Innovative QC/QA Compaction Method for HMA Pavement using Intelligent Compaction (IC) Technology

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ABSTRACT: It has been found that intelligent compaction (IC) technology recently implemented in the USA and Japan to improve compaction quality and process is adaptable to Quality Control and Quality Assurance (QC/QA) applications for hot mix asphalt (HMA) pavement. Most of the IC systems provide compaction information such as density, roller passes and pavement temperature during rolling, which samples 100 % of the data from the rolling area. Conventional QC/QA criteria for HMA pavement in most countries is based on a limited number of core samples. For example in Japan, only one core per 1,000 m^2 with a minimum of 93.0 % Marshall lab density is required for QC/QA. There are various types of "Roller Measured Values" developed by different equipment manufacturers, which all provide stiffness or modulus values of the HMA pavement by processing acceleration signals of vibrating drums. However, it could be more beneficial if the data is processed statistically as relative values to evaluate the compaction quality of the entire pavement. In this paper, updated information on IC technology and its implementation will be reported, along with comparisons of statistical analysis by the conventional and IC QC/QA methods for HMA compaction. It will be demonstrated that the IC-QC/QA method is beneficial to improve not only the quality of HMA pavement, but also reduce the life cycle cost from construction, inspection to maintenance using a real time QC/QA process.

KEY WORDS: Intelligent compaction, Roller Measured Value, CCV, Stiffness, Modulus, CIS

1 INTRODUCTION

1.1 Intelligent Compaction

Intelligent Compaction (IC) technology recently implemented in the USA to improve the quality of compaction for hot mix asphalt (HMA) pavement is supported by two major technical advances in measurement methods. For the relative values of the material stiffness, the Roller Measured Value (RMV) for HMA mixes and granular soils is obtained by processing drum acceleration and roller positioning is accomplished by using Global Positioning Systems (GPS) and auto tracking Total Station Systems (TSS). In addition, the development of a heavy duty computer with data processing software for displaying, recording and documenting IC data and a Computer Aided Design (CAD) system have allowed significant development of IC systems.

Various RMVs have been invented by different roller manufacturers since the Compaction Meter Value (CMV) was developed (Thurner, 1980). Those systems with various formulae are listed in Table 1. There are dimensionless RMVs values such as CMV and Compaction Control Value (CCV, Sakai, 2005) while other RMVs that measure stiffness in units of MN/m such as ks (Andergg et al., 2004), or with the dimension of a modulus in units of MN/m^2 such as Alfa (Scherocman et al., 2006) and Evib (Kloubert, 2006).

Table 1: Intelligent compaction systems with various formulae

Vendors	IC system	Accel ero meter	Unit	Measurement and Analyzing method	CAD Compatibility
Caterpillar	CMV	Yes	None	$GeodynamikCMV = C\left(\frac{A_{2\Omega}}{A_{\Omega}}\right)$ $MDP - P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b)$	None
Dynapac	CMV	Yes	None	$GeodynamikCMV = C\left(\frac{A_{2\Omega}}{A_{\Omega}}\right)$ $BouncingValue = \frac{A_{0.5\Omega}}{A_{\Omega}}$	None
Sakai	CCV	Yes	None	$CCV - \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] \times 100$	Yes(2&3D)
Ammann	ks	Yes	MN/m	$ks = 4\pi^2 f^2\left(md + \frac{m_r \gamma_t \cos(\varphi)}{A}\right)$	Yes
Obayashi-Maeda	Alfa	Yes	MN/m^2	$Ft = \frac{\frac{\sum_{i=1}^{3} S_i + \sum_{i=1}^{3} S_i'}{S_0 + S_0'}}{F/(m_1 + m_2)g}$ $E = \frac{2 \cdot (1-\nu^2)}{B \cdot \pi} \cdot \frac{\left(\frac{4}{3} \cdot Ft + 1\right) \cdot (2\pi f_0)^2 \cdot m_2}{1 - 0.32\alpha + \sqrt{0.1024\alpha^2 - 1.64\alpha + 1}}$ $\alpha = 1 - \left(\frac{F}{(m_1 + m_2)g}\right)^2$	Yes(2&3D)
Bomag	Evib	Yes	MN/m^2	$Z_a = \frac{(1-\nu^2)}{E_{VIB}} \cdot \frac{F_t}{L} \cdot \frac{2}{\pi} \cdot \left(1.8864 + \ln\frac{L}{B}\right)$ $where, B = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-\nu^2)}{E_{VIB}} \cdot \frac{F_s}{L}}$	None

