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Abstract

The linkage between air voids content and durability in footways reinstatements with the limits currently in SROH is non–proven and unsupported by evidential research or trial data. Compounding of errors, particularly in density measurement of core samples and subsequent variability, generate biased air void content results that make the compliance largely a matter of chance. This led to a very wide range of predicted outcomes, putting both the contractor and the client at unacceptable risk. The use of a measured in-situ air voids content criteria in a specification for footway reinstatements, where the entire operation is in restricted areas with hand laying process using recipe mixed materials, cannot be sustained on technical grounds with respect to relevant British Standard and Transport Research Laboratory (TRL) guide. Taking account of the service loads, nature and scale of works in footways, an in-service guarantee by the undertaker for an agreed extended period, linked to an allowable intervention level, could be a simple, realistic and acceptable solution, ensuring a durable reinstatement that removes the financial risk of failure from the highway authority.

Key Words: Specification for the Reinstatement of Openings in Highways (SROH); utility reinstatement; air void content; asphalt layers; variability; footways; end result specification; method specification; variability

1. Introduction

Coring (the taking of samples of asphalt materials) programmes of utility reinstatements initiated by the UK Local Authorities have been identifying consistent failure in respect of air voids contents in surface course material of footways when assessed against the requirement of the Specification for the Reinstatement of Openings in Highways (SROH) [1] for air voids content compliance. This is an issue which currently affects all National Joint Utility Group (NJUG) members of the UK, presenting a significant and growing challenge as more Local Authorities in the UK apply the SROH air voids content standard to utility reinstatements. This study is intended as an introduction and overview investigating some possible causes for noncompliance with the SROH by the undertakers, in terms of the air voids content in asphalt materials.

The Public Utilities Street Works Act 1950 [2] was replaced by the Public Utilities Act 1991 by implementing some of the recommendations of the 1985 Horne Report (Horne, 1985) on roads and the public utilities. As per article 70 and 71 of New Roads and Street Works Act 1991 [3], it is the responsibility of the Undertaker by whom street works are executed to reinstate the road/footway surfaces complying the requirements prescribed in specification, whereas, responsibility for inspecting the quality of reinstatements lies with the UK Local Authorities.

For reviewing the existing Public Utilities Street Works Act 1950 (PUSWA), the UK Government set up a committee chaired by Professor Horne in 1984. PUSWA was replaced by the 1st edition of SROH in 1992 by implementing some of the recommendations from Horne Report [4], and, the second edition of SROH [5] was released in 2002 introducing a number of changes including end result specification, a new road category, alternative specification for materials, layer thickness, compaction methods and/or new compaction equipment. Currently the reinstatement of utility works is covered by the 3rd edition of SROH [1] which was enforceable from October 2010 in England.

The third edition of SROH contains three sections, namely Specification, Appendix and Notes for Guidance (NG). It defines Specifications and Appendices as integral part of the code of practice and hence enforceable under law, whereas, the NG are complementary to support the practitioners. The specification for compaction control in the first edition of the SROH was in terms of the method to be applied (hereinafter referred to as 'method specification'), whereas in the second and third edition, end- product specification (hereinafter referred to as 'end result specification') through complying with an in-situ air voids content requirement (Table S10.1 in SROH) of all asphalt materials was introduced. The guidance for achieving the specified air void content of asphalt mixtures using the specified materials and compaction plants has been provided as NGA in the current edition of SROH (Table NGA8.3 in SROH).

The genesis of the move toward Quality Assurance (QA) began in 1956 with the American Association of State Highway Officials (AASHO) Road Test (1956-1958), and the analyses that emanated from that historic study. The unsuspected discovery of the large magnitude of the variability in materials and construction was found in this road test and led to the conclusion that specifications must be improved [6, 7]. Highway engineers realised that these variabilities were not being handled properly in specifications [8]. To establish realistic specification limits, several state Departments of Transportation (DoT) started to measure the variability of asphalt volumetric properties, air voids content, binder content and grading in the 1960s [9-11]. After the AASHO Road Test, a sufficient number of unbiased test results of construction materials and techniques also became available to expose the true variability of these results and their relationship to specifications [12].

Coring programmes of utility reinstatements initiated by local authorities consistently show significant failure rates in respect of air voids contents in surface course material when assessed against the SROH. Utility undertakers are experiencing difficulties in complying with the SROH air voids content requirement while using the specified materials and construction method and also following the guidance on compaction plants (NGA 8.3) quoted in SROH [13].

This research has been initiated to examine the achievability of the SROH specified air voids content limits using currently recommended materials and operating methods stipulated in the SROH. This study was also intended as an introduction and overview investigating possible causes for noncompliance with the Specification for the Reinstatement of Openings in Highways (SROH) by the undertakers, in terms of the air voids content in asphalt materials. The observations and conclusions of this study are primarily based on the review of the published literature, related standards and three completed trial studies conducted on compaction methods and equipment for reinstatement by Affinity Water - London Borough of Enfield [14], Transport Research Laboratory [15] and Balfour Beatty - Pavement Testing Services (PTS) Ltd [16].

2. Method of research

This research highlights the process and factors to be considered for establishing specifications and associated limiting values and the performance of street reinstatements compared with those embedded within SROH by;

- Reviewing the results and associated variability obtained from the available related trial studies concerning the performance of SROH ;

- Reviewing the published documents regarding the measures for establishing a realistic specification and
- Reviewing the related Standards regarding the use of a measured in-situ air voids content criteria in a Specification for footway reinstatements, where the entire operation is in restricted areas with hand laying process using recipe mixed materials

3. Review of results from published reinstatement trials

So far, a comprehensive review has not been conducted on the performance of the utility reinstatement with respect to current edition of the SROH. However, the London Borough of Enfield in partnership with Corehard Laboratory Ltd, Affinity Water and SQS Ltd conducted a trial in 2012 [14] and Balfour Beatty – Pavement Testing Services (PTS) Ltd in 2011 [16] for determining the suitability of the compaction devices stipulated in the code of practice. Transport Research Laboratory (TRL) conducted a study in 2003 [15] for validating the performance of 600-1000 kg/m single drum roller in relation to the compaction of the asphalt materials for inclusion in SROH. These trials were not truly conducted for assessing the achievability of the SROH covering all possible scenarios that could be encountered while executing the reinstatement works in real life:, however, the trend of performance of the compaction plants used, as well as the achievability of the SROH air voids content requirement can be obtained by reviewing the results from these trials.

The methods used within these three trials allowed for full and controlled scrutiny of material selection, equipment selection, and methods applied or required when compacting both unbound and asphalt materials. Continuous monitoring of the methodology prescribed, temperature of material, and digital imaging utilised to ensure no deviation from the requirements. All testing was carried out under controlled and accredited by laboratory conditions. This provides traceable results to ensure compliance with method under current SROH requirements. In each case asphalt materials from the same respective plant load were used. The findings related to the performance of compactive effort are described in the following sub sections.

