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STATISTICAL ASSESSMENT OF CONCRETE COVER IN THEORY AND PRACTISE

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Research area: *non-destructive testing of concrete*

ABSTRACT

It is widely recognised that the failure of compliance of the cover depth with the specifications is one of the main causes of premature deterioration of reinforced concrete structures. Typically the building codes specify a minimum cover to ensure that there is a low risk of the reinforcement becoming excessively corroded and requiring significant repairs before the end of the intended working life (design service life), on the assumptions that the designer has chosen a practical allowance for deviation to add to the minimum value and that the level of workmanship on site is adequate to achieve the minimum cover.

The assumption that the workmanship on site is adequate is a key statement here. Despite being a key factor in the durability of the structure, current EN standards do not provide any recommendation for the assessment of concrete cover. Individual countries are left to decide themselves how this is carried out, if at all. In Switzerland there is no unified method. This has been recognized as a problem and moves are underway to develop a national guideline. In Holland there is no unified method. The Rijkswaterstaat is looking into implementing its own recommendations. In the UK there is a guideline for the use of cover meters, but no recommendation about the assessment of the results obtained.

Two examples of where practical guidelines have been developed are in Singapore and Germany. The German Concrete and Construction Association have published a practical guideline for assessing concrete cover on real structures based on the use of a statistical assessment with acceptance levels depending on the exposure class [1]. Another method has been developed by the Building and Construction Authority in Singapore [2].

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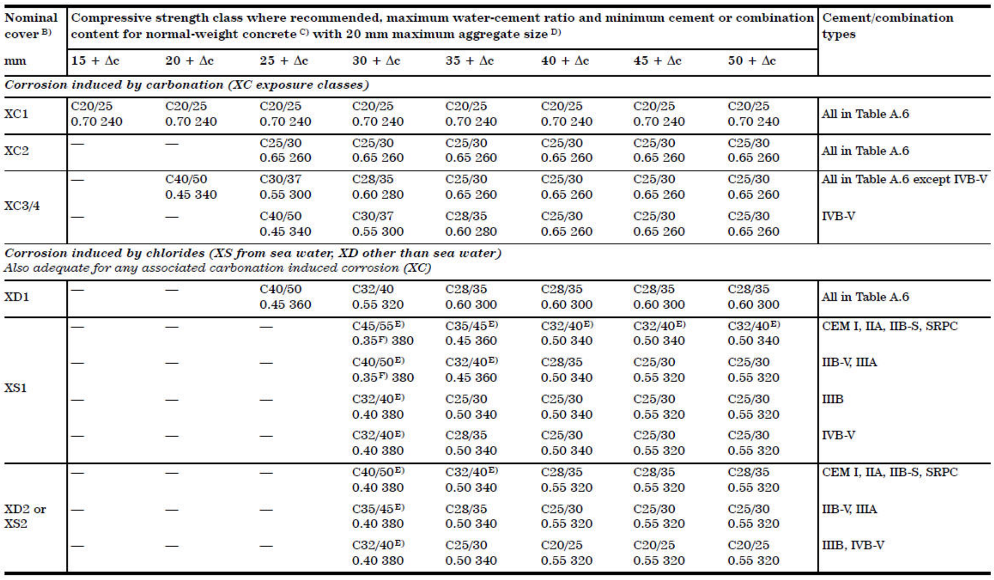
This paper will provide information about the requirements of various design codes, how these can be tested on site for compliance, with reference to the two established guidelines mentioned and the capabilities of modern cover meters.

1. Introduction

New concrete structures are usually designed for a minimum service life. Typically, this could be 50 years or even 100 years. In order to achieve this in reality it requires good design codes and also good construction practices that implement the requirements of the design codes. Furthermore, it requires a method of assessment to verify that the installation work has been carried out according to the specification. In Europe and North America the design codes tend to be prescriptive, although there is a movement now towards performance based specifications which would allow the contractors more freedom in the choice of materials and concrete mix design. Figure 1 shows an extract from BS8500-1 [3] which is a good example of such a prescriptive guideline. Similar guidelines exist in other countries.