Auto-feedback control of drum vibration mechanisms were also developed, which adjusts the direction of the vibrating force and amplitude of the roller drum in response to a change of RMVs. However, careful application of auto-feedback control is required because drum acceleration is affected by several factors including temperature, mix design, lift thickness of HMA, underlying layer conditions, etc.

In the USA, since the Federal Highway Administration (FHWA) began the first IC test on HMA pavements in Minnesota in 2007 (Chang et al., 2007), the benefit of IC was clearly demonstrated as a full report can be found at www.intelligentcompaction.com. FHWA is working with 12 State Departments of Transportation (DOT's) through Transportation Pooled Fund (TPF) Solicitation No. 954. The goals for the Georgia DOT (GDOT) IC test quoted later in this paper are (1) To demonstrate HMA IC technology to GDOT's personnel, contractors, etc., (2) To correlate the IC roller measurement with GDOT's current in-situ density measurement, and (3) To indentify and prioritize needed improvements and further research for IC equipment, which will be reported in detail (Gallivan, et al., 2010). An initial IC trial for HMA pavement was conducted in California in 2006 using a high frequency, double drum, vibratory roller (Sakai SW850) equipped with a real-time kinematic (RTK) GPS, an accelerometer, an infrared temperature sensor, and a laptop computer. This result revealed the real world of rolling operations and supported the need for the IC technology. Figure 1 shows inconsistent roller passes over the pavement as expected (Scherocman et al., 2006).

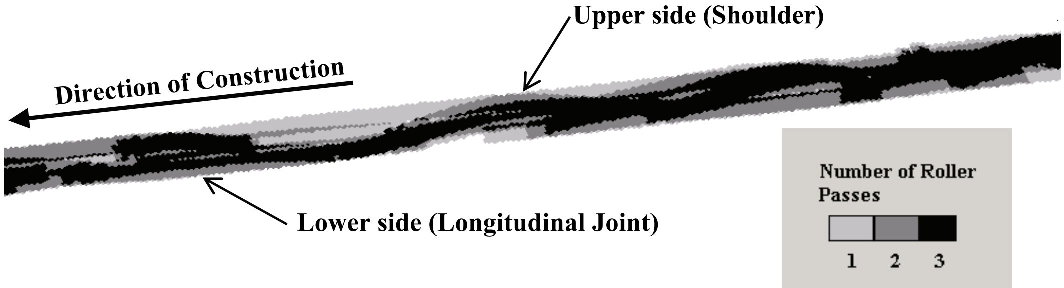


Figure 1: Inconsistent roller passes over the pavement (Scherocman et al., 2006)

1.2 Brief Survey of Conventional QC/QA Method for HMA Pavement

Conventional QC/QA compaction criteria for HMA pavement in most countries is based on a limited number of core samples. For example in Japan, only one core per 1,000 m^2 with a minimum of 93.0 % Marshall lab density is required for QC/QA (Japan Road Association, 1980). Some countries such as the USA (Asphalt Institute, 1978) and the UK (Highway Agency, 2009) allow the use of a calibrated nuclear density gauge. Sampling inspection criteria by cores and/or nuclear density gauge for select countries is indicated in Table 2. However, the question remains whether the sampling frequency is sufficient to ensure a durable pavement and meet performance specifications. The answer may be "no".