3.1 London Borough of Enfield - Affinity Water study

The objective of this trial was to determine the suitability and selection of compaction devices in reinstatement works. The trial was undertaken between April 2012 and August 2012 at Scratchwood recycling facility. Nine test beds were excavated to a depth of 1m with surface area of $1m^2$, which allowed for introduction of backfill layers using differing materials and methods with the top 100 mm being left for asphalt materials. The top 100 mm (asphalt layer) of all of the nine test beds were reinstated in different lifts (50 mm+50 mm, 35+35+30 mm and 25+25+25+25 mm) with a single product from the same plant batch each time, using the following materials:

- 6ACDSC (referred to as AC 6 dense surf in BS EN 13108-1)
- 10ACCSC (AC 10 close surf in BS EN 13108-1)
- 10SMA (SMA 10 surf in BS EN 13108-5)
- 14HRASC (HRA 30/14 surf in BS EN 13108-4)
- 20ACBC (AC 20 dense bin in BS EN 13108-1)

The trial was undertaken through accredited measurement and the methods used within this trial allowed for full and controlled scrutiny of material selection, equipment selection, and methods applied. The air voids content was determined using the method stipulated in the relevant British Standard at UKAS accredited testing laboratories. Three combinations of compaction effort and different lift layer for 100 mm asphalt materials, permitted in SROH, were used in this study. The compaction effort were, vibrotamper (VT) with roller (R), vibrotamper (VT) with vibrating plate (VP) and vibrating plate (VP) only. The results of air voids (AV) content of the cores after using three combinations of compaction effort are shown in Figure 1 to Figure 3.

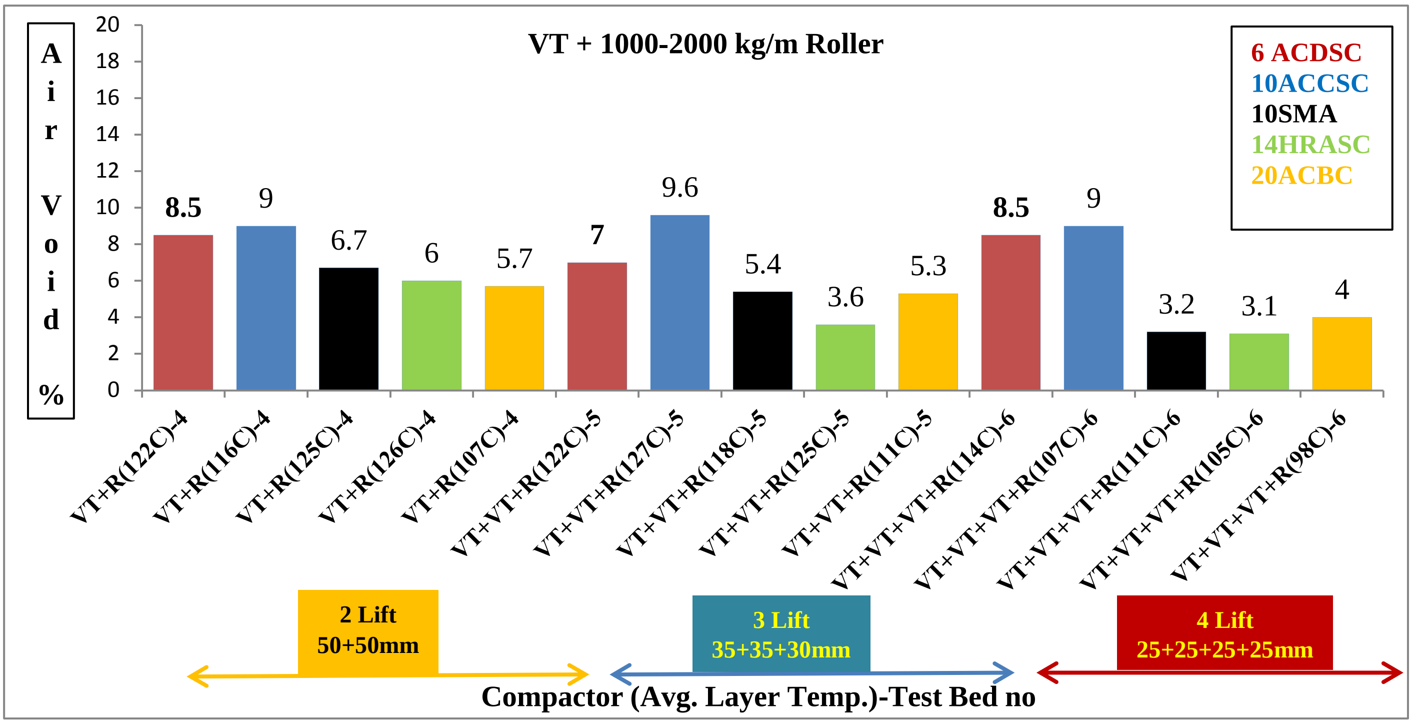

Figure1: Air void content in Affinity water trial using combination of vibrotamper and roller

The AV content (data label) displayed in red colour (in Figure 1 to 3) indicates the non-compliance of SROH requirement. Irrespective of the bound material type, all specimens satisfied the SROH air voids content requirement when VT with roller was employed (as shown in Figure 1), whereas, significant number of non-compliance with the SROH requirement was observed in the case of other two combinations of compactor. Though, the laid asphalt materials on all test beds were each from the same single load of the respective mixture, surprisingly, the rate of success on complying with the SROH void requirement was: vibrotamper + roller = 100%, vibrotamper + vibrating plate = 46% and vibrating plate = 40%. The weight category of roller used in this trial was 1000-2000 kg/m, which is generally not used by practitioners because of its heavy weight relating to surrounding street structure though included in SROH [13]. For trench reinstatement, different suggested compaction plants (readily available in the UK) or their combinations (required by the site condition), might not provide the same degree of compaction but should at least be able to provide acceptable air voids content provided a reasonable method of construction is followed. Moreover, no improvement and possibly even an increase of AV content in some cases, was evident with increase of successive lift layers for three combinations of compactor. A key point to emerge from the trials was that tests indicated that the air voids content criteria for bituminous surfacing stipulated in SROH was not achievable in many cases, even when fully complying with the methods prescribed within the SROH under controlled conditions. This finding has also been reported by [17].

