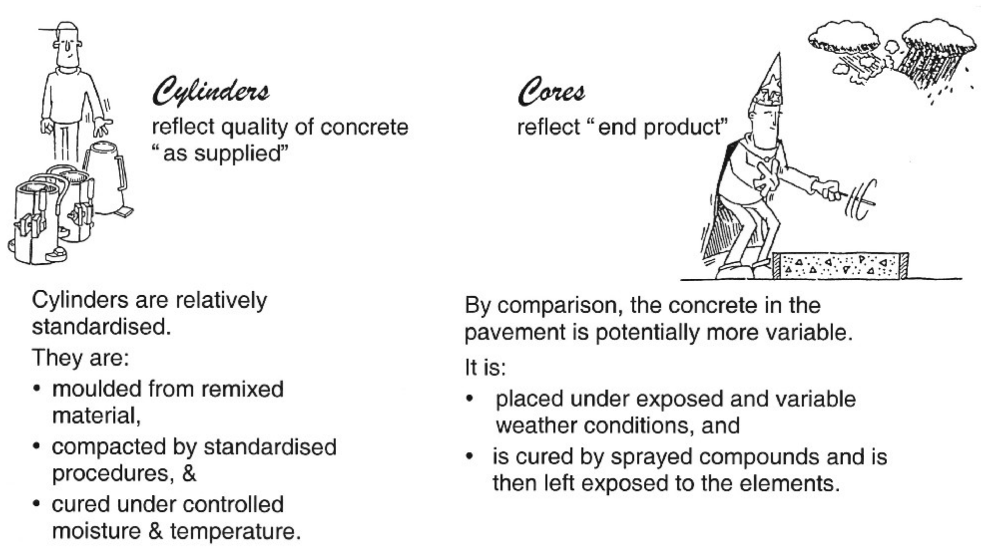

Figure 12. Comparison of cores and moulded specimens

To the maximum extent possible, NSW specifications seek to minimise the differences between the properties of the cores and those of the moulded specimens. In other words, we seek to place the concrete well, compact it thoroughly and cure it well, in the same way that Test Methods set standards for production of the moulded specimens. Too often, however, the differences are substantial and, in the absence of insitu results, the specimens would give the designer a false sense of security.

Rollings (2001) expressed concern in this regard in stating that *"unlike any other layer of a rigid or flexible pavement, there is normally no evaluation of any in-situ property of the portland cement concrete other than thickness ..."*.

Another view on this is the revealing comment by a paving inspector (outside Australia[7]) to the effect that, since the introduction of performance-related

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6 In some cases, the published conclusions regarding the cause(s) of failure were (in this author's opinion) unsubstantiated and untenable. For this reason, sources have not been quoted.

7 In the author's opinion, the use of the term "performance" in relation to moulded specimens is a naive and flawed concept which only serves to distract focus from the critical issue of insitu properties.

specifications (PRS), *"the pavement quality hasn't changed, but the cylinders and beams have improved markedly"*.

NSW paving specifications require that the specimens be moulded to a high level (substantially higher than the corresponding Australian or ASTM Standard), and then the conformance of the insitu concrete (for compaction) is based on correlation with those specimens. In other words, our specifications seek to ensure that we purchase good pavements, and not just good specimens.

Technical standards in paving operations

Mixing uniformity

Mix uniformity is a critical requirement for good concrete but is an aspect which generally appears to receive inadequate attention throughout the construction industry. The USA National Materials Advisory Board (1997), states that *"although large-scale fabrication plant and small-scale truck drum mixers have been used for years, much remains unknown about their operation and effectiveness."*

Experience with mobile mixers on NSW projects (for example) indicates that inadequate mixing is a significant and recurring issue. This experience is supported by convincing anecdotal evidence from the wider construction industry, demonstrated by the widespread confusion over the difference between "mixing" and "agitation". For example, agitation during transit is commonly but incorrectly counted as legitimate "mixing time".

Concrete is commonly defined using terms such as *"a thoroughly mixed combination of cement, aggregates and water, with or without the addition of chemical admixtures or other materials ...."*. Hence, by definition, a batch which is not "thoroughly mixed" does not constitute concrete but is merely a truck full of ingredients.

However, "uniformity" is a difficult property to assess and it remains a contentious issue even amongst experienced personnel.

Consistent production (both within and between batches) is most likely to be achieved by dedicated batch plants employing systematic batching procedures and proven mixing times but, even under these conditions, major problems sometimes occur.