Table 2: Sampling inspection criteria by cores and/or nuclear density gauge

	Method	Frequency	Remarks
Japan	Core sampling	every 1,000 m^2	
US	Nuclear gauge or Core sampling	every 150 m, 500 t	Stratified random sampling
UK	Indirect density gauge	20 m intervals	BS 594987, at wheel-tracks
	Core sampling	every 1,000 m	BS 594987, at wheel-tracks
		every 250 m	100mm from unsupported edge
Australia	Nuclear gauge or Core sampling	every 30 t or homogeneous section	

2 COMPARISONS OF QUALITY CONTROL METHODS FOR PAVEMENT

2.1 RMV and Core Density for Pavement Layers

Density measurement of compacted pavements has been widely accepted as a QC/QA method because of its simplicity compared with measuring pavement stiffness using tools such as the falling weight deflectometer (FWD). Reliable correlations between density and stiffness or RMV are limited to moisture contents on the dry side of the optimum moisture content (OMC) for a given material type used in base and subbase of the pavement. Based on this fact, correlation of stiffness or RMV values to density without considering the OMC of the materials, and then the use of the RMV-derived density values have practical limitations to predict long-term pavement performance as discussed in detail below. Three primary limitations to using density as an acceptance criterion for the long-term performance of pavements are discussed below.

First, the measurement sensitivity of density is much lower than that of stiffness or RMV measurement. Generally, the variation of density stays within a narrow range when consistent compactive effort is given to material that is uniformly mixed and leveled. In Table 3, the coefficients of variation (CV) for density, stiffness (K30) and RMV for two different strata are compared. The results in Table 3 were measured on an airport runway project in Japan where IC technology using RTK-GPS was implemented under strict control of materials and the compaction process (The Japanese Geotechnical Society, 2010). The CV for the density measured by a nuclear gauge ranges from 2.3 in upper subgrade to 3.4 in roadbed, while the CV for the other methods are greater than 30. Consequently, due to lower sensitivity of density measurements, it is difficult to compare variations in pavement quality based on RMVs to variations in pavement quality based on density measurement. It is known that meeting density requirements alone does not ensure adequate structural strength, but only that the process to achieve adequate density requires a minimum level of structural strength of the base, subbase and subgrade. Density is only a convenient proxy for structural strength because, until the advent of IC systems, measuring modulus was too cumbersome, time-consuming and expensive. RMV directly measures the structural strength characteristics of the underlying pavement structure. Now, with IC systems capable of measuring stiffness available, historical limitations on using randomly located stiffness measurements has been lifted.

Table 3: Comparison of variation coefficient for density, moisture content, stiffness and RMV

	Coefficient of variation (%)			
	Density	Moisture content	K30 (Plate loading)	RMV
Subgrade (upper)	2.3	17	36	32
Roadbed	3.4	15	34	35

Second, it should be noted that an acceptable correlation between density and stiffness or RMV can only be found on the dry side of OMC as stated above. On the wet side of OMC, the stiffness values will not meet the required quality specification. RMVs that fail to meet the specification thus indicate that the load-bearing capacity of the pavement structure is greatly reduced, which is what engineers expect RMV to predict. Similarly, for materials used in base or subbase that have moisture contents on the wet side of the OMC density measurements could meet a minimum requirement and the pavement structure would be considered acceptable.

Third, the nature of density sampling limits its practical use to the sampling frequencies presented in Table 2. Increased sampling rates would reduce consumer's (owner's) risk.

In summary, with emerging IC technologies, density methods may no longer be the measure of choice for QC/QA. RMV based on IC technology is capable of measuring the entire compacted area which minimizes sampling error and bias. RMVs could become a useful tool not only for QC/QA, but also for verification of pavement designs because it enables the pavement designer to directly compare design values with measured ones. RMVs with a good correlation to stiffness could replace conventional proof rolling. Soft spots can be identified during compaction work in real-time and any pre-treatment can be done before construction continues.

3 TEST SECTIONS USING IC TECHNOLOGY IN JAPAN AND USA

In 2009, tests using Sakai's IC system were conducted both in Japan and the USA to prove its applicability to HMA pavement as a new inspection tool for highway construction.

In Japan the Sakai IC roller was used both on the subbase and HMA pavement layers in a container yard adjacent a canal of Tokyo Bay. First, it was successfully used to proof roll the entire compacted area. On the HMA pavement, however, all data was lost due to radio frequency jamming. Radio jamming is common around airports and military installations where it is critical that outside radio frequencies do not interfere with navigation systems. It exposed one of risks of the IC technology and identified the need for a data backup system.