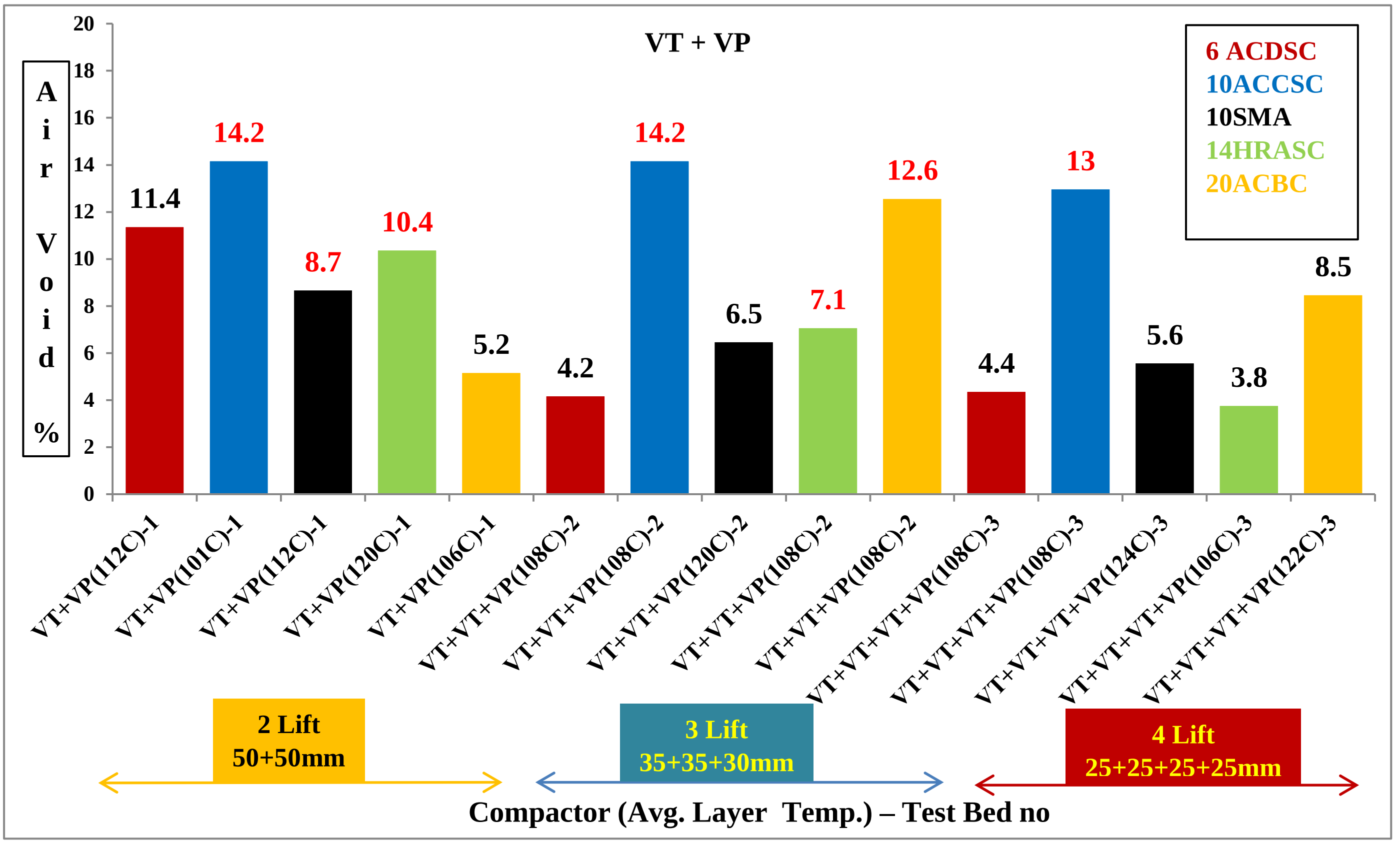

Figure 2: Air void content in Affinity water trial using combination of vibrotamper and vibrating plate

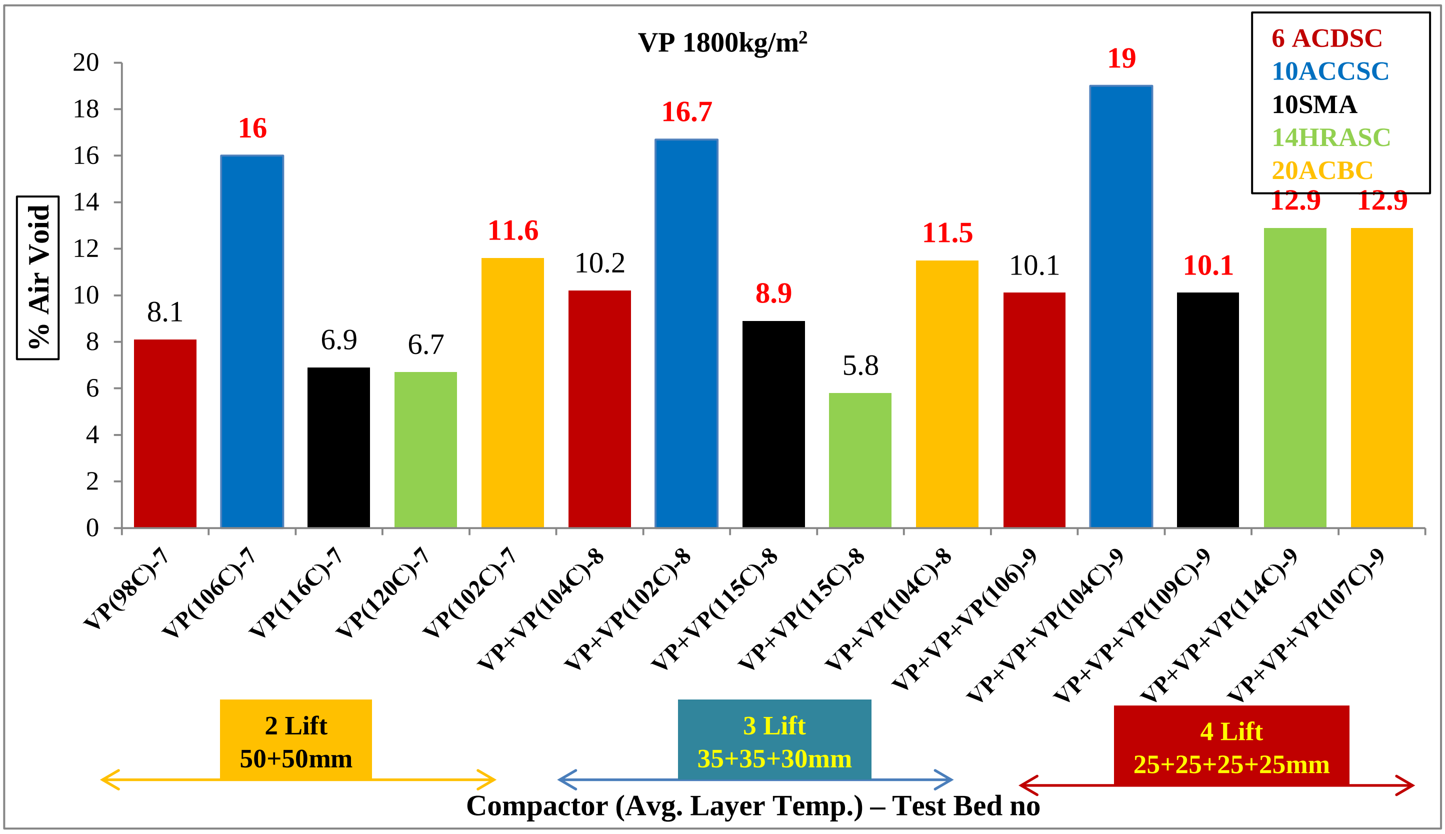

Figure 3: Air void content in Affinity water trial using vibrating plate

3.2 TRL study

This trial was conducted and published as TRL 624 [15] to verify the performance of 600-1000 kg/m single drum roller and for subsequent inclusion in the SROH, because it had been excluded after the 2nd edition of SROH (Department for Transport, 2002). In this respect, Scott Wilson Pavement Engineering (SWPE) was appointed by TRL as the contractor responsible for the verification trial. The field trial took place between 19 and 25 November 2003, at a car park in Raynesway, Derby using following types of materials:

- AC 6 dense surf
- AC 10 close surf
- SMA 10 surf
- HRA 15/10 surf

The main trial on the effectiveness of 600-1000 kg/m roller took place in the top 40mm or 60mm of above mentioned asphalt surface course at 280mm width trenches. The entire process was witnessed by representatives from TRL, the contractor (Scott Wilson Pavement Engineering-SWPE) responsible for the verification of the trial, and the roller manufacturers (Benford Ltd and Bomag GB Ltd). All testing was carried out under controlled and accredited laboratory conditions in order to provide traceable results to ensure compliance with the method under then current SROH requirements.