Table 1. Extract from BS8500-1 Table A.4 - Durability recommendations for reinforced or prestressed elements with an intended working life of at least 50 years



Nominal cover B)	Compressive strength class where recommended, maximum water-cement ratio and minimum cement or combination content for normal-weight concrete C) with 20 mm maximum aggregate size D)								Cement/combination types
mm	15 + Δc	20 + Δc	25 + Δc	30 + Δc	35 + Δc	40 + Δc	45 + Δc	50 + Δc	
Corrosion induced by carbonation (XC exposure classes)									
XC1	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	All in Table A.6
XC2	—	—	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	All in Table A.6
XC3/4	—	C40/50 0.45 340	C30/37 0.55 300	C28/35 0.60 280	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	All in Table A.6 except IVB-V
	—	—	C40/50 0.45 340	C30/37 0.55 300	C28/35 0.60 280	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	IVB-V
Corrosion induced by chlorides (XS from sea water, XD other than sea water) *Also adequate for any associated carbonation induced corrosion (XC)*									
XD1	—	—	C40/50 0.45 360	C32/40 0.55 320	C28/35 0.60 300	C28/35 0.60 300	C28/35 0.60 300	C28/35 0.60 300	All in Table A.6
XS1	—	—	—	C45/55 E) 0.35 F) 380	C35/45 E) 0.45 360	C32/40 E) 0.50 340	C32/40 E) 0.50 340	C32/40 E) 0.50 340	CEM I, IIA, IIB-S, SRPC
	—	—	—	C40/50 E) 0.35 F) 380	C32/40 E) 0.45 360	C28/35 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	C32/40 E) 0.40 380	C25/30 0.50 340	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIIB
	—	—	—	C32/40 E) 0.40 380	C28/35 0.50 340	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IVB-V
XD2 or XS2	—	—	—	C40/50 E) 0.40 380	C32/40 E) 0.50 340	C28/35 0.55 320	C28/35 0.55 320	C28/35 0.55 320	CEM I, IIA, IIB-S, SRPC
	—	—	—	C35/45 E) 0.40 380	C28/35 0.50 340	C25/30 0.55 320	C25/30 0.55 320	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	C32/40 E) 0.40 380	C25/30 0.50 340	C20/25 0.55 320	C20/25 0.55 320	C20/25 0.55 320	IIIB, IVB-V

A quick study of this table shows that a number of factors are to be considered to achieve the required design life of 50 years. First of all the exposure class to which the structure will be subject to. Once this is known the concrete can be specified in terms of its compressive strength class, the water/cement ratio, the minimum cement content in kg/m^3, the type of cement and finally the specified concrete cover together with a safety margin Δc that is intended to allow for variations in the cover that will occur during placement. The first four of these are physical properties of the concrete which largely determine the resistance to ingress of corrosive elements. The latter is a factor that is purely determined by on-site installation practices.

Despite the fact that it is a key factor in the durability of the structure, the current European standards do not provide instruction on how to determine the concrete cover on site to verify if it is adequate. Concrete cover meters have existed for many years and their use is widespread. There are several technologies capable of measuring concrete cover, but by far the most widely used are electromagnetic covermeters based on magnetic eddy current detection or the low frequency ferro-magnetic principle. Figure 2 shows a selection of typical instruments.

Figure 1. Covermeters

In principle ground penetrating radar may also be used to detect concrete cover, but it is necessary to calibrate the wave propagation speed each time as it is heavily affected by moisture content. The electromagnetic instruments are unaffected by outside influences or moisture content. They are only affected by the presence of magnetic materials within their operating range.

Assuming that it is checked at all, the absence of standardization may lead to disputes if the contractor employs a different method or a different instrument from that used by the owner’s representative. Also the expertise or experience of the operator can lead to significant differences in the results. Taking all of these things into consideration, it is clear that there is a need for a systematic unified method of assessing concrete cover. This has been recognized in various countries. In Switzerland a program is underway to establish a national guideline. In Germany and Singapore there are clear guidelines which will be explained below.