Experience in Germany (Springenschmid 2001) indicates that: *"... concrete produced in continuous mixing plants resulted in the same average values and standard deviations in terms of bending tensile strength and air void content as concrete from batch mixing plants. In some cases, the standard deviations were even lower."* This is consistent with comments by the USA National Materials Advisory Board (1997) that *"... continuous processes generally yield more consistent products than batch processes."*

For fixed-form paving, mixing and transport will typically be by mobile mixers (agitators) and, because of the greater component of subjective human intervention, the potential for problems is much higher. The most likely sources of problems include variable (and/or poor) charging procedures and inadequate mixing times.

For all batch mixers, the following issues are fundamental to field control:

- *Mixing* does not technically commence until all ingredients are in the bowl, hence the charging period does not count towards effective mixing time. This is justified because some constituents may not be added until late in the cycle.
- *Mixing* must be carried out at a specified high speed and for a specified minimum number of revolutions.

  For practical purposes, this is typically converted to a specified mixing period (at the specified speed).

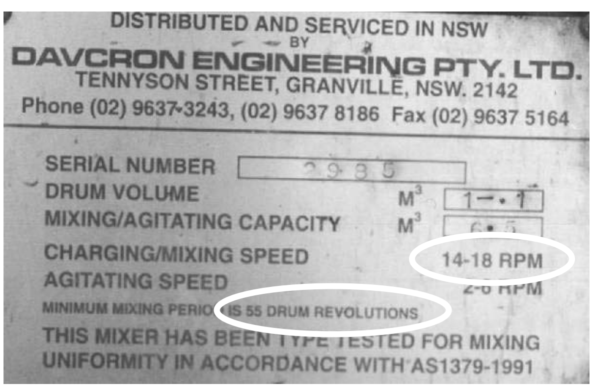
By contrast:

- *Agitation* is at low speed, typically about 4 revs/min.

  Agitation does ***not*** contribute to mixing because it is too slow to provide any worthwhile shearing or particle collision and therefore does not constitute part of the mixing period. Its action is analogous to turning over shovels full of concrete in a barrow; it merely turns over clods of concrete without achieving effective particle mixing.

  Agitation applies during transit (when higher speeds would be dangerous) and during waiting periods. Strictly speaking, therefore, the term "*transit mixer*" is a misnomer, hence the author's preference for the term "*mobile mixer*".

Figure 13 shows the certification plate on a typical mobile mixer. It shows that a minimum of 3½ to 4 minutes of mixing is required in order to achieve mix uniformity. By contrast, random observations throughout the construction industry suggest that actual mixing times are often less than one minute.



$$\frac{55 \text{ revolutions}}{14 - 18 \text{ RPM}} = 3\tfrac{1}{2} - 4 \text{ minutes}$$

Figure 13. Typical certification plate on a mobile mixer

With SFRC, the sequence and method of charging the mixer is even more critical. *'Balling'* or "*clumping*" of the fibres can periodically occur and may indicate the need for changes in the charging and/or mixing procedures.

Admixture incorporation

There is a risk with some combinations of admixtures that adverse interactions will occur, especially if intermixing occurs prior to separate dilution.

This is known to have contributed to major problems on several projects in NSW, in one case requiring the removal of 5 km of pavement concrete prior to opening to traffic. Cores removed at 0.3 m centres across a specific chainage yielded compressive strengths ranging from 8.0 MPa to 45.0 MPa.

Cores from the pavement exhibited distinctly non-uniform drying after saturation. The "wet" areas were those where admixture dosage and air content were highest.

The fractured slabs showed clear "marble-cake" composition. Note the horizontal lens of mortar (outlined).

Figure 14. Non-uniformity related to admixture interaction.

Investigations revealed that AEA[8] dosage rates 400 to 500% higher than recommended levels had been used in order to try to achieve the specified air content. The elevated dosage had little effect because it was being neutralised by interaction with the WRA[8] in the water supply line.

Inadequate mixing can sometimes be detected by the following indicators:

- unusually variable surface texture, commonly including wet patches;
- atypical fluctuations in admixture dose rates or in measured air contents;
- noticeably different workability from different parts of the load.

Consistence (slump) and retempering

The measurement and control of slump is arguably the most contentious issue in concrete placement. The practice of *wetting up* the mix (retempering) to aid workability is one which is discouraged by most clients but one which nevertheless occurs on a regular basis throughout the construction industry.

Retempering can have significant deleterious effects. For example, to increase the slump (of a typical paving mix) by 25 mm requires a water addition of about 10 litres/m^3.