Maximum density (test 1) of loose asphalt sample was determined according to BS EN 12697-5[18] and bulk density of asphalt cores to BS EN 12697-6, procedure C [19], using paraffin wax as sealing agent. As maximum density influence the air voids content greatly, another test house (Nottingham Centre for Pavement Engineering-NCPE) was used to measure the maximum density (test 3) according to the same test specifications used by SWPE. The maximum density according to theoretical values (test 2) for the specific mixtures was supplied by material supplier. The overall results in this trial indicated that the materials compacted with this roller complies with the requirements for the air voids content in the SROH; however, a maximum of 8% difference of air void contents was notable when the test was performed in two laboratories (SWPE and NCPE) on cores from the same mixture taken after SROH recommended roller passes (as shown in Table 2) [15]. As shown in Table 1 and 2, both laboratories measured the maximum density (Test 1 and Test 3) once from the loose mix and only SWPE laboratory measured the bulk densities from cores taken after different roller passes. Moreover, after eight roller passes, in terms of air void content compliance with SROH requirement, the AC close surf cores fails by 100% when tested in SWPE laboratory, whereas the same mixture type passed by 100% in NCPE laboratory as shown in Table 2.

3.3 Balfour Beatty – Pavement Testing Services (PTS) Ltd Trial

Balfour Beatty Utility Solutions (BBUS) decided to evaluate the performance of the compaction plant usually used in utility reinstatement works after experiencing significant failure rates relating to air voids contents in surface course materials during coring, despite following the method and materials specified in the SROH and following the suggested guidance of compaction procedures quoted in NGA8.3 [13, 16]. The primary objective of this trial was to review the effectiveness of various SROH recommended compaction plant. The trial was undertaken in Worsley Depot car park on July 2011 using two different models of Trench rammer (VT), three different models of plate compactor (VP) and a 720kg/m pedestrian roller (R). The compaction plant, supplied by the manufacturer, was new and in full operational condition, as witnessed by the Technical Manager from the plant manufacturer throughout the trial [20].

Three different sizes (1m x1m, 2m x1m and 3m x1.5m) of excavation were reinstated with AC 20 dense bin (60mm layer) and AC 10 close surf (40mm layer) and the materials were delivered to the trial areas in a hot box to ensure that temperatures remained reasonably consistent throughout. All testing was carried out under controlled and accredited laboratory conditions in order to provide traceable results to ensure compliance of the SROH requirements. Asphalt materials laid in all test beds were from the same single load of the respective mixture. Each of the asphalt layers were initially compacted in accordance with SROH Table NGA8.3, method compaction, and in-situ density testing performed using a Nuclear Density Gauge (NDG). Two combinations of compaction plant were used, namely VT+VP (on the small and medium test hole) and R+R (on the large test hole) on binder and surface course respectively.

Overall, binder course (20 AC bin) materials on all 9 test beds complied, whereas surface course (AC 10 close surf) materials showed 8 out of 9 test beds failed to meet the relevant air void requirement of SROH, exhibiting an average air voids content of 15.3% (BBUS and PTS, 2011) . In the case of VT+VP, the success rates on binder and surface course were 100% and 0% respectively, relating to the compliance with the SROH air voids content requirement in the carriageway. Whereas, in the case of R+R, the success rates on binder and surface course were 100% and 33% respectively.

Table 1: AV content in 6mm dense surface course in TRL Trial [15]

Trench/ Section/ Compactor	Nominal thickness (mm)	Actual thickness	Number of roller passes	Bulk density (Mg/m^3)	Calculated air voids content (%)		
					Test 1 (Maximum density = 2.521 Mg/m^3)	Test 2 (Maximum density = 2.503 Mg/m^3)	Test 3 (Maximum density = 2.323 Mg/m^3)
S/A Benford	60	59	2	2.048	19	18	12
			2	2.036	19	19	12
			4	2.107	16	16	9
			4	2.108	16	16	9
			6	2.143	15	14	8
			6	2.119	16	15	9
			8	2.136	15	15	8
			8	2.169	14	13	7
			10	2.146	15	14	8
			10	2.147	15	14	8
			12	2.198	13	12	5
			12	2.162	14	14	7
I/C Bomag	40	50	2	2.149	15	14	7
			2	2.140	15	15	8
			4	2.181	13	13	6
			4	2.158	14	14	7
			6	2.207	12	12	5
			6	2.203	13	12	5
			8	2.190	13	13	6
			8	2.210	12	12	5
			9	2.196	13	12	5
			9	2.206	12	12	5
			10	2.172	14	13	7
			10	2.217	12	11	5
2/C Bomag	40	46	2	2.101	17	16	10
			2	2.074	18	17	11
			4	2.133	15	15	8
			4	2.134	15	15	8
			6	2.185	13	13	6
			6	2.190	13	13	6
			8	2.217	12	11	5
			8	2.218	12	11	5
			9	2.206	12	12	5
			9	2.196	13	12	5
			10	2.230	12	11	4
			10	2.190	13	13	6

Test 1 : Maximum density from SWPE report to BS EN 12697-5:2003
Test 2 : Theoretical maximum density supplied by Aggregate Industries
Test 3 : Maximum density from TRL/Nottingham tests to BSEN 12697-5:2003

Table 2: AV compliance with the SROH requirement after 8 roller passes [15]

Lift thickness	Product type	Calculated air voids content using three maximum densities		
		SWPE	Theoretical	NCPE
60mm	AC 6 dense surf	Pass (in 50% of results)	Pass (in 50% of results)	Pass
	AC 10 close surf	Fail	Pass	Pass
	HRA 15/10 surf	Pass	Pass	Pass
	SMA 10 surf	Pass	Pass	Pass
40mm	AC 6 dense surf	Pass	Pass	Pass
	AC 10 close surf	Pass (in 25% of results)	Pass (in 75% of results)	Pass (in 75% of results)
	HRA 15/10 surf	Pass	Pass	Pass
	SMA 10 surf	Pass	Pass	Pass
A pass without percentages means that all the duplicate results had complied with the SROH				

4. Variability and Specification Limits

The basic mathematical measure of variability is the variance;, however, the most commonly used term to measure the variability is the standard deviation, because it considers the effect of all of the individual observations and the units of standard deviation are the same as those in the measurement. The variance is equal to the mean-squared deviation of the variable from the population mean (as shown in following equation) and standard deviation is the square root of the variance.

$$\sigma_p^2 = \frac{\Sigma(x - \mu)^2}{n}$$

where:

σ^2_p = the population variance

σ_p = the population standard deviation

x = the individual values

μ = the population mean

n = the number of observation s in the population

To estimate the population parameters, sample standard deviation are almost always used in highway materials and construction using a day's production or a mile length of pavement which involves small sample sizes (rarely more than 10) [21]. The sample standard deviation (σ_s) is calculated using following equations:

$$\sigma_{s} = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$$

where

σ_s =the sample standard deviation

x = the individual values

$\bar{x}$= the sample mean

n = the number of observations in the population

n -1= the degree of freedom

4.1 Sources of Variability

Four specific factors responsible for controlling the test results have been reported as (i) natural inherent variation in materials, (ii) variation due to sampling, (iii) variation due to processing and (iv) variations attributable to testing procedures [22]. Similarly Hughes [21] suggested that these four types of variability must be considered in establishing specification limits, as shown in the following equation and indicates that the materials producer and/or contractor can only control manufacturing/construction variability.

$$\sigma^2_T = \sigma^2_m + \sigma^2_s + \sigma^2_t + \sigma^2_{m/c}$$

where

σ^2_T = the total variance

σ^2_m = materials variance

σ^2_s = sampling variance

σ^2_t = testing variance

$\sigma^2_{m/c}$ = manufacturing and construction variance

σ_T = the overall standard deviation

4.2 Use of Variability in Specification Limits

A study conducted by Amirkhanian [23] concluded that, if sampling and testing variability are not considered when developing specification tolerance limits, contractors may be unfairly penalised because of the imprecision of a test method that is beyond their control. Hence, a realistic specification tolerance must be large enough to allow for these four types of variability. If they are not, then the contractor will be penalised for variability that is beyond his control. An estimate of 40% to 80% of a specification tolerance for only sampling and testing variance has been suggested by Hand [24]. Furthermore, Warden [25] stated that an enforceable specification must be realistic statistically, in the sense that the required tolerance limits reasonably reflect; (i) the random variation inherent in the material itself and (ii) the error of measurement during sampling and testing.

