A RECIPE FOR COMPACTION OF CONCRETE

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ABSTRACT

Compaction has a substantial influence on the flexural strength and fatigue life of concrete pavements. However, few authorities specify compaction criteria in contract documents. Reference to vibrator performance charts indicates that they are often used in both slipform and fixed-form paving at rates exceeding those which will achieve uniform compaction at satisfactory levels.

The Roads & Traffic Authority of New South Wales has been using and refining compaction criteria since 1985. Acceptance is based on the unit mass of cores relative to that of standard test specimens. In order to minimise specimen variability, it has been necessary to refine moulding procedures. This paper discusses the warrant for, and the development of, the specifications.

Nomenclature

Symbol	Description	Symbol	Description
A [3]	Refer to Reference 3.	NSW	New South Wales (Australia)
$C^{(3)}$	Refer to Footnote 3 or Table Note 3.	RTA-NSW	Roads and Traffic Authority, NSW

INTRODUCTION

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. If the topic does receive a mention, it is more likely to be a warning about the risks associated with over-compaction rather than with under-compaction.

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 [5] states that, *"... full compaction is more important than a low w/c coupled with a poorly compacted concrete."*

Despite the immense volume of information in the international literature, it appears that the construction industry generally ranks it as a low priority issue. Srinivasan [1] states, *"... there has been repeated criticism of poor construction practices, especially regarding compaction and curing. These criticisms are not confined to any nation or ... any category of builders. It is universal, and applies ... to every category of contractors."*

Many experienced engineers challenge such claims, and sceptics will ask the question, *"if compaction is typically so poor, why are the consequences not more obvious in structures?"*

A full response is beyond the scope of this paper but the following issues appear relevant:

- frame structures are designed with substantial safety factors and so under-compaction of, say, 3% (and a strength loss of 15-18%) is unlikely to be of major structural consequence;
- concrete used in frame structures is generally of higher workability than paving mixes and so requires less compaction to achieve "adequate" density for structural purposes;
- under-compaction appears to be responsible for many durability problems but does not receive its due blame because of difficulties with identification and testing. Additionally, the consequences of poor compaction rarely become apparent for several years, and staff who may have witnessed the original poor workmanship are rarely involved with subsequent repairs.

Notwithstanding the above, Swedish experience shows that structures are not immune to such problems. Forssblad [2] reported that, *"In Swedish bridge construction, several cases were reported in the 1980's where insufficient consolidation resulted in serious defects, necessitating ... in one case, total demolition and reconstruction."*

Pavements appear to be far more sensitive to variable quality because of the probing nature of truck loading (which, in time, will find every single weak slab) combined with the fact that pavements perform in flexural fatigue which is very sensitive to under-compaction.

Pavement life is sensitive to many parameters, compaction being just one of them. However, in the author's experience, the efforts which are devoted to aspects such as thickness design, mix design and production control are too often needlessly negated by marginal compaction.

The Influence of Compaction on Pavement Performance

Pavement fatigue life is dictated largely by flexural and tensile strength. However, compressive strength is also important for its correlation with abrasion resistance and arris spalling.

Compaction has a major impact on both the compressive and flexural strength. It also influences reinforcement bond which, in the case of CRC pavements, may influence cracking patterns, particularly in concert with the lower tensile strength of under-compacted concrete.

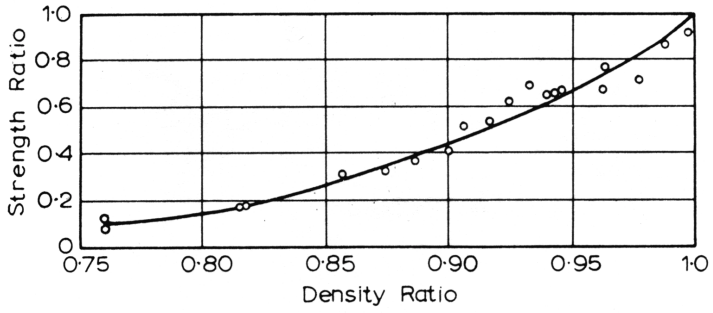
Neville [3] states that, *"In engineering practice, the strength of concrete .... is assumed to depend primarily on two factors only; the water/cement ratio and the degree of compaction"*.

For example, 1% air voids theoretically causes:-

- a 6% reduction in compressive strength (see Figure 1) and;
- a 4% reduction in flexural strength [4].

Fig 1.

Relationship between strength ratio and density ratio [3]



The impact on actual strengths is shown in Figure 2 for a range of cement contents. It will be seen that to maintain strength, an under-compaction of 2% would need to be countered with an additional cement content of 30 kg/m^3. If contractors were asked to supply an extra 30 kg/m^3 of "compensating" cement, their interest in compaction would no doubt increase significantly.