In the US, the IC test was conducted at a "Park & Ride" facility owned by GDOT as part of the FHWA TPF Solicitation No. 954 described in Section 1.1.

3.1 Measurement System

The IC system, named Compaction Information System (CIS) manufactured by Sakai Heavy Industries, Ltd., consisted of the CCV (Table 1), an auto-tracking Total Station System (TSS) or RTK-GPS, an infrared temperature gauge, and a color video display as shown in Figure 2. The roller location was measured by a TSS in Japan and by an RTK-GPS system in the US.

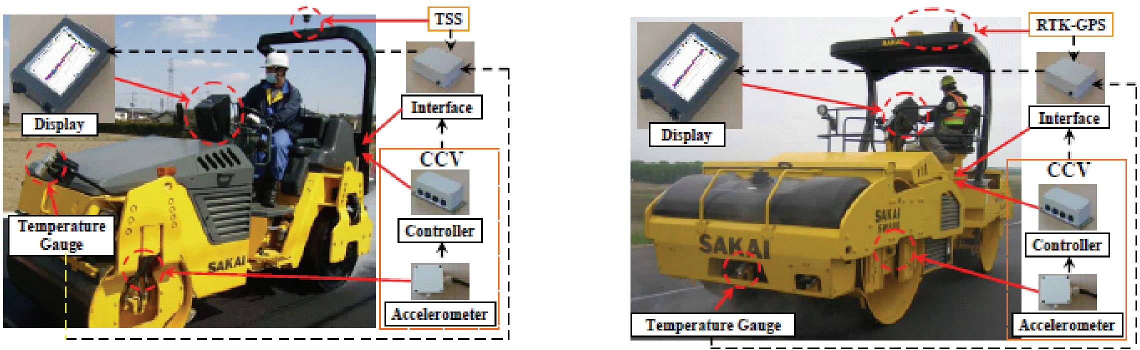


Figure 2: Sakai IC systems used in Japan (left) and the USA (right)

3.2 IC Test Project Sites

In May 2009, the IC test in Japan was conducted in a 38 000 m^2 container yard constructed beside a canal adjacent Tokyo Bay. The pavement structure consisted of the upper and lower subbase (200 mm thickness each) and HMA base and surface course layers of 100 and 50 mm thickness, respectively. The IC roller was used to proof roll the subbase in all compacted areas and then to measure CCV on the HMA pavement during construction.

The test project conducted in the US in September 2009 was at a "Park and Ride" facility constructed in Clayton County, near Atlanta, Georgia. The total tonnage of HMA used was approximately 5,000 tonnes placed in two layers. Both the parking area for bus and car consisted of graded aggregate base (GAB) of 200 mm thickness and HMA base and surface pavement layers of 75 and 50 mm for the bus and 50 and 25 mm for the car parking areas, respectively. The original construction schedule was delayed due to heavy rain. Water that pooled in the excavated GAB increased the moisture content of clay soil in the subgrade.

3.3 Job Mix Formula Data

In Japan, recycled crushed concrete material (RC-40) and recycled crushed aggregates (RM-40) were used for the lower and upper subbase, respectively. The job mix formula (JMF) data is shown in Table 4. Reclaimed Asphalt Pavement (RAP) HMA mixes with a maximum nominal aggregate size of 20 and 13 mm were used for the base and surface course layers. The JMF data is also shown in Table 4 along with the asphalt binder content, asphalt binder type and Theoretical Maximum Density (TMD).
In the US test section, three HMA Superpave mixes with nominal maximum aggregate sizes of 25.0, 19.0 and 9.5 mm conforming to GDOT specifications were used. The JMF data is shown in Table 4.