4.3 Measuring Specification Effectiveness by Variability

The comparison of the results of actual test data with existing specification requirements can provide a measure of how well a specification is being met and can indicate the suitability and practicality of the required limits [25]. The procedure to assess specification effectiveness has been described by the collection and analysis of data to quantify materials and construction quality (wanted quality versus specified quality versus delivered quality) in statistical terms using the mean and, standard deviation (SD), offset from target [26].

Therefore, many state highway agencies first conducted experimental projects or gathered historical construction quality data, or both, while determining the limits during developing specification. Hence, by performing statistical analysis of the test results in terms of SD of air voids (AV) content found in the three trial studies, an indication of the gap between the work specified (in the SROH) and the work received (following the SROH) can be assessed, even though these trials were not fully representative in terms of real life environment.

4.4 Variability Found in Three Trial Studies

In the SROH, the use of compacting effort and their combinations is dependent on undertaker's choice and the specified air voids content requirements are different for different materials (Table S10.1 in SROH). Hence the overall variability in terms of sample standard deviation and coefficient of variation (CV) of the three trial studies for respective materials, irrespective of employed compaction efforts, have been analysed and are shown in Figure 4. In figure 4, the number of samples or observations used in determining the sample Standard Deviation (SD) has been denoted by 'n'. The number of sample (n) were 9 in the case of Affinity water and BBUS-PTS trial and in the case of TRL trial, it was 6.

Even though the trials were conducted in the period ranging from 2003 to 2012, the illustrated variability shown in Figure 4 substantiates the extent of variability in any reinstatement. It is evident from Figure 4 that, as the combination of compacting effort employed in the Affinity water study was more than BBUS-PTS study, the variation of AV content was also more in the Affinity water study. In the case of the TRL trial, the low variability was due to use of only one type of compacting effort (roller). However, the 4.35% SD in the TRL trial (Figure 7) for AC dense surf was due to the inter-laboratory variation.

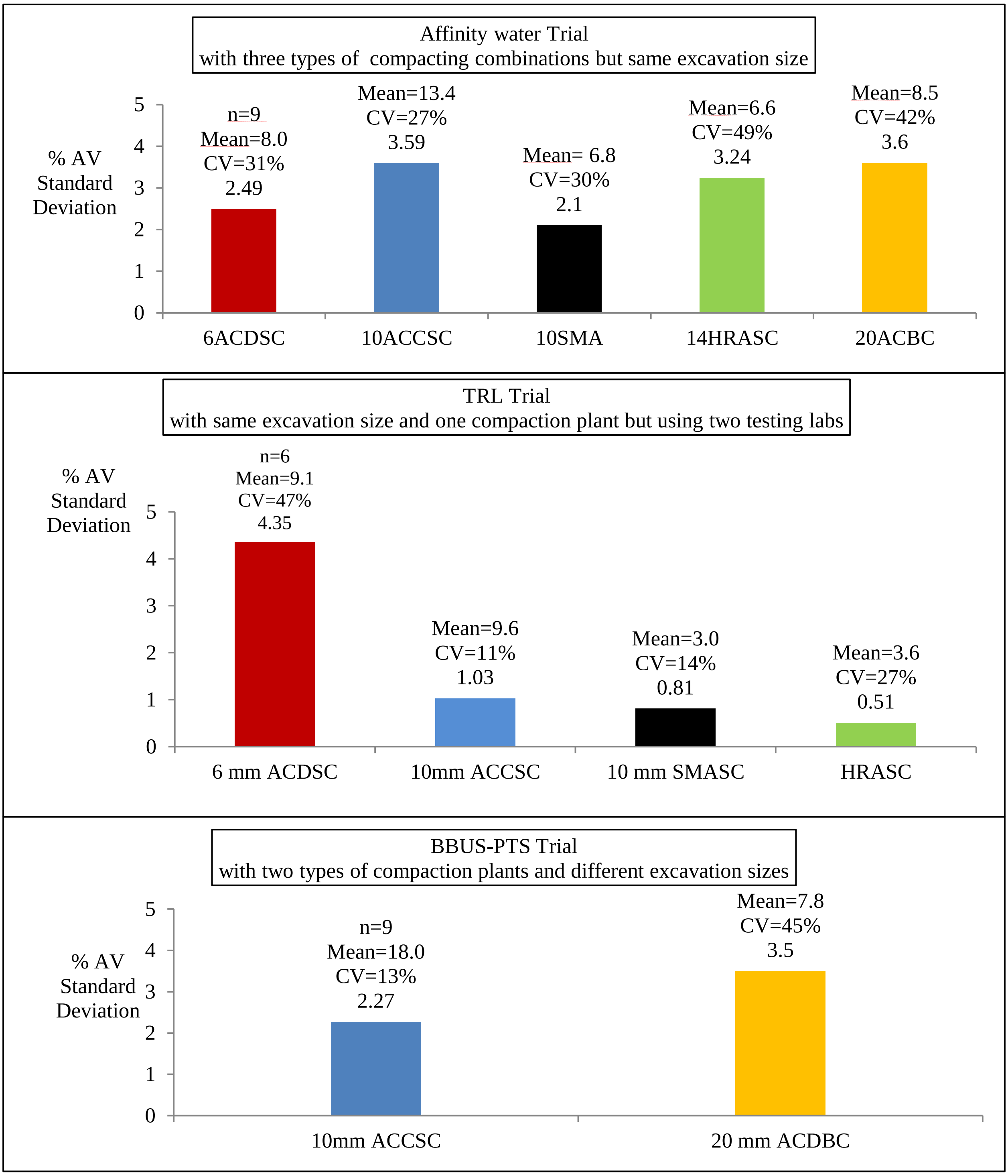

Figure 4: Overall variability in three trial studies

Table 3: Calculated air void using two extreme values of maximum density found for 6 AC dense surf in the Affinity water trial

	Original Air void content recorded in trial	Calculated Air void content using **maximum** value of recorded maximum density	Calculated Air void content using **minimum** value of recorded maximum density	**Difference** between the upper and lower value of air void content of same core
	Vibrotamper + Vibrating Plate			
Core 1	11.4%	15%	8%	**7%**
Core 2	4.2%	6%	-2%	**8%**
Core 3	4.4%	12%	4%	**8%**
	Vibrotamper + Roller			
Core 4	8.5%	11%	3%	**8%**
Core 5	7.0%	9%	1%	**8%**
Core 6	8.5%	9%	1%	**8%**
	Vibrating Plate			
Core 7	8.1%	10%	3%	**7%**
Core 8	10.2%	10%	3%	**7%**
Core 9	10.1%	12%	5%	**7%**

4.5 Influence of Variability on Producing Biased Test Result

In the London Borough of Enfield - Affinity Water trial, each core of respective mixtures, showed fluctuating maximum density values, although in theory, the maximum densities for a mixture should be identical. For example, for the 6 AC dense surf mixture (which had 100% SROH compliance as shown in Figure 2), the difference between the recorded maximum (2449 kg/m^3) and minimum value (2257 kg/m$^{3)}$ of maximum density was 8.5%. Hence, the air voids content of the cores, using these two extreme values of maximum densities of same mixture (6 AC dense surf) has been calculated and shown in Table 4. The difference between the maximum and minimum calculated air void contents were found to be in the range of 7% to 8%, as shown in Table 3.The sources for this lower repeatability in the maximum density measurements have led to possible biased compaction measurements and make compliance largely a matter of chance, essentially embedded either;

- Within the testing procedure or
- Redistribution of the mixture's ingredients due to hand laying operation which is less likely in the case of machine laid work, or
- Both

These two embedded sources that generate biased compaction assessment results are likely for any utility reinstatement work. However, more biased compaction measurement is to be expected when reproducibility is also an influencing factor, as found in the case of the TRL trial.