Conversely, if satisfactory strengths are being achieved at low density levels (say, 98%) then it could be argued that 30 kg/m^3 of cement is being wasted.

Fig 2.

Influence of density on concrete strength.

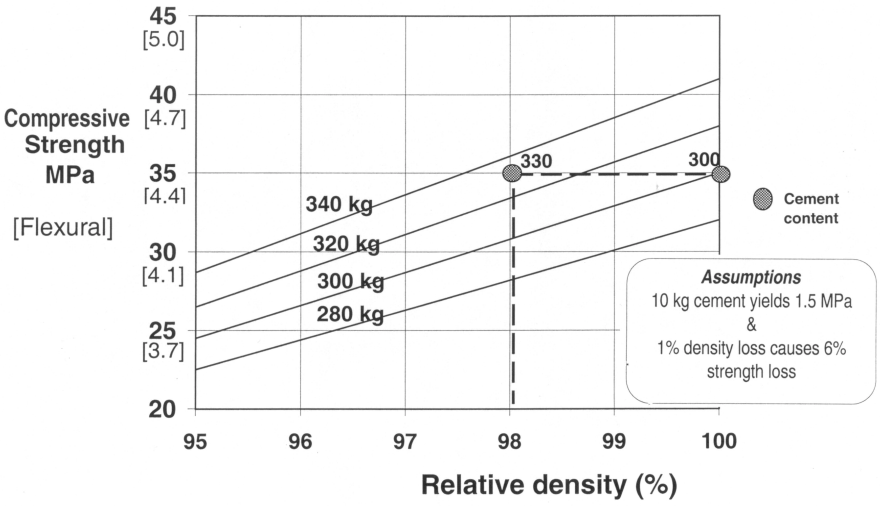


Figure 3 shows the influence of concrete strengths and density ratio on the fatigue life for a typical highway design. The significant difference between the two curves appears to be related to the load-damage relationship. AASHTO's 4th power law is far lower than PCA's, and its apparent insensitivity to compaction/strength appears inconsistent with observed performance.

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:

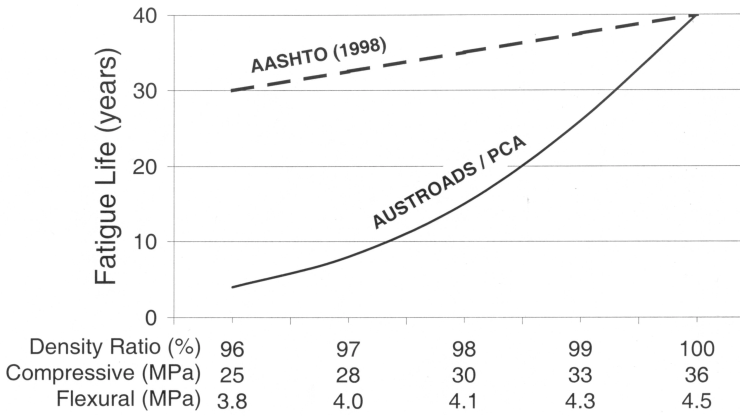
- a flexural strength increase of 4% (or compressive strength increase of 6%), and hence;
- an additional 15 kg/m^3 of cement.

Applying this to practice, if a contractor's proposed mix design is approved on the basis of trial mix results for specimens moulded at, say 2400 kg/m^3 (150 pcf) whereas the mean pavement density is 2% lower at only 2350 kg/m^3 (147 pcf), then the designer's assumptions have obviously not been realised and the pavement life will be significantly short of expectation.

Fig 3.

The influence of density ratio on fatigue life.

(These curves are provided merely to show indicative relationships between compaction and fatigue life. The x-axis values have been derived by applying the typical density-strength relationships as quoted above. The curves have been derived by inputting the flexural strength values into the appropriate design model.)



On the basis of the above discussion, compaction should justifiably be a pareto item receiving comparable attention to strength testing. A program aimed at controlling compaction standards should include the following features:

- a suitable test method for determining an acceptable compaction standard, and
- a knowledge of practices required to achieve the established standards in the work.

Specification Options

Regarding compaction, Neville [5] asks *"how do we know that full compaction has been achieved? And what precisely does full compaction mean? Answers to these questions are not yet available*". This author attests to the challenge of the task, and much work remains.

The intent of RTA-NSW specifications is to produce very consistent compaction of a high standard rather than "excellent" standards. However, there are many challenges in defining "good" compaction and then in formulating a generic test method.