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[8] AEA = air entraining agent. WRA = water-reducing admixture.

Assuming this water is replacing purely hydration losses, the addition would:

- reduce the compressive strength by about 15% (5 MPa in a 35 MPa mix);
- reduce the flexural strength by about 10% (0.4 MPa in a 4.5 MPa mix);
- reduce the pavement fatigue life from 40 to 20 years;
- waste the equivalent of 30 kg/m^3 of cement;
- increase the shrinkage by about 10%;
- increase the permeability by up to 50%.(9)

Moreover, experience indicates that the above consequences are likely to be compounded by the fact that the batch is unlikely to be fully re-mixed after retempering.(10) Given these consequences, it is far preferable to control or adjust slump losses using admixtures (such as plasticisers) rather than water.

Under these circumstances, the author's experience suggests that the following two options (regarding retempering) are available to an informed client:

(a) prohibition

(b) acceptance, but under closely controlled conditions.

The author's opinion is that Option (a) is generally impractical (for both the supplier and the client), it is contractually unreasonable, and is potentially wasteful and disruptive. Most importantly, prohibition is invariably ineffective (consistent with historical precedents in other fields). A client or supervisor who thinks otherwise should possibly be spending more time in the field.

RTA specifications have (for the past 10 years) successfully adopted Option (b). In brief, it reflects the following attitude (after Malhotra, 1982):

(i) manageable tolerance is preferable to delusional denial;

(ii) loss of workability (i.e. stiffening) derives largely from three sources, viz aggregate absorption, evaporation and hydration;

(iii) the degree of hydration that occurs within the first 30 - 40 minutes will be minimal (in moderate climates, using normal cements), hence;

(iv) water and slump losses within that period will largely be due to absorption and/or evaporation, in which case;

(v) the replacement of that water will not compromise the quality of the concrete because it will merely restore the w/b(11) ratio which the mix designer anticipated and which was tested in the laboratory trial mix;

(vi) in other words, water which is added within the first 30 - 40 minutes is essentially water which should have been added during the original batching operation and is therefore effectively only a correction.

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9 The curing time required to achieve discontinuous capillaries (i.e. impermeability) increases rapidly as the w/c ratio increases, from about 28 days at w/c = 0.5, to 6 months at a w/c = 0.6.

10 Random observations at multi-storey construction sites indicate that remixing times typically range from 15 to 45 seconds, compared with the 3½ to 4 minutes which would be required to restore uniformity.

11 w/b = water/binder ratio

However, beyond about 40 minutes, hydration begins to account for an increasing proportion of the slump losses (and moreso at higher temperatures) and so retempering is considered to be unacceptable thereafter because of the resulting excessive w/b ratio. RTA specifications impose a series of controls including:

(A) all retempering must be carried out in the presence of a nominated representative;

(B) full duration of remixing after any retempering (i.e. 3½ to 4 minutes);

(C) no retempering beyond 40 minutes;

(D) mandatory slump testing after retempering.

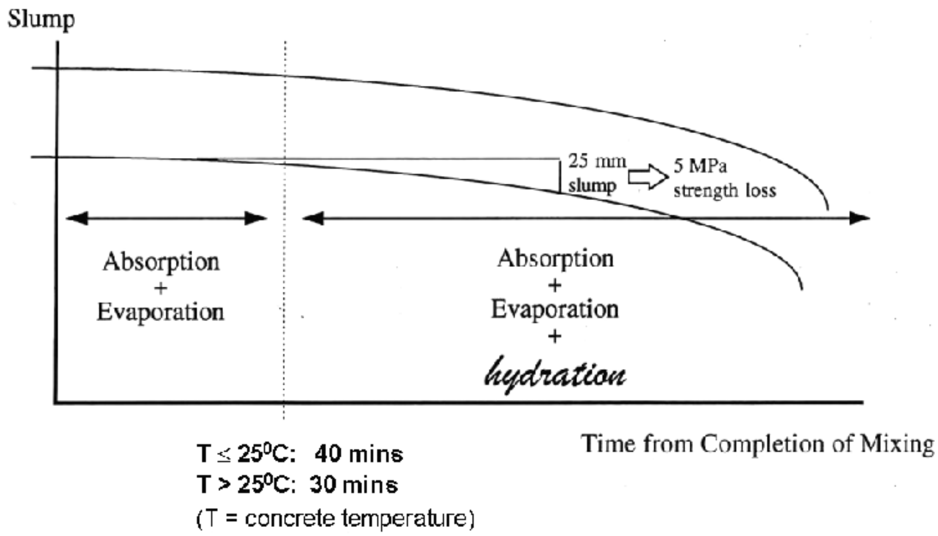

Figure 15. Time limitation on retempering.