Table 4: Job Mix Formula data for subbase and HMA in Japan and USA

	Sieve Size \ % Passing	Japan (Subbase) Upper (RM-40)	Japan (Subbase) Lower (RC-40)
Aggregate Gradation	53.0 mm	100	100
	37.5 mm	97.5	97.5
	19.0 mm	75.0	65.0
	4.75 mm	47.5	27.5
	2.36 mm	35.0	15.0
	425 um	20.0	--
	75 um	6.0	--
Lift thickness	mm	200	200

	Sieve Size \ % Passing	Japan (HMA mix) Surface course layer	Japan (HMA mix) Base course layer	USA (GDOT Superpave HMA mix) Surface course layer (Car)	USA (GDOT Superpave HMA mix) Surface (Bus) and Base (Car) course layer	USA (GDOT Superpave HMA mix) Base course layer (Bus)
Aggregate Gradation	37.5 mm	--	--	--	--	100.0
	26.5 (25.0) mm	--	100.0	--	100.0	98.0
	19.0 mm	100.0	97.5	--	98.0	86.0
	13.2 (12.5) mm	97.5	80.0	100.0	82.0	68.0
	9.5 mm	--	--	97.0	72.0	--
	4.75 mm	62.0	45.0	61.0	--	--
	2.36 mm	42.5	27.5	45.0	33.0	33.0
	600 um	24.0	17.0	--	--	--
	300 um	15.5	10.5	--	--	--
	150 um	11.0	8.0	--	--	--
	75 um	6.0	4.5	6.5	5.6	5.0
Mix Properties	Binder Content	5.6	5.3	5.8	4.8	4.5
	Asphalt Binder	Pen.60/80	Pen.60/80	PG67-22	PG67-22	PG67-22
	TMD (g/cm^3)	2.479	2.520	2.474	2.503	2.509
Lift thickness	mm	50	100	30	50	100

3.4 Proof Rolling Application on Subbase in Japan

The IC roller used was a Sakai TW352-1 (2,500 kg) combination roller with a 1.2 m wide drum operated at an amplitude of 0.33 mm and a vibration frequency of 50 Hz as shown in Figures 3. The roller was instrumented to measure the location of roller passes, CCV of the subbase and HMA surface temperature.


Figure 3: IC roller for proof rolling with TSS on base (left), and HMA application (right)

3.5 Aggregate Base Mapping and Paving Operations in USA (Chang, et al., 2009)

The asphalt paver was a Roadtec RP-190 paving at a width of 3.1 m. The HMA mix temperature behind the screed was an average surface temperature of 130 ºC for all mix types and layer thicknesses. The IC roller used was a Sakai SW880 (13,410 kg) with a 2 m wide drum operated at amplitude of 0.66 mm and a vibration frequency of 50 Hz as shown in Figure 4. The roller pattern was decided by the roller operator. The majority of the time, the first breakdown pass was done in vibratory mode at the settings and average temperature noted above. The SW880 was not used as the breakdown roller in some areas because of its size. Due to the geometric layout of the site, it was difficult to establish a consistent roller pattern and paver speed through the entire project, however, the paver speed and roller patterns were consistent within each area of the project.

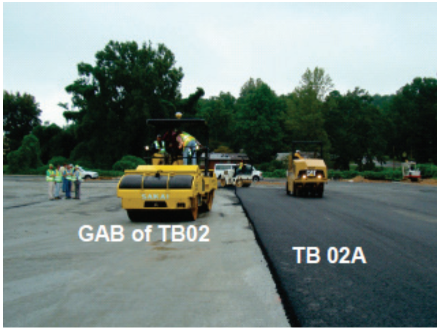
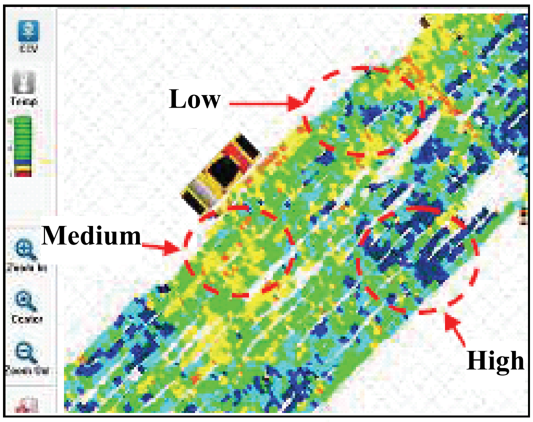