There appear to be two practical methods of assessing density in the works, both being relative measures. Under those options, the unit mass of core specimens is assessed relative to either:

(a) a value such as the theoretical maximum dry density (TMDD) for that specific mix, or

(b) the unit mass of reference specimens cast by standard procedure (such as cylinders).

The RTA test method is based on Option (b). Periodically, a switch to Option (a) has been considered, but the main deterrent has been related to the use of air entraining agents (AEA). Specifications typically allow a range of ± 1.5%, hence the TMDD can vary over a 3% range. This value, if added to testing variability, is considered too wide a range for contract purposes.

Further discussion will be confined to Option (b), referred to as "relative density" testing.

The formulation of "standard" compaction procedures for the reference specimens is one of the critical issues because it effectively sets *"the height of the bar"*. In NSW, these procedures are covered by Test Method T304 [6]. T304 seeks to blend accepted compaction theory and empirical feedback. However, before proceeding with discussion of the test method, it would seem worthwhile to briefly review the theory of concrete compaction.

Principles of Good Compaction

Respected sources in the literature such as Potter [7] describe the compaction process as follows:

> *When first placed in the forms, typical concretes ... will contain between 5 and 20 per cent by volume of entrapped air. Compaction of these concretes is a two stage process.*
>
> *(1) In the first stage, the particles are set in motion and .... the concrete is "liquefied" and slumps to fill the forms and give a level top surface.*
>
> *(2) During the second stage, bubbles of entrapped air are displaced to the surface, the aggregate settles into its tightest configuration and the mortar is forced in to fill the spaces between the coarse aggregate.*
>
> *Too frequently the conclusion of the first stage, usually within 3 to 5 seconds, is mistaken for the finish of the second. However, practical completion of Stage 2 is reached only when air bubbles cease breaking the surface, and this will normally take between 10 and 20 seconds.*
>
> *... there will still be some air voids in the mix at that stage, but removal of all of the entrapped air would take an unreasonably long vibrating time; as much as 2 minutes ... for a stiff mix.*
>
> *It is therefore considered normal to have as much as 1% of large entrapped voids in properly consolidated concrete, and for practical purposes this would be considered "fully compacted".*

The distinction between these two phases is so fundamental and critical that the terms *"Stage 1"* and *"Stage 2"* should be promoted for everyday use in concrete construction.

The study of compaction is complicated by the necessary distinction between *entrapped* and *entrained* air. In brief, the aim of good compaction is considered to be the comprehensive removal of entrapped air (consistent with the above) without excessive removal of entrained air.[(1)] For simplicity, we will confine the discussion at this stage to non-entrained concrete.

In a major study of USA paving practices, the NCHRP [8] reported:

> *"Significant problems often resulting from improper consolidation are caused by the fact that specifications are neither uniform nor specific enough ... and ... the determination of the adequacy of consolidation is restricted by the experience and judgment of the inspector."*

In the author's experience, manually paved[(2)] concrete in the works rarely undergoes compaction beyond Stage 1. It is rare to see vibrators used in a systematic pattern or be held in one position longer than 2 to 3 seconds, which is insufficient to complete even Stage 1 compaction.

Often, the vibrator will spend much of its time at the bottom of the agitator delivery chute (or at the leading edge of the pour) where the vibration energy is wasted in generating lateral movement and so provides very little effective compaction. Testing of such variable concrete is clearly no more than a "lucky dip" operation.

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1 For current purposes, we can differentiate between the two types by saying that, at arm's length, most people are unable to see entrained air voids but are able to see the significant entrapped voids. Also:-

- Entrained air is relatively limited in diameter and is well distributed. It enhances workability and hence its deleterious impact on strength can be partially offset by reducing the water/binder ratio.
- Entrapped air is highly irregular in shape and size and (to the author's knowledge) has no positive features.

2 ie, excluding slipformed and paver-train works.

There are many examples of pavements in NSW which have been vibrated in this manner and their performance has (predictably) been very poor. Repair crews are assured of ongoing work from this standard of workmanship.

Typical Specifications for Moulding of Specimens

NCHRP [8] comments regarding specifications which are *"neither uniform nor specific enough in describing the compaction process"* were aimed at compaction "in the work". However, these comments apply equally well to many standard test methods for the moulding of specimens.

For example, Australian Standard AS 1012.8 [9] allows rodding for all slumps down to 40 mm (1½ in.), it allows internal vibration for all slumps down to 10 mm (3/8 in.), and allows external vibration without limit. ASTM C 31-96 [10] allows both rodding and vibration for slumps between 25 mm and 75 mm (1in. - 3in.).