2. Existing Guidelines

2.1. German Guideline

The guideline for assessing concrete cover published by the German Concrete and Construction Association (DBV – Deutsche Beton Verein) refers to minimum cover requirements defined in the German standard DIN 1045-1. As can be seen in Table 1 there are similarities to the British recommendation. The guideline refers to the DGZfP (German Society for non-destructive testing) technical bulletin B2 – Technical bulletin for non-destructive concrete cover measurement on reinforced and prestressed concrete [5] for information about the type and use of instrument to be used.

The evaluation uses a statistical approach based on the right-shifted distribution (Neville Distribution) which does not contain any impossible negative values. Its efficacy has been demonstrated by practical tests. The analysis is simple to work with. The user must only calculate the mean, the median and the standard deviation. All other parameters are derived from these. An acceptance criteria based on a 5% or 10% quantile is calculated depending on the exposure class that is applicable. A practical example is shown in chapter 4.

Table 2. Minimum concrete cover and safety margin, extract from DIN 1045-1, 6.3 and table 3 and table 4

Exposure Class		Minimum concrete compressive strength class	**Minimum concrete cover c_{min} (mm) $^{1)\,2)}$**		**Safety margin Δc (mm)**
			Reinforcing steel	Pre tensioning and post tensioning tendons	
XC1	Dry or permanently wet	C16/20	**10**	20	**10**
XC2	Wet, rarely dry	C16/20	**20**	30	**15**
XC3	Moderate humidity	C20/25	**20**	30	
XC4	Cyclic wet and dry	C25/30	**25**	35	
XD1	Chloride + moderate humidity	C30/37 $^{3)}$	**40**	50	
XD2	Chloride + wet, rarely dry	C35/45 $^{3)}$			
XD3	Chloride + cyclic, wet and dry	C35/45 $^{3)}$			
XS1	Exposed to airborne salt but not in direct contact with sea water	C30/37 $^{3)}$	**40**	50	
XS2	Permanently submerged	C35/45 $^{3)}$			
XS3	Tidal splash and spray zones	C35/45 $^{3)}$			

2.2. Singaporean Guideline – CONQUAS System

CONQUAS stands for the Construction Quality Assessment System. It is a standardized method of assessing buildings through site inspection developed by the Building and Construction Authority in Singapore. It was introduced in 1989 and has been subsequently finetuned. The assessment uses sampling based on building size and a points system based on various tests. Concrete cover is one of the tests specified and the points system is explained in figure 2.

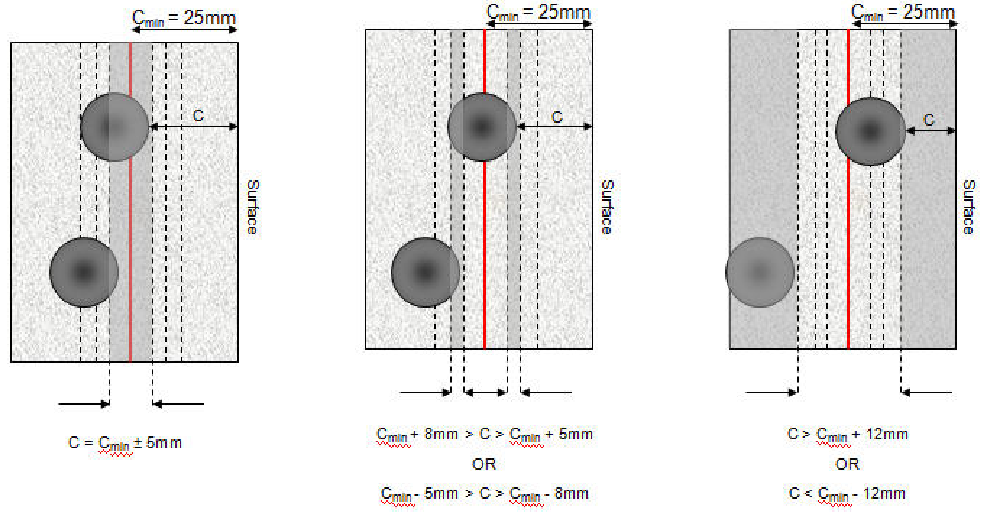


Figure 2. CONQUAS points system for cover measurements

- 1 point is awarded for each reading within 5 mm of c_{min}.
- Half a point is awarded for each reading between 5 and 8 mm of c_{min}.
- If any of the four readings on a structural element exceed 12 mm away from c_{min} then zero points are awarded for that structural element.