4.6 The Influence of Variability on Precision

The precision for testing air voids content quoted in the Standard BS EN 12697-8 (European Committee For Standardization, 2003) provide allowances in the range of 1.1% (for standard deviation of 0.4%) to 2.2% (for standard deviation of 0.8%) as repeatability and reproducibility respectively. These precision allowances have been inserted in the British Standard by considering only the variables associated with the operator/s and testing equipment/s.

The overall standard deviation for 6 AC dense surf in the Affinity water trial was 2.49% (as shown in Figure 4), leading to a repeatability of measured air voids content in the range of 7%. In the case of the TRL study, the SD for the same type of mixture was 4.35%, leading to a reproducibility of measured air voids content in the range of 12% as calculated following the precision statement quoted in BS EN 12697-8 (European Committee For Standardization, 2003).

In the Specification for Highway Works (The Highways Agency, 2008), a 2% tolerance above the maximum permitted air voids content has been allowed in the case of core pairs whose centres are not more than 100 mm from the joints to allow for the poorer compaction achievable in such locations. However, though all reinstatement works are essentially surrounded by construction joints, no such allowance has been explicitly provided in the acceptance plan or testing regime of SROH.

4.7 Variability in Real Life and its Effect on Utility Reinstatement

Reinstatement work in real life usually encounters different types of variables (as shown in Table 4) or uncertainties. These uncertainties will cumulatively intensify the probability of receiving end product with added dispersive nature, resulting requirement of higher ranges of precision provisions for repeatability and reproducibility. The inclusion of end product specification using air voids content through publication of the SROH 2nd Edition in 2002 might not embed the allowances for precision, as the precision statement from BS EN 12697-8 was not then available and BS 594987 had not been published.

Table 4: Sources of variability relating to SROH prescribed method of construction

	Sources of variability			
Category	**Construction**	**Material**	**Sampling**	**Testing**
Items	• 10 types of compaction plant under three generic groups (table NGA8.3) • Combination of compaction plants as per site requirements (NG 10.2.3) • 4 generic categories of excavation and trenches (S1.5) • Various weather condition • Dissimilar geographical location	• 6 types of unbound materials (table A2.5) • 5 types of bound materials (table A 2.5) • Inherent material variability • Different sources of mineral aggregates • Within-batch variation • Batch-to-batch variation	• Sampling technique variation • Sampling frequency • Sample location • Sample size	• Operator variation • Equipment variation • Within-lab variation • Lab-to-lab variation

5. Development of Specifications and Limiting Values

Specification limit(s) has been defined in the Transportation Research Circular [27] as "The limiting value(s) placed on a quality characteristic, established preferably by statistical analysis, for evaluating material or construction within the specification requirements". Specification limits used to control and accept a product are most appropriate when they take account of the variability typically found in the process that produces the product [21]. A research report on statistical quality control of highway construction materials stated that specification requirements do not govern variation, yet variation in materials and construction does govern the establishment of realistic specification limits [28].

5.1 Example of Using Variability in Specification

It is more realistic to determine typical process capability and use that variability in establishing the appropriate specification limits. Likewise, in the national asphalt specification for Australasia [29], the compaction is assessed through relative compaction where relative compaction is the percentage ratio of the in-situ density of the compacted asphalt and the reference density of the asphalt of a particular lot, whereas, the reference density is the mean of the five most recent maximum density measurements of the same mixture. The work represented by a lot is assessed as the characteristic value of in-situ air voids content specified in the specification.

Characteristic value of in-situ air voids content (%) = 100 – Characteristic relative compaction

Characteristic value of relative compaction = Mean of relative compaction – Kx sample standard deviation of the relative compaction results

Where:

K = Acceptance constant (a factor that depends on the number of tests, varies from 0.719 to 0.828 for 6 to 10 respectively, as the number of tests).

Not only process capability but also process variability has been embedded in the specification limiting values. This makes the national asphalt specification of Australasia realistic. However, no density test has been assigned in this specification in the case of lot less than 30t or layers with nominal thickness less than 30mm. Determining the air voids content limiting values through comprehensive research for both materials and equipment commonly used for works other than the machine lay method has also been recommended in the Affinity water trial report [14].

5.2 Updating Specification on the Basis of Variability

Establishing the process variability and the resultant specification limits is not a one-time procedure. A database should be established to accumulate the variabilities and should be reviewed periodically to determine whether any significant changes in the variability are taking place. Similarly, the Horne Report, which encouraged the Government of the UK to establish the Highway Authorities and Utilities Committee (HAUC) by the Local Authority Association and the National Joint Utilities Group (NJUG) in 1986, also stated that, "*The new specifications should not be regarded as the last word on the subject, but should be kept under review in the light of the results of further research as these emerge*" [4]. However, until now, there has been no study conducted for addressing this issue highlighted by Horne in 1985.

Even when the construction methods described in the specifications are comprehensively followed, they may not always produce the desired end result. The specified construction methods should be based on past positive experience, and if variables unknown to the specification writer change under new conditions – for example, machine laid operation and requirement to employ hand laying operation in restricted areas), the end result may not be satisfactory even if the specified construction methods are followed. Although specifications state that the contractor is responsible for the end result, this is usually not legally enforceable if the material and method requirements have been met [26].

5.3 Specification Development Process

The overall specification development process has been stated by Burati [6] with three primary phases; Initiation and Planning, Specification Development and Implementation. The steps for the implementation phase have been described with the flowchart shown in Figure 5.

It is evident from Figure 5 that trying the new specification on pilot projects (before implementing in agency-wide) would allow the specification writing agency to examine the outcome and, if desirable, to fine tune the specification further under ‘real world’ conditions.

Horne’s recommendation “*In short term, there must be an immediate study of methods of measuring performance with field trials of their feasibility, as an aid to the production of performance specifications*” [4], prior to the first edition of the specification for utility reinstatements emphasised the significance of pilot field trial in producing a realistic specification.

5.4 Influence of Specification Development Process on Limiting Values

The importance of establishing the specification limits under sampling, testing, and process conditions similar to those to which they will be applied has been indicated by Hughes [21]. Likewise, Burati also commented that, “letting an untested (specification) agency–wide without first testing it on pilot projects is not a good idea and should not be done” [6]. In a TRL study [30], commissioned by Department of Transport, problems relating to compliance were identified following the introduction of the SROH in 1993, where method specification was followed for assessing compaction performance.

Recently, a study was conducted by Aggregate Industries Ltd to develop a binder-rich formulation containing low in-situ air void for footways [31]. In this study, AC 6 dense surf 160/220 complying with the BS EN 13108-1 [32] has been used as a reference mixture in controlled laboratory conditions using impact compaction (2x 50 blows) at 130°C. Two types of specimens (12 specimens per mixture) were prepared, applying the upper and lower target limit of aggregate gradation and corresponding tolerances provided in guidance note PD 6691 [33] for preparing asphalt mixtures. The resulting air void content of compacted specimens are shown in Table 5.