Local experience over many years shows that an unacceptably wide range of density results are likely from these different methods. Given that compaction in the works is only ever undertaken by vibration, and that slipform mixes are too dry to be rodded, the author can see no reason to allow rodding in reference specimens.

Trials have been conducted with both internal and table vibration[3], but internal vibration has now been established as the only acceptable method, consistent with universal practice in the works. This has been further standardised by allowing only electric vibrators because petrol models allow too wide a range of frequencies.

Regarding vibration thoroughness, AS 1012.8 provides only the following guidelines:[4]
"Vibrate each layer until the surface becomes relatively smooth in appearance. Vibration should not be prolonged beyond the point at which mortar commences to collect on the surface."

The only comment referring to the need to expel air is contained in the advisory Note: *"Exercise care when withdrawing the vibrator and ensure that no air pockets are left in the specimen."*

Under vibration guidelines such as Potter's [7], and consistent with everyday field and laboratory observations, the achievement of a *"relatively smooth"* surface and *"mortar* (commencing) *to collect on the surface"* constitutes only Stage 1 compaction, and substantial air bubbles will continue to break the surface long after this time. However, an operator who prolongs vibration long enough to ensure that *"no air pockets are left in the specimen"* will be contravening the advice to cease vibration soon after achieving a relatively smooth surface.

Observations of many testing operators over many years indicate that the interpretation of such clauses is subjective and their application is variable.[5] The potential consequences are unacceptable under contracts where the density is required as a reference measure.

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3 Table vibration of specimens proved highly variable and inefficient. In one contract, the author specified the mandatory use of vibrating tables. Trials later showed that table vibrating times of 1 to 2 minutes were required to achieve densities equal to those from short-duration internal vibration. Results also varied across the table.

4 ASTM C31-96 contains similar guidelines.

5 The author questions whether subjective "Standards" such as these should be termed "Guidelines".

Prior to the introduction of T304, compaction standards both in the specimens and in the work were often highly variable. Core and cylinder densities sometimes varied over a range of up to 10% within a single project. Consequently, relative densities (core ÷ cylinder) sometimes ranged from 93% to 106%.

Specifications for air entrainment typically allow a range of ± 1.5%[6], which could explain a density range of 3%, or about 70 kg/m^3. However, on well controlled projects, the actual entrained air level on any day is invariably within a range of ± 0.5%, which accounts for a density range of only 20 - 30 kg/m^3 (1.2 – 1.9 pcf).

Experience indicates that, from a well-controlled plant using systematic compaction, the theoretical maximum range in concrete unit mass (from all sources including entrained air) is less than ± 50 kg/m^3, or ± 2.0%. Paving projects with ranges up ± 5.0% served to highlight the need for closer control on the moulding of standard reference specimens.

Key Features of Current Specifications

In preparing T304, the two main goals were to reduce the variability in the specimens, and to raise the overall standard of specimen compaction.

The key features of T304 for cylinders are as follows.

(a) Compaction must be by internal electric vibration.

(b) Vibrators must have a frequency within the range 115 - 220 Hz (7,000 – 13,200 vib/min). (The upper limit was imposed to minimise the risk of cavitation.)

(c) Minimum vibrator insertion times are specified, together with controls on withdrawal rate.

Under RTA model specifications for concrete pavement construction [11], the following provisions also apply:

(d) the reference cylinder value is based on a rolling mean of 5 pairs, in order to minimise the impact of short-term fluctuations in properties such as entrained air content;

(e) all cores must be assessed to check whether waxing of the specimen is warranted in order to fill excessive surface voids.[7]

(f) the relative density of cores must exceed the following values.
- 98% independent of core strength, or
- 97% subject to satisfactory core compressive strength.[8]

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6 In the author's opinion, concerns about cylinder moulding procedures apply equally to the moulding of air content specimens. Depending on the method of compaction used, entrapped air may form a significant portion of the total measure air content, hence the entrained content is likely to be significantly lower than indicated.

7 Determination of the "true" unit mass of specimens becomes more difficult with increasing void content. When measuring the specimen's volume by water displacement method, voids are filled with water and this yields a low apparent volume, hence a high apparent unit mass. Concrete which visually resembles "no-fines concrete" can yield relative densities of around 97%. Wrapping of the specimen has been unsuccessful.

8 The 98% acceptance density may seem inconsistent with statements about the harmful impact of a 2% loss, but a reasonable construction tolerance must be provided. Its potential impact should be taken into account in setting the contract strength level. Experience to date gives no cause to revise the 98% value.