Paving

In assessing an acceptable maximum age for concrete, specifications typically specify a fixed age from the time of batching, commonly around 90 minutes.

However, this practice has limitations because:

(a) this time may be too liberal under hot summer conditions but unnecessarily restrictive in mild conditions;

(b) a mix which is too old for hand paving may still be acceptable for slipforming;

(c) a high-energy slipformer may readily cope with a mix which is too old (and dry) for a lower powered paver;

(d) depending on design factors such as admixtures, one concrete mix could be unworkable after 60 minutes whilst another (under like conditions) could be readily workable at 90 minutes or beyond.

For these reasons, NSW specifications use the concept of a variable *"forming time"* which the Contractor must nominate and monitor according to the prevailing conditions. The *forming time* is defined as the time between completion of batching and final forming. By definition, it includes forming (as in *slipforming* and *hand forming*) but excludes hand finishing and texturing.

The intent is that the contractor will regularly monitor the paving conditions and nominate a maximum concrete age beyond which paving is unlikely to consistently and reliably satisfy the assessment criteria, with the key issues being:

- the supply of a homogeneous end product (i.e. pavement), and
- concrete workability (at the time of paving) which is compatible with the capacity of the equipment to achieve the specified compaction and surface condition with only nominal hand finishing.

In other words, if the mix is too dry to be placed, compacted & formed etc to satisfy these requirements then, by definition, it has exceeded its "maximum forming time". If properly applied, the forming time would be varied throughout the day to account for significant changes in local conditions. If slipforming and hand paving were in progress simultaneously, it is likely that the forming time would be different for each.

In practice, there may be various ways of assessing the forming time but one common method is to walk back from the paver and regularly assess the condition of the slab by touch test. At some distance from the paver, the concrete will reach a condition where an experienced assessor will judge that the paver would not cope well with a batch in that condition. Based on information contained on the tally sheets, an estimate can be made of the age since "completion of batching" for that section of concrete. The forming time would be derived by applying a reasonable safety margin to that age.

Compaction

Compelling evidence in the international literature shows that under-compaction has a profound effect on concrete performance. Compaction has a very good correlation with several important properties such as strength, permeability (and hence durability) and shrinkage.

However, on typical construction sites, concrete compaction receives very little attention or effort and, very often, specifications for major engineering projects do not require its testing or assessment.

Throughout the wider construction industry, evidence of this can be seen by observing typical multi-storey and bridge construction sites being served by pumps, commonly discharging at a rate of around 40-60 m^3/hr (50 - 80 yds^3/hr). The international literature is very consistent in showing that a single vibrator (of 50 – 60 mm dia, or 2 in.) can effectively compact at a rate of 5 to 10 m^3/hour (7 – 13 yd^3/hr).

In other words, each pump needs to be accompanied by 5 to 10 vibrators in order to achieve satisfactory compaction.

By contrast, random observations indicate that typical practice involves only one or two vibrators per pump, and in multi-storey residential construction, it is not uncommon to see no vibrators whatsoever.[12] This situation seems to be routinely tolerated by contractors and clients alike, which is a cause for real concern.

Experience in Australia with the correlation between under-compaction and performance of concrete pavements has been consistent with the textbook theory, and it is widely acknowledged that poor compaction has been one of the most common causes of premature distress.

In other concrete structures (in the author's opinion) under-compaction is also a major cause of distress more frequently than is generally acknowledged. Even if the structural integrity is adequate, durability could well be compromised. On this topic, Neville (2000) states *"... full compaction is more important than a low w/c coupled with a poorly compacted concrete."*

The RTA has enforced compaction criteria in pavements since the mid-1980s, and is regularly updating the specified criteria (Ayton 2001). They have also been incorporated into RTA bridge construction specifications. Maintenance crews on our major highways regularly report under-compaction as the major cause of premature distress, and this ongoing feedback only serves to strengthen our conviction that it is an essential parameter requiring close construction control. It is surprising, therefore, to learn that many authorities still do not require testing of compaction in concrete.

Finishing

Few clients require a higher quality of concrete in the surface zone.

Finishing and curing techniques must be of a very high standard in order to achieve the specified surface tolerances with a surface texture which is durable under the abrasive action of high speed traffic. Few clients in the concrete industry require as high a standard of surface durability than a highway agency. To most clients, the top few millimetres are expendable but, on a highway, that mortar has significant influence on safety and noise.