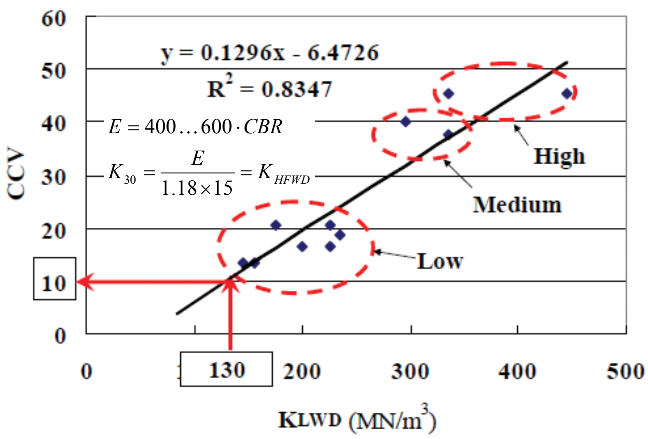
Figure 4: IC roller on GAB subbase (left), and HMA application (right)

4 TEST RESULTS IN SAITAMA JAPAN AND GEORGIA USA

4.1 Test Results in Japan

Three locations with three different ranges of CCV values identified as high (greater than 40), medium (30 to 40) and low (less than 30) were roughly chosen from the CCV map as marked with circles in Figure 5(a) immediately after proof rolling. At each circled location, the stiffness of the subbase was measured using a falling lightweight deflectometer (LWD). The results indicate that CCV can be used as a threshold of compaction QC/QA, because the correlation between CCV and stiffness (KLWD) is high (R^2=0.8347) as shown in Figure 5(b).





(a) CCV map (left), (b) Correlation between K_{LWD} and CCV (right)
Figure 5: Distribution of CCV after proof rolling and correlation between KLWD and CCV

4.2 Test Results in USA

The major findings on the Georgia test section were (Chang, et al., 2009):

a) Lower CCV values measured on the GAB correlate by location with lower CCVs on the HMA layer. This result is strong evidence that a sound subbase/base course should be constructed to achieve the integral strength of the entire pavement system.
b) The moisture of GAB significantly affects the CCV values based on the mapping data. Therefore, it is recommended to pave the HMA layer when the GAB is drier condition.
c) The mapping of subbase using the Sakai double drum IC roller can be correlated to conventional in-situ nuclear density gauge measurement.
d) The FWD deflections and back-calculated moduli of the GAB layer are correlated to CCVs at some test areas but not at others. Further investigation is warranted.
e) The densities of HMA core samples correlated with CCVs on the HMA layer showing an inverse relationship (Figure 6). However, it should be noted that only five HMA core densities were measured and more samples are required to reach a statistically significant correlation.
f) The measured LWD deflections and derived CBR values did not correlate with CCVs on the HMA layer on this site.

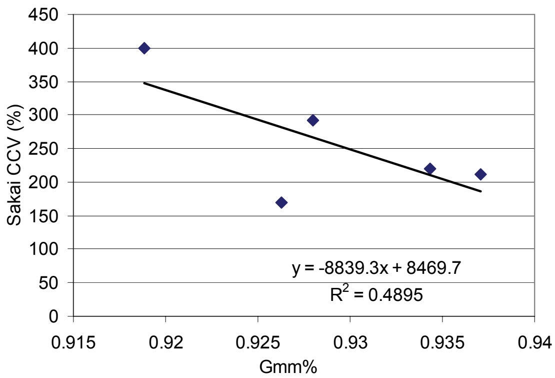
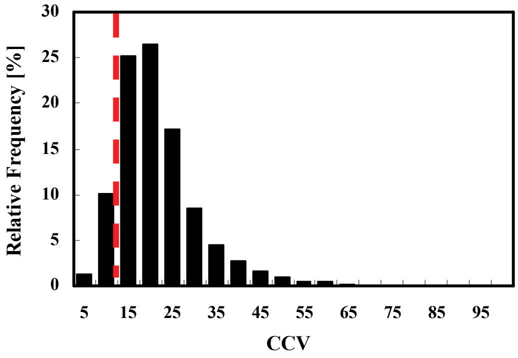