RECIPES FOR FIELD COMPACTION

Techniques for fixed-form (manual) paving

The placement of concrete in pavements demands the highest standards of workmanship. The finished work must be well compacted, whilst close surface tolerances are required to achieve a satisfactory ride quality.

In order to achieve these standards, it is necessary to use both internal and surface vibration. Recommended practice is therefore to place and spread the mix (by means other than vibration), followed by internal vibration and then two passes (minimum) of a vibrating screed.

Vibrating screeds alone (without prior internal vibration) are unlikely to achieve compaction beyond the upper part of the slab. Much of the literature on screeds appears to quote work by Kirkham [12,13] for their compacting capacity and in advocating their use without prior internal vibration. However, Kirkham in those studies dealt only with heavy vibrating beams of the type used in paving trains. Hence, the application of those results to vibrating screeds would appear to constitute a very liberal extrapolation of the data.

- **Internal vibration**

The claim was made in an early part of this paper that "*practical completion of Stage 2 compaction is reached only when air bubbles cease breaking the surface, and this will normally take between 10 and 20 seconds.*"

The author's experience is that most concrete practitioners deem vibration periods of around 10 secs to be excessive, and so it is worth checking other reliable (and independent) sources.

Various sources such as the ACI [14] publish guidelines on the performance of internal vibrators. Table 2 provides a selected extract for the vibrator size typically used in road paving.

Table 2 - Vibrator characteristics and outputs [14]

ACI Data (A)					
1	**2**	**3**	**4**	**5**	**6 (B)**
Group	**Dia cm (in)**	**Recommended frequency Hz (vibs/min) (C)**	**Radius of action cm (in)**	**Placement rate per vibrator (D) m^3/hr (yd^3/hr)**	**Insertion spacings cm (in)**
3	5 – 9 (2 – 3.5)	130 – 200 (8,000 – 12,000)	18 – 36 (7 – 14)	4.6 – 15 (6 – 20)	27 – 57 (10 – 20)

Notes
A. Data is derived from Reference [5].
B. Column 6 has been added by this author but is based on ACI literature.
C. This frequency applies while the vibrator is operating in concrete.
D. Assumes the vibrator operates two-thirds of the time concrete is being placed.

Table 3 – Vibration durations

Output (C) m^3/hr/vib	Dip method: Insertion time (sec) (A) 2/3 time (D) (full-time)			Drag method: Drag speed (m/min) (B) 2/3 time (D) (full-time)		
	Poker spacing (cm)			Drag spacing (cm)		
	30	35	40	30	35	40
4.6	12 (18)	16 (25)	20 (32)	1.5 (1.0)	1.3 (0.8)	1.1 (0.8)
10	6 (8)	8 (11)	10 (15)	3.3 (2.2)	2.7 (1.8)	2.5 (1.6)
15	4 (6)	6 (7)	7 (10)	5.0 (3.3)	4.1 (2.7)	3.7 (2.5)

Notes

A. Values in this group show the insertion time (per dip) which is available for the given hourly output and poker spacing.

B. Values in this group show the drag speed which would be required (or available) to achieve the given outputs at the given spacings.

C. Output range as per Table 2 Col 5.

D. The 1st value assumes the vibrator will work 2/3 time as per Table 2 Note E. The 2nd value (in brackets) assumes full-time work.

In Table 3 under the Dip method, the shaded values are those which show agreement with the statement that *"Stage 2 compaction ... will normally take between 10 and 20 seconds"*. The results indicate general agreement within the following parameters:

(a) for a vibrator working full-time: for outputs not greater than 10 m^3/hr/vibrator;

(b) for a vibrator working 2/3-time: for outputs not greater than 4.6 m^3/hr/vibrator (though this could probably be increased by extrapolation to 6 - 7 m^3/hr/vibrator).

In Table 3 under the Drag method, the shaded areas are those where the travel speed of the vibrator is less than 1.8 m/min (6 ft/min). The author's experience is that (in typical paving mixes) speeds exceeding 1.5 to 1.8 m/min are unlikely to achieve *"the completion of Stage 2 vibration ... when air bubbles cease breaking the surface"*. Iowa trials [15] indicated that the optimum paving speed (for air void distribution and paver finishing) is 1.2 - 1.9 m/min.[9]

The author concedes that none of the above analyses is conclusive, and that further work is required. However, it does serve to indicate reasonable consistency on the long-established guidelines for good vibrating practice as published by various sources.

It is also consistent with the author's experience that, as a guide in the absence of controlled test results, it should be assumed that a single 50–70 mm vibrator (in either slipform or fixed-form paving) is unlikely to achieve uniform compaction at a satisfactory level for outputs exceeding:

- 10 m^3 /hr when working full-time, or
- 6 m^3/hr if working for only two-thirds of the paving time.