The un-achievable SROH compliance by the laboratory prepared mixture prepared from applying the specified lower target values of aggregate gradation (coarse) in terms of mean air voids content of 12 samples (as shown in Table 5) was notable from this recent study [31]. The out-of specification material (for coarse mix (as shown in Table 6) in terms of air voids content, even under controlled laboratory condition using specified materials indicate the too restrictive nature of the SROH air voids content limiting values. At the same time, materials complying with BS EN 13108and PD 6691 are not sufficiently specified to ensure the compliance of the SROH air voids content requirements was apparent from the results of this laboratory study by Aggregate Industries Ltd. A greater air voids content is expected in some of the samples taken from the pavement prepared with a similar type of mixture (specified in the SROH) under real life condition. Therefore, appropriateness relating to the compliance of the SROH specified level of compaction (measured by in-situ air void content) using the material quoted in the SROH is not convincing.

Table 5 : Air void content of laboratory compacted samples applying PD 6691 specified upper and lower aggregate gradation limits after [31]

Mix Type	Air void Content (%)			Remarks
	Minimum	Mean	Maximum	
AC 6 dense surf – Fine	5	7	8	The used binder content of 5.7% for coarse and 6.7% for fine mixture of crushed rock aggregate-granite was in accordance with the tolerance limit stated in PD6691.
AC 6 dense surf – Coarse	14	15	16	
Supertrench (A newly developed proprietary mixture)	1.5	1.9	2.8	An out of specification material with respect to PD6691 containing high binder and filler content

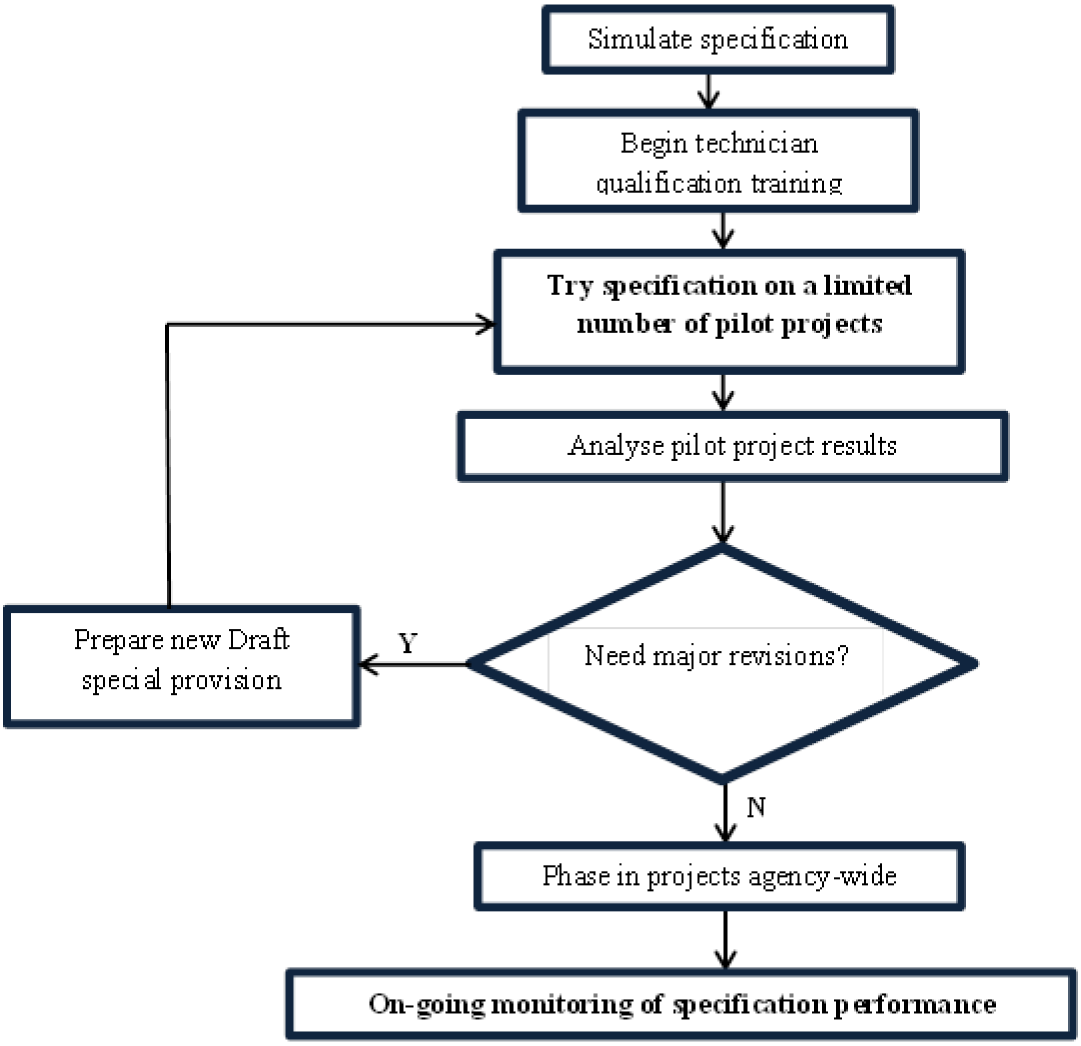

Figure 5: Flowchart for implementing a new specification after [6]

6. Asphalt Compaction in British Standards

Through implementing the 2nd Edition of the SROH, the Department for Transport introduced an end result specification (ERS) in place of method specification for assessing asphalt material, and accordingly, removed the compaction method from the specification. The compaction for asphalt material for major road construction in British Standards BS 594987 [34] is assessed by stating the following:

- *End result compaction shall be applied to designed dense base and binder AC mixtures which have been type tested in accordance with BS EN 13108-20. A method of compaction shall be adopted and detailed in a suitable quality plan so as to ensure that the void content of the finished mat conforms to the required limits on void content.*

NOTE: This method is applicable for works intended to carry heavy traffic. The scale of works should be such as to justify the cost of testing and control (clause 9.5.1.1).

- *Compaction control requirements for performance‑related HRA surface course (clause 9.5.2).*

A sampling regime for determining the air voids content and permanent deformation (wheel tracking) has been prescribed in clause 9.5.2.

- *Compaction control requirements for SMA binder course (clause 9.5.3).*

Sampling regime for determining air voids content and permanent deformation (wheel tracking) has been prescribed in clause 9.5.3.

However, the following note has been quoted concerning the compaction of asphalt materials in BS 594987:

NOTE: End result compaction is more appropriate for machine‑laid work on major road contracts (clause 9.1).

The general requirements for compaction of asphalt stated in clause 9.2 are only applicable for machine‑laid asphalt. Hence, the use of end result specification (for air voids content) and associated testing regime for footways reinstatement works is acknowledged to be not totally suitable in the relevant British Standard due to service load (footways), scale of work (utility reinstatement), nature of construction (hand laid) and material used (recipe mixed).

6.1 Practicality of Using Air Voids Content for Utility Reinstatement

In the national asphalt specification for Australasia [29], no density test has been assigned in the case of a lot of less than 30t, reflecting the practicality associated with the nature and/or scale of work and testing regime.

BS 594987 clause 9.3 also states that,

"In areas where the methods specified in machine laid asphalt section are impractical for reasons of restricted access, limited working area or restricted width of surfacing, and for situations where the underlying construction will not support a heavy static roller, one of the following alternative methods of compaction shall be used.

a) On footpaths and similar areas, either static rollers of 2.5t deadweight or vibrating rollers of a minimum deadweight of 750kg, unless it can be demonstrated that an equivalent compactive effort can be provided by a vibrating roller of a lesser deadweight.

b) In trenches and other extremely restricted areas, vibrating plate compactors".