2.3. Sampling

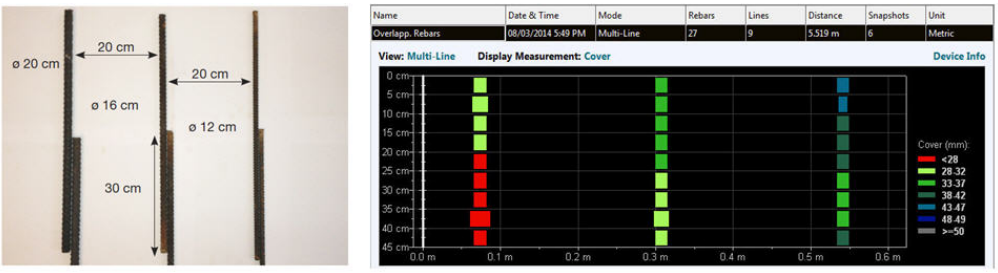
Both guidelines provide information about how to sample and where to carry out measurements. Table 2 below shows a comparison of the sampling plans.

Table 3. Comparison of the DBV and CONQUAS guidelines

Test Parameter	**DBV**	**CONQUAS**
Sample Size	If structural elements are manufactured in pour sections, then the building element surfaces defined below may be combined together	Area 5000 m^2. Minimum sample is 2 sets. Maximum sample is 20 sets. 5 structural members per set
Measurement surface	- each side of a wall - the upper side of a ceiling - the under side of a ceiling - the sides of rectangular pillars - the vertical sides of a beam - the under side of a beam - the upper side of a beam	Soffit Column Beam
Number of measurements per surface	≥ 20 on each side	3 on a slab soffit 2 on each side of a column 2 on soffit side of a beam plus 2 on one side of the beam
Minimum cover	According to table 1 of DIN 1045-1.	25mm or higher as specified
Acceptance criteria	5% or 10% quantile based on statistical analysis and exposure class.	Point system: Full point for ±5 mm Half points for ±5 mm > ±8 mm No points if any reading in a structural sample exceeds ±12 mm
Instrument specification	≤ ± 1 mm up to 40 mm of concrete cover and ≤ ± 2 mm for concrete cover between 40 and 60 mm	Electromagnetic covermeter within ± 2 mm or ±5%, whichever is the greater, over the working range given by the manufacturer
Instrument calibration	Checked by comparison tests on a test object of known cover before and after the measurements.	Regular calibration checks – at least every 6 months. Site calibration strongly recommended.

2.3. Measurement locations

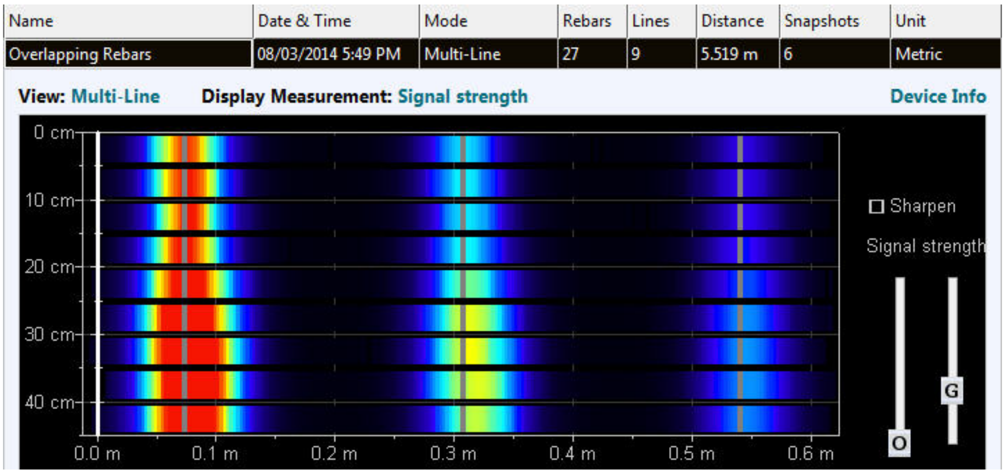
Another issue is that electromagnetic covermeters in particular make the assumption that there is only one rebar in their magnetic field. The cover readings shown are based on the rebar diameter programmed into them. Assuming that the correct rebar diameter has been entered, the presence of overlapping or dense rebar configurations will lead to an underestimation of the actual cover. This is a typical problem that is illustrated in figure 3. The rebar arrangement can be seen in the photo to the right. They are all at the same depth, but are of differing size and also with overlapping sections. The covermeter results can be seen on the right. In this case there is a good chance, especially for an inexperienced operator to misinterpret the results and think that the cover is insufficient. Some instruments are also capable of showing signal strength as is indicated in figure 4. This is an aid to the detection of overlapping rebars, but this feature is not standard and again requires some experience in interpretation.