By contrast, many contractors would place 30 m^3/hr with one vibrator, and even then would often vibrate only part-time.

The author's preference is for vibrators to be "dragged" in paving work rather than "poked". This runs contrary to conventional advice, but is consistent with the action of a slipform paver.

9 Investigations in Iowa [15] serve to reaffirm the risks of cavitation associated with vibrator frequencies above about 12,000 vib/min. However, a reduced frequency does not necessarily constitute *"reduced vibration"*. ACI work [17] indicates that, in general, plastic mixes are most efficiently compacted with vibrators of high frequency and low amplitude, whilst stiff mixes are best compacted at lower frequency and larger amplitude.

Warnings are sometimes sounded that dragging can produce vibrator trails but the author has never found one case of this in over 20 years of experience. In hand paving, the surface lines which appear to be trails are only an indicator of localised liquefaction of the mix and, in well graded mixes, cores will show that they do not represent segregation. However, even if minor segregation were to be found, it is the author's view that the benefits of systematic and thorough compaction will far outweigh any risk associated with minor slurrying at the surface.

- **Surface vibration**

Two passes of a vibrating screedboard are required, analogous to using a pre-spreader followed by a paver. The first screed pass is used to level the mix. The second pass is required to achieve final surface tolerances and to finish compaction of the concrete in the upper zones, including those areas disturbed by workers' boots during the first pass. A third pass may also be warranted.

The principles outlined above have been summarised in "Recipe" format in Fig 4.

Techniques for Slipform Paving

ACI guidelines [14] indicate that a vibrator of the type used on slipformers has a likely output of:

- 4.6 to 15 m^3 (6 - 20 yd^3) per hour, if the vibrator works for two-thirds of the time. During periods of continuous slipforming, this will convert to:
- 7 to 23 m^3 (9 - 30 yds^3) per hour

These ranges are obviously quite wide, and the safe output (for a specific target density) will vary according to factors such as the workability of the mix and the operating characteristics of the vibrators. The presence of reinforcement can also create variability with depth. For a given mix and a particular paver, the safe range will only be determined by controlled trials[(10)], together with ongoing monitoring of results.

However, for the purpose of demonstration, Table 4 is provided to show the influence of paving speed on the requisite vibrator outputs for a 250 mm (10 in) thick slab. As an example, if a paver has vibrators at 400 mm (16 in.) centres and is paving at a speed of 3.0 m/min (10 ft/min) then each vibrator is being required to vibrate 18 m^3/hr (23 yd^3/hr).

Table 4 - Theoretical vibrator outputs

		Output m^3/hr (yd^3/hr) [(A)]			
		Vibrator spacing (mm)			
		300 c/c	**400 c/c**	**500 c/c**	**Notes**
Paver speed [(B)] m/min (ft/min)	**1.0 (3)**	4.5 (6)	6 (8)	7.5 (10)	A. Outputs are based on a thickness of 250 mm (10 in.)
	1.5 (5)	6.5 (8.5)	9 (12)	11.5 (15)	B. Speed is "instantaneous", not "average"; see discussion below.
	2.0 (6.5)	9 (12)	12 (15.7)	15 (20)	C. Shaded areas indicate outputs which exceed 10 m^3/hr.
	2.5 (8)	11 (14.5)	15 (20)	19 (25)	
	3.0 (10)	13 (17)	18 (23)	23 (30)	

[10] Under RTA specifications, the contractor is required to carry out a paving trial of between 50 and 100 lineal metres before full-scale paving commences. Compaction criteria are a key issue in the trial.

In general, operation within the shaded areas raises the risk of under-compaction.

A word of caution is sounded here regarding the distinction between "average" paving speed and "instantaneous" speed. For example, for an output of 900 lin m (3,000 lin ft) in a 10-hour shift, the average output will be 90 m/hr or 1.5 m/min (5 ft/min).

This would appear to comply with the guidelines contained in Table 4. However, if paving had been discontinuous throughout the day then the "instantaneous" paving speed may have regularly been 30% higher, or 2 m/min, in which case the compaction could be marginal in those areas. Hence, it is the maximum instantaneous paving speed which is critical in terms of ensuring adequate compaction and, in this context, the average speed is somewhat academic.

Reports in international journals frequently report slipforming projects where daily *average* speeds exceed 3.0 m/min (10 ft/min). If instantaneous speeds were some 30%-50% higher at over 4.0 m/min (13 ft/min), then the paver's compacting capacity is likely to have been exceeded.