NOTE 1: In all cases the procedure adopted should be as close as is practicable to that specified in 9.2 for the larger scale work.

Hence, no compaction control measure using air voids content and/or wheel tracking has been specified in the British Standard for hand laid and patching work (clause 9.3 of BS 594987). End result compaction control has only been assigned in BS 594987 for designed AC dense base and binder course (these mixtures are not specified in the SROH for footways reinstatement).

6.2 TRL Guide for Footways Compaction Control

The TRL guide [35], intended to provide a practical field guide for highway engineers involved in the structural design, construction and maintenance of footways and cycle routes (asphalt is generally laid by hand or mini-pavers), stated that, in the case of hand- laid operations, the required level of compaction may be difficult to achieve.

Furthermore, a study on footway maintenance by TRL report-134 [36] suggested that, *"Because of the confined areas of work, the compaction of bituminous material is normally by the use of pedestrian roller and a method specification is universally adopted. Manual compaction is often applied around street furniture and other restricted areas. A further restriction on compaction is the presence of utilities' apparatus. In order to achieve the required level of serviceability, a high level of compaction is required and the restrictions imposed in footway compaction can limit performance. With this consideration it is important that the method specification is followed and that adequately trained and supervised resources are available to ensure the requirements are achieved"*.

6.3 Specification for New Footways in DMRB

The Design Manual for Roads And Bridges (DMRB) sets out the requirements, guidance and advice for **new footway construction** in HD 39/01 [37] and maintenance in HD 40/01[38]. Following specification has been stated in HD 39/01 for compaction for asphalt material in new footway construction:

Compaction of asphalt materials can be carried out by a method specification (refer to Annex D of this Part), but it is important that the work is adequately supervised to ensure that the requirements are being achieved. However, as dense bitumen macadams are more difficult to compact it is recommended that they are compacted to satisfy an end-product specification, in terms of air voids (refer to Annex C of this Part). [Cl 4.17 of [37]]

Compliance should be judged from the determination of air voids for areas of 1000m² or from the area laid in one day where the area is less than this. Three 100mm nominal diameter core pairs should be taken from each area in a random manner. [Annex C-C2]

Hence, the assessment of large scale newly constructed footways, exclusively without any repair in trenches or small sized openings, requires air voids content compliance similar to major carriageway construction, has been quoted in the case of just dense bituminous macadams. However, the assessment of compaction on newly constructed footways by method specification (except dense bitumen macadams) in this specification (HD 39/01) is in accordance with the suggestion provided by the TRL report-134 [36]. It can also be noted that the relevant method for compaction (Annex D) in HD 39/01 is a part of this specification to be followed by the users.

7. Problems in end result specification and an realistic approach for assessing Performance

Research by [39] reported the key contributors to risk in end result specification as:

- Contractor testing versus agency testing
- Frequency of testing and/or number of samples
- Variability and/or bias of test device and/or test procedure
- Specification parameters, including:
  - Specification limits
  - Pay factor equation
  - Pay ‘caps’
  - Acceptance test frequency and acceptance tolerance
  - Third-party testing provisions

It can be noted that, relating to engineering and statistical principle, the above stated factors are applicable for reinstatement work in the UK except the pay factor and pay caps which are often practiced in USA Quality Assurance (QA) plans.

The adoption of a performance- based specification instead of using air voids content for hot mix asphalt surfacing materials has been specified New Zealand [40], whereas, the performance requirement is controlled by the mix design properties (binder drain-down, VMA, wheel tracking), production testing (process control monitoring using JMF, Maximum Theoretical Specific Gravity) and field criteria (surface ride, permeability, texture).

Similarly, no in-situ compaction requirement for asphalt materials in footways has been defined in the Australian utility restoration specification [41] but just the material with desired design parameters is specified [42].

The requirement for establishing logical relationships between expected pavement performance and the material characteristics that are measured to judge contactor performance while developing end result specification (ERS) has been stated by Freeman [8]. Measured material characteristics such as air voids content used in specifications must have previously been found to correlate with fundamental engineering properties that affect pavement performance.

7.1 An Evidence Based Approach for Assessing Utility Reinstatement Performance

The evidence of satisfactory performance of the reinstatement works [43] comprising SROH non-compliant air voids contents (as shown in Figure 6) indicate that, the linkage between air void content and durability, with the limits for footways currently in SROH, is non-proven. Moreover, any engineering justification for coring a well performing reinstatement work, even after 27 months and 12 years of installation, when the existing surfaces are at the end of its service life [Figure 6(a)] or the performance of the reinstatement is closely matching with the existing construction [Figure 6(b)], was not found in this research.

The evidence of well performing reinstatements even including SROH non-compliant air voids content levels, were due to the absence of significant service load to cause surface distress on footways. Hence an in-service guarantee by the undertaker for an extended period linked to the agreed intervention limit might be a simple, realistic and acceptable solution with low risk on footways reinstatement. This extended method of monitoring performance would remove any cost risk of poorly performing utility reinstatements from the highway without the need for costly and unreliable coring programmes**.**

Figure 6: Satisfactory performance of reinstatements works even comprising SROH non-compliant air voids contents. Photograph taken; (a) after 27 months of installation, (b) after 12 years of installation [43]

8. Conclusions

Air voids content limiting values, if used, must be backed by evidential research and statistical analysis of the data obtained from field trials. Piloting experimental field projects using sampling, testing, and process conditions similar to real life reinstatement conditions or gathering historical construction quality data, or both, for determining the realistic limits is vital. This is also mentioned in the historic Horne Report of 1985, but has not been followed in the development and subsequent implementation of the 2nd and 3rd edition of the SROH.

This study has shown that:

i) At the time of publication of the SROH 2nd Edition in 2002, the precision statement from BS EN 12697-8 was not available and BS 594987 had not been published. The former shows the inaccuracy of a repeated test for air voids content without consideration of construction procedure, mixture, compaction, testing and sampling variables identified in this research. These variabilities and subsequent biased compaction measurement (leading to a very wide range of unpredicted outcomes) was apparent in the UK trial data but the significance was not appreciated.

ii) The use of air voids content determination on single cores is so inaccurate as to make compliance largely a matter of chance, as a result of compounding errors in the measurement of bulk density and maximum density. The use of air voids content other than for design mixtures, does not comply with UK best practice as outlined in BS594987: 2010, due to the within mix variability for recipe mixtures and the use of hand laying as the principal method of installation. The use of a measured in-situ air voids content criteria in a Specification for Footway reinstatements cannot be sustained on technical grounds.

iii) A specification should be realistic, practical, and sustainable and be able to predict performance. The current specification based upon coring for air void content, fails on all of these basic requirements. It could lead to a very wide range of unpredicted outcomes, putting both the contractor and the client at unacceptable risk.

iv) The linkage between air voids content and durability in footways reinstatements with the limits currently in SROH is non–proven. Use of air voids content limits may be possible using a statistical approach as used in Australasia and the USA. However, in cases, this approach is implemented only for machine-laid large scale construction.

v) The SROH already covers the actual performance of reinstatements under S2 during the guarantee period and in practice, reinstatements that fail air voids content rarely have issues relating to surface profile (S2.2) and surface regularity (S2.4).

vi) Taking account of the service loads, nature and scale of works in footways, an in-service guarantee by the undertaker for an agreed extended period**,** linked to an allowable intervention level, could be a simple, realistic and acceptable solution ensuring a durable reinstatement that removes the financial risk of failure from the highway authority. This will encourage utilities to improve, innovate and develop to increase the durability and life span of their reinstatements.

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