Name	Date & Time	Mode	Rebars	Lines	Distance	Snapshots	Unit
Overlapp. Rebars	08/03/2014 5:49 PM	Multi-Line	27	9	5.519 m	6	Metric

View: Multi-Line **Display Measurement:** Cover

Figure 3. Overlapping rebar arrangement and cover measurement made with Profometer PM-650



Name	Date & Time	Mode	Rebars	Lines	Distance	Snapshots	Unit
Overlapping Rebars	08/03/2014 5:49 PM	Multi-Line	27	9	5.519 m	6	Metric

View: Multi-Line **Display Measurement:** Signal strength

Figure 4. Signal strength measurement of overlapping rebars made with Profometer PM-650

In order to try and avoid this kind of problem, both of the guidelines offer advice about where to carry out measurements on specific structural elements.

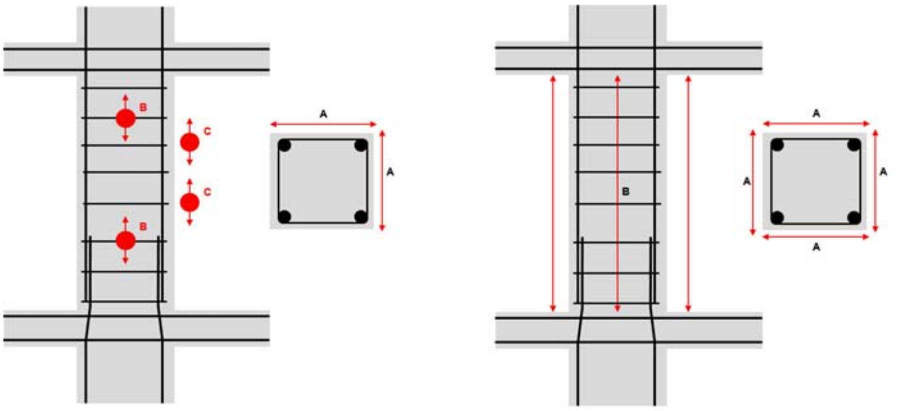


Figure 5. CONQUAS and DBV recommendations for measurement locations on a column

Here we can see how each of the guidelines recommends carrying out measurements on a column. Both DBV and CONQUAS recommend locating the second layer vertical reinforcement first. Then the cover is measured over the first layer stirrups in a line parallel to the vertical reinforcement and at the midpoint between two rebars. The only difference between the two guidelines is in the number of measurements required, with CONQUAS requiring four readings in total on two sides of the column and DBV requiring an unspecified number of measurements on all four sides of the column. Similar recommendations are provided for wall slabs and beams. The practise of mapping out the rebars first to identify good locations for suitable measurements is a must, but is not always followed.

4. Practical Example

Figure 6 shows data collection with a covermeter taking place and the resulting measurements of a 20 m x 0.5 m scan. This data is a typical example of what might be expected in a practical situation. The minimum cover was specified at 30 mm and the exposure class was XC4. As can be seen from the data presentation, a number of measurements are below that limit and are indicated by the red colour. So the question for the assessment team would be whether or not to accept this structure or not? There could be several reasons for the low readings excluding poor installation as explained above. In this particular case the reason was that those low measurements were around a column with very dense overlapping rebars leading to an underestimation of the cover. In reality those measurements should be excluded from the analysis, but for this example they have been left in and the evaluation of the data was carried out using the DBV statistical analysis. The results can be seen in table 4 below.