In slipform paving, there are two areas which require special compactive effort, as follows:

(a) Transverse construction joints are a source of frequent failure, particularly in CRC pavements. The concrete removed from these areas often resembles no-fines concrete.

(b) Voids can be created if tiebars are depressed through the surface of the formed slab without adequate recompaction of the concrete above their injection path. These so-called *"slotted voids"* weaken the slab in the same way as sawcuts.

- **Systematic techniques - Recipes**

Few supervisors or managers seem to appreciate the need for a system or "recipe" for compaction of concrete. In earthworks and asphalt, there is widespread acceptance of the concept of providing a specified number of rolling passes within defined paths. In concrete, the same concept has been encouraged for decades by organisations such as ACI [14].

However, much of the concrete which is placed daily in major structures appears to be vibrated in a *"lucky dip"* process. In the author's experience it is rare to see vibration being undertaken in any form of systematic pattern with an adequate number of vibrators and good techniques.

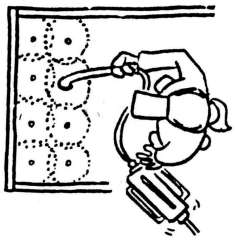
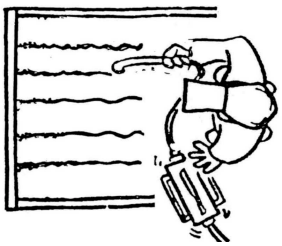
Given that compaction is one of the two primary factors in concrete strength and durability (Neville [3]), it is unacceptable that managers entrust this work to operators with little training and no basic recipe. In Neville's words [16], low-tech failures are ruining high-tech projects.

The term "recipe" has been chosen carefully. The complexity of concrete rheology is such that there are no fail-safe formulae to calculate the required amount of vibration. So, as in cooking, one option is to begin with a sound basic recipe and to refine it with experience and testing.

The author proposes the recipes in Figure 4 as a starting point for controlled trials at the beginning of a project. For pavements and bridges costing millions of dollars which are expected to provide a low-maintenance life in harsh environments for 30 to 100 years, it must be accepted that a substantial effort is warranted to test and refine these recipes to achieve conforming results.

Figure 4

Recipe for compaction in hand (fixed-form) paving

You will need:	*Tips*
For internal vibration: • vibrator diameter: 50 – 65 mm (2 - 2½ in.) • frequencies @ 8,000-12,000 vib/min (130 – 200 Hz) • vibrator insertions @ 300-350 mm c/c *and* (12 – 14 in.) insertion durations of 5-10 secs *or* drag speed @ 1.0 – 1.5 m/min[(1)] (3½ - 5 ft/min) ***For upper compaction, and finish tolerances:*** • 2 vibrating screedboards [(2)] ⇨ Travel speed 1.5-2.0 m/min [(3)] • The 1st screed is the "pre-spreader" • The 2nd screed is the "paver/finisher"	 The "dip" technique [(1)]  The "drag" technique [(1)]

Notes

1. The author's personal view is that "dragging" is preferable to "dipping", for following reasons:
   - With dragging, the vibrator spends less time out of the concrete and so is more efficient.
   - With dipping, the vibrator is invariably withdrawn too quickly, leaving a void in its path.
   - The idea of dragging will have traditionalists muttering *"you should never drag"*. Vibrators on slipformers are dragged through the concrete, so why not in fixed-form paving ?
2. Petrol and electric vibrating beams: typically @ 2,500 - 3,000 vib/min (40-50 Hz)
   Pneumatic models: typically @ 9,000 – 11,000 vib/min (150-190 Hz).
3. The travel speed can be varied according to its influence on the particular mix. Watch for effective expulsion of air voids and good surface finish behind the 2nd pass.

Recipe for compaction in slipform paving

You will need:	*Tips*
• vibrator diameter: 65 – 80 mm (2½ - 3 in.) • frequencies @ 8,000-10,000 vib/min (130 – 170 Hz) • vibrator spacing @ 400-500 mm c/c (16 – 20 in.) • paver speed @ 1.0 – 1.5 m/min (3 - 5 ft/min)	***Watch for:*** ➢ Suitable surface finish behind the paver. If intensive floating is needed then the mix and/or the paver need tuning ➢ Signs of voided surface within a longitudinal band, which may indicate a failed or lazy vibrator.

Criticism of T304

For balance, it must be acknowledged that the introduction of T304 has drawn concerted criticism from the industry. In practice, however, nonconformances have been rare and have been largely confined to small areas of manual paving. These areas have traditionally suffered a high failure rate which can be readily explained by unacceptable paving practices.