Figure 6: Inverse correlation of HMA core densities vs. CCV

5 CONSIDERATIONS

5.1 Test Results in Japan

The derived K_{LWD} (130 MN/m^3) is correlated to CCV=10 according to the correlation shown in Figure 5(b), since the K_{LWD} under a design CBR=4 for the subbase is derived approximately 130 MN/m^3. Figure 7 shows the frequency distribution of CCV for proof rolling with a threshold value of CCV=10 indicated by the dashed line, in which relatively symmetrical normal distribution is obtained due to subgrade and subbase constructed uniformly. This is the reason why the CCV measurements include the averaged value for all strata of the pavement structure up to 0.6 m in depth underneath the roller drum, which will be discussed Section 5.2. Figure 7 indicates that approximately 10 % of the entire lot is less than the CCV=10 threshold and thus not acceptable. This failed area indicates that some weak or failed spots of subbase and/or subgrade, and this percentage of 10 % coincides with the allowable defect rate that is commonly used as a statistical quality control criterion known as "consumer's risk" for industrial products as shown in Figure 8. Using the Consumer's Risk criterion above, the quality of the subbase is guaranteed statistically at the same level as industrial manufactured products using IC technology capable of measuring the entire compacted area.



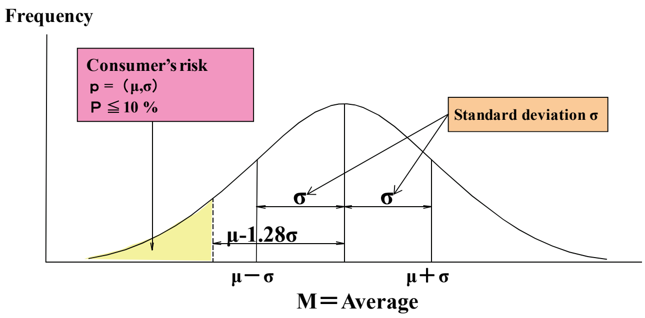


Figure 7: Statistic of CCV mapping (left)
Figure 8: Statistic quality control criterion (consumer's risk) for industrial products (right)

5.2 Test Results in the USA

The inverse correlation between the densities and CCV shown in Figure 6 is a paradoxical result. It can, however, be interpreted as follows; the dispersion range of density data plotted in Figure 6 looks wide because of the scale used on the x-axis, however, note that the actual dispersion is only 2.0 % ranging between 91.7 and 93.7 %. This uniformity of compaction can be obtained with proper rolling procedures and uniform underlying base conditions along with many other factors. On the other hand, the y-axis distribution of CCV shown in Figure 6 is wide and ranges from 175 to 350 %. This is one reason why the correlation appears in Figure 6 as an inverse relationship.

This trend is also affected by the "influence depths" of various measurement devices. The densities of HMA cores include only the thickness of the HMA pavement to be evaluated, while the CCV measurements include the mechanical properties for all strata of the pavement structure up to 0.6 m in depth underneath the roller drum (The Japanese Geotechnical Society, 2010). In this test section, the stiffness of subgrade under the GAB was reduced by the rain before the test started. It is considered that the CCV was affected significantly by the stiffness of subgrade rather than that of HMA pavement and GAB.

This US results provide very important suggestions. In the near future, roadway structures will be designed according to performance requirements for durable, long life roadways. Designs based on theory such as multiple elastic layer analysis, etc. should be verified during the construction. The CCV or RMV could be a valuable tool used for proof rolling and measuring the structural integrity of the entire pavement system. In addition, interpretation of the IC results presented in this paper reinforces existing knowledge that the subgrade and subbase must be uniformly and carefully constructed in order to build a durable HMA pavement.

6 CONCLUSIONS

a) RMVs can be used as a new QC/QA tool because it can sample the entire compacted area, and the quality of the pavement can be evaluated statistically (consumer's risk).
b) The R^2 correlation between RMVs and density or stiffness is not always high, however, the "influence depths" of various measurement devices along with material properties such as

temperature, type of soil, moisture content, etc. must also be considered.
c) Interpretation of the US test results reminds us that constructing a durable HMA pavement is dependent on constructing a uniform and structurally-sound base and subbase.
d) RMVs could be used for proof rolling to measure the quality and soundness of the entire pavement structure.
e) IC technology could be beneficial to verify pavement designs, including multiple elastic layers, during construction.

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