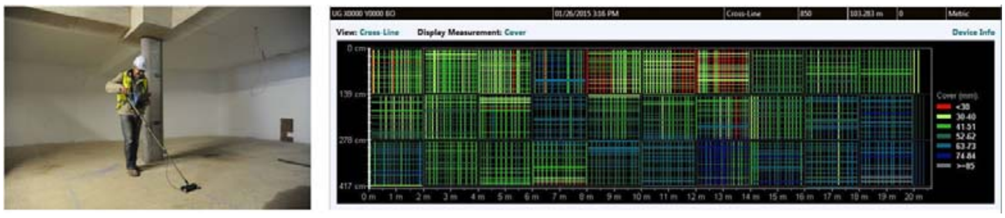
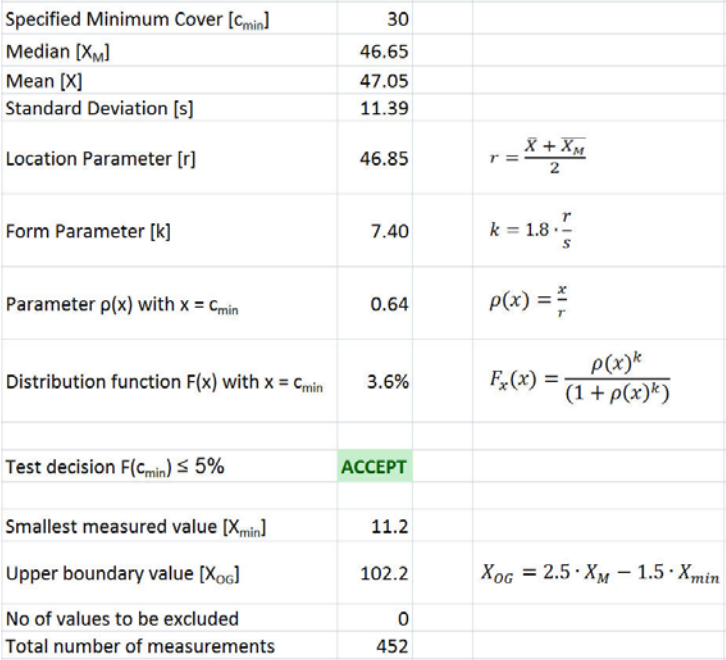


Figure 6. Data collection in the basement of the Proceq building

Table 4. Evaluation of the data from the basement floor of the Proceq Building



Specified Minimum Cover [c_{min}]	30	
Median [X_M]	46.65	
Mean [X]	47.05	
Standard Deviation [s]	11.39	
Location Parameter [r]	46.85	$r = \frac{\bar{X} + \bar{X}_M}{2}$
Form Parameter [k]	7.40	$k = 1.8 \cdot \frac{r}{s}$
Parameter ρ(x) with x = c_{min}	0.64	$\rho(x) = \frac{x}{r}$
Distribution function F(x) with x = c_{min}	3.6%	$F_x(x) = \frac{\rho(x)^k}{(1 + \rho(x)^k)}$
Test decision F(c_{min}) ≤ 5%	ACCEPT	
Smallest measured value [X_{min}]	11.2	
Upper boundary value [X_{OG}]	102.2	$X_{OG} = 2.5 \cdot X_M - 1.5 \cdot X_{min}$
No of values to be excluded	0	
Total number of measurements	452	

As we can see, the distribution function shows the number of readings on the lower side are less than the 5% quantile required for exposure class XC4, so in this case the structure would be accepted. We can also see how simple the procedure is with all parameters being derived directly from the mean, median and standard deviation.

5. Conclusions

There is a definite need for a standardized method of assessing concrete cover on a sound statistical basis. The fact that this is already being done in at least two countries, shows the way forward. Care must be taken to implement procedures for avoiding or handling disputes when various parties obtain differing results. This would include a method of carrying out comparison testing between different instruments on standardized test objects.

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