One objection has been that the degree of vibration required in the cylinders is excessive and is effectively *"raising the bar too high"* for compaction in the work. In response, the author contends that T304 merely requires thorough compaction to a degree which is consistent with the well-established principles as expressed by various authorities such as ACI [14]. Further, there have been no known cases where competently vibrated concrete has proven nonconforming.

A second objection is that T304 is expelling significantly more entrained air from the specimens than occurs under a slipformer. It is acknowledged that concrete placing operations cause the removal of some part of entrained air. NCHRP [8] states:
"... there is no doubt that vibration is expected to remove 25 to 40% of the total[11] *volume of air voids* (and) *this removal may be beneficial to strength and abrasion resistance ..."*.

However, the critical contractual issue is the differential between its removal in the specimens and in the slab. Further laboratory work is required to investigate this issue but, on the basis of studies to date, the impact appears to be insignificant.

A third claim is that, in order to comply with compaction criteria, slipformers are paving so slowly that an excess of slurry is being generated. The NCHRP [8] states: *"Unfortunately, whenever segregation, excessive surface fines, or other evidences of overvibration are observed, the initial reaction is to reduce vibration. The proper solution is to adjust the mixture."* Further, *"Normal-weight concretes which are well proportioned and have the recommended slump are not readily susceptible to overvibration. Consequently, if there is any doubt as to the adequacy of consolidation, it should be resolved by additional vibration."*

Impact of T304

T304 has significantly increased the likelihood of distinguishing between good and poor practices. Its introduction has created a degree of concern in the industry, but this is understandable given the implications for an increased need for training and site surveillance.

However, the volume of concrete removed and replaced since its introduction is insignificant compared with the volumes which were regularly replaced during the early 1990s. Table 5 provides a summary which indicates the impact of T304 on project test results. In brief, the data indicates the following trends:

- The coefficient of variation on the unit mass of both cores and cylinders has been halved.
- The coefficient of variation on 28-day cylinder strengths has been noticeably reduced;

[11] Author's comment: In this context (of the effect on freeze-thaw resistance) the word "total" is thought to refer to *"total entrained air"* rather than *"total entrained plus entrapped air"* but this is not certain.

Table 5 - Indicative impacts of T304

	Property	Indicator	Period (A)		
			Pre-T304	Post-T304	
28-day cylinders	Strength	Coeff of Variation %	6.5 – 13.5	5.5 – 9.5	**Notes** A. Data not available for pre-T304 period because flexural strength criteria were introduced simultaneously with T304.
	Unit mass	Standard deviation	25 – 35	11 – 18	
	"	Coeff of Variation %	1.2 – 1.5	0.5 – 0.7	
Cores	Unit mass	Standard deviation	30 – 50	15 – 25	
	"	Coeff of Variation	1.3 – 2.0	0.6 – 1.1	
28-day beams	Strength	Standard deviation	(A)	0.3 – 0.5	
	"	Coeff of Variation %	(A)	6.0 – 9.5	

CONCLUSIONS

Variable construction quality is usually associated with one or more of the following factors:

- "good" practice is not well defined in some areas;
- specifications are inadequate (and/or their intent is not complied with);
- staff are under-trained to distinguish between good & poor practices;

In the case of concrete compaction, each of these issues appears applicable.

Miller [18] states:

"Concrete technology is an area in which engineers have dropped the level of their game... The control ... of concrete ... is an art form. The most brilliant design depends for its success on the skill of the craftsmen dealing with the wet concrete. Project managers are severely constrained by cost and time ... and they no longer afford the time and money to ensure that the ... concrete placing and compaction, and the curing are of the necessary quality."

In concrete pavements, the *"brilliant design"* of those who refine our analysis and design methods is too often annulled by poor construction quality.

In a 1998 report on the construction industry, Francois [19] stated:

"the construction industry ... is having a hard time finding skilled workers and job superintendents. This raises the question of quality with untrained people on the job and a lack of proper supervision."

The following statement by McMillan [20] was written in 1929 but applies equally well in 2001.

"There must be a recognition ... that uniform concrete of good quality requires ... proper materials, proper design, proper mixing and transporting, and special care in placing and protecting. If ... quality is subordinated to first cost, durable structures cannot be expected.

This conference focuses on the development of long-lasting concrete pavements for the 21st century. In March 2001, Mehta [21] wrote:

> *"... instead of strength, the 21st century concrete practice must be driven by considerations of durability. The transition can be achieved by major paradigm shifts in the selection of materials, mixture proportions, and construction practice ...."*.

In the author's experience, for any pavement to be long-lasting and durable, it must be given a serious measure of old-fashioned good compaction. Further development work is required to enhance our understanding of "good compaction".

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