Durability is related to concrete strength which, in turn, is largely influenced by water/cement ratio and effectiveness of curing. In this regard, the two most common abuses of concrete involve:-

- the use of over-wet mixes, and
- wet slurrying of the surface.

Both of these practices are intended to aid the finishing operation, but they also result in a surface mortar of high water/cement ratio and hence low strength.

Supervisors should also be alert to the common abuse of sprayed evaporation retarders (aliphatic alcohols) as finishing aids. Such compounds are typically diluted with water and hence their use must be closely controlled to ensure that they are not slurried into the surface. Advertising brochures which encourage their use as finishing aids should be treated with caution.

12 In the author's experience, self-compacting concrete is not commonly used, hence there is no apparent justification for the lack of vibrators.

There are few options available in periods of high evaporation potential. The safe option is to cease paving. Alternatively, an evaporation retarder such as aliphatic alcohol can be used. However, it should be realised that it might have mixed success in severe windy conditions.

If sprayed retarders are used, they require close control. In brief, they can significantly reduce plastic cracking if used correctly, but it should also be realised that they are only a temporary solution and the best deterrent to evaporation is a good curing compound uniformly applied at the right time. If the retarder is used inappropriately, it can delay texturing and curing operations and hence may actually increase the risk of plastic cracking.

Additionally, it can cause serious damage to the surface if it is used incorrectly, by actions such as slurrying it into the surface mortar.

The importance of finishing techniques (on joint durability) has been well demonstrated by Rollings (1998).

Curing

Pavements are typically constructed under severe exposure conditions and therefore the RTA's specifications require the use of high quality curing compounds and a high standard of application.

The timing of application can also be critical, particularly under conditions which are conducive to plastic shrinkage cracking. Research (Clarke 1984) shows that curing compounds rapidly lose effectiveness if they are applied too early or too late. Experience shows that they are best applied soon after bleed water evaporation changes the surface from a gloss to a low-sheen condition.

Curing must be in place before significant drying occurs and must thereafter be maintained long enough to achieve the required strength and durability, and to minimise shrinkage. The importance of timely and effective curing cannot be overstated, particularly in relation to the requirement for a highly durable surface texture.

Recommendations

The significance of these issue is that there would seem to be a warrant for a serious review of priorities as follows:

For asset owners, there would seem to be a good case for taking at least as much interest in the construction phase as in the design phase.

For asset managers, try to identify the real cause of distress rather than the obvious cause, otherwise the rehabilitation strategy may be totally inappropriate. Exotic repairs are frequently more expensive but less effective than application of the good old-fashioned principles of concrete technology. More importantly, having established the cause(s) of distress, provide feedback to the designers and project managers.

For project managers, a reassessment is warranted of priorities for the supervision of pavement construction projects.

For public authorities, it has long been recognised that our skills base is rapidly depleting, for a variety of reasons. It is long overdue that governments took a more proactive role in training activities for both young recruits and for current serving employees. The warrant would seem to be growing for widescale expansion of accreditation schemes for construction team members.

Research Significance

In NSW we have an inventory of modern concrete pavements of 2500 lane-km worth a total of about AUD$1 billion. Examination of the performance of this network indicates that if we had been more aware of the risks associated with variability in construction, and had been more vigilant in ensuring the achievement of higher and more consistent standards, then our maintenance problems would be relatively insignificant. In brief, if we had focused on ensuring that all the concrete had been properly batched, thoroughly mixed and well compacted, we would be enjoying a very low maintenance commitment

Feedback suggests that (in relative terms), some American states (such as Georgia) and some European countries enjoy positions such as this.

Reference to the culture map (Figure 4) suggests that maintenance contractors are the only ones who might be unhappy about this. Nevertheless, it provides a clear lesson for future direction.

"Build it for the long haul; delay the over-haul".

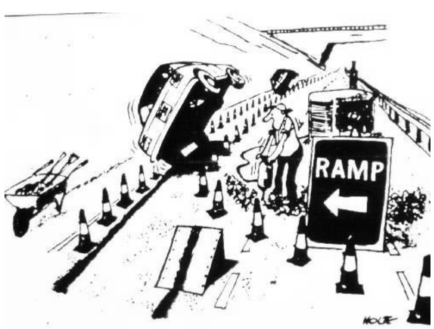

Figure 16. Pavement restoration under traffic.

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