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Variation in Cover to Reinforcement: Local and International Trends

Author: P D Ronné

Senior Structural and Forensic Engineer, BKS (Pty) Ltd., Cape Town

ABSTRACT: Concrete cover to reinforcement is a critical parameter for durability. Despite a common perception that cover is a relatively simple subject, the terminology for cover suggests the converse. A brief review of cover meter devices, their operating principles and their appropriate use is presented. In particular, the lack of guidance in taking reliable cover surveys is identified and a suitable survey method is suggested. The variability of cover is further defined.

Analyses of both international and local cover survey data are used to quantify the relationship of the relative variability measure using the coefficient of variation with the mean cover. The absolute variability measured using the standard deviation, is presented for the trend.

An investigation has shown that the relative variability of cover increases significantly at low covers, and decreases at increased covers. South African construction exhibited higher absolute variability regarding the achievement of cover, as measured using the standard deviation. In building construction, the achievement of specified cover is quantitively shown to be more variable than that achieved on bridge construction projects in South Africa. Recommended tolerance margins for South African construction practice are proposed at 10mm, 15mm and 20mm for precision, normal in-situ and heavy civil works respectively.

Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

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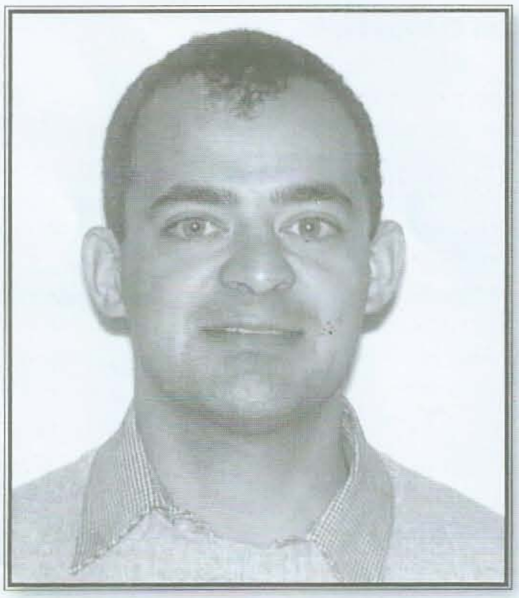
Technical Paper

Variation in Cover to Reinforcement: Local and International Trends

Philip D. Ronné
BKS (Pty) Ltd



Biography

Philip Ronné is a Senior Structural and Forensic Engineer with BKS (Pty) Ltd at their Cape Town office. Particular interests include the investigation, diagnostic testing and developing appropriate remedial strategies to repair and rehabilitate reinforced concrete-, as well as structural steel-structures and performance-based specifications for new concrete construction. He holds MSc(Eng) and BSc(Eng) degrees in Civil Engineering from the University of Cape Town, was selected as a finalist in the 2005 SAACE Glenrand MIB Excellence Awards: Young Engineer category, and is currently the elected Chairman of the Western Cape Branch of CSSA.

Abstract: *Concrete cover to reinforcement is a critical parameter for durability. Despite a common perception that cover is a relatively simple subject, the terminology for cover suggests the converse. A brief review of covermeter devices, their operating principles and their appropriate use is presented. In particular, the lack of guidance in taking reliable cover surveys is identified and a suitable survey method is suggested. The variability of cover is further defined. Analyses of both international and local cover survey data are used to quantify the relationship of the relative variability, measured using the coefficient of variation, with the mean cover. The absolute variability, measured using the standard deviation, is presented for the trend.*

An investigation has shown that the relative variability of cover increases significantly at low covers, and decreases at increased covers. Compared to international construction practice, South African construction exhibited higher absolute variability regarding the achievement of cover, as measured using the standard deviation. In building construction the achievement of specified cover is qualitatively shown to be more variable than that achieved on bridge construction projects in South Africa. Recommended tolerance margins for South African construction practice are proposed at 10mm, 15mm and 20mm for precision, normal in-situ and heavy civil works respectively.

Introduction

Durable reinforced concrete structures are inherently well designed and constructed while poor construction attracts a disproportionate economic penalty in unnecessary maintenance and repair costs during the life of a structure. The durability performance is generally the degree of success of the concrete's response to the

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aggressiveness of the exposure environment, and the response is governed the properties of the concrete in the cover layer and the depth of concrete cover. This paper focuses on the issue of concrete cover and quantifies, through a review of internationally published data and South African site data, the inherent variability of cover to reinforcement.

Previous investigations and reporting on the issue of cover to reinforcement have reflected particular problems with specifying and ensuring adequate concrete cover. Typical problems, resulting from the complex interaction of human factors in design and construction, can be categorised as cover incorrectly specified, specification incorrectly formulated, actual cover not as specified (Neville 1999), or the accumulation of negative construction tolerances in practice (Gee 1995).

There appears to be a common perception that concrete cover is a relatively simple concept, while the number of technical terms used to describe cover points toward the underlying complexity of the subject. A selection of these terms is explained below.

- **Nominal cover:** The nominal cover is that dimension used in design and indicated on engineering drawings.
- **Minimum cover:** Minimum cover is the basis on which the durability and fire provisions are implemented.
- **Mean cover:** The arithmetic mean cover determined from sample readings taken from an actual cover survey.
- **Characteristic cover:** Cover depth for a specified, probability-based standard of compliance (or failure).
- **Standard deviation:** A measure of how widely values are dispersed from the mean cover.
- **Coefficient of variation:** The calculated ratio expressing the standard deviation as a percentage of the mean cover.

In South African design codes, the term "cover" indicates the minimum thickness of concrete between the surface of the reinforcement and the face of the concrete (COLTO 1998). Concrete cover to reinforcement is commonly specified and detailed using formulations based on either the minimum or nominal cover. However problems with low cover are persistent. Specifications based on characteristic cover are being formulated but concerns relating to the measurement of a suitable sample size and to the quantification of cover variability for South African construction practice remain unresolved.

In European design codes, the nominal cover to reinforcement comprises a minimum cover plus a variable margin for construction tolerances. This margin for surfaces cast against formwork is typically in the range of 5 to 15mm. The designer selects the margin taking into account consequences of low cover, the level of workmanship expected on site and the quality control procedures (British Cement Association 2003). This paper aims to quantify this margin from actual site data for typical South African construction practice.

Covermeters and their use

The most common method of measurement of cover thickness is the use of non-destructive covermeters. Covermeters are electromagnetic devices consisting of a search head and a control box, an example being shown in figure 1. The design of covermeters is either based on measuring the eddy current or using magnetic inductance principles. With covermeters based on the first principle, alternating currents in the search coil set up eddy currents in the reinforcement which in turn cause a change in the measured impedance of the search coil. With covermeters using magnetic inductance, one set of coils carries the driving current while another set of coils picks up the voltage transferred via the magnetic circuit formed by the search head and embedded reinforcing bar (BS 1881 1988).

Figure 1: A typical covermeter device.

BS1881 Part 204 (1988) is one of the few standards for covermeters and requires that the error in the indicated cover (when measuring cover to a single bar under laboratory conditions) should be within 5% or 2mm whichever is the greater. Unfortunately this standard focuses on the measurement of cover on a single bar and is more concerned with the covermeter than taking a cover survey. A recent comparative study (Fernández Luco 2005) determined that the assessment of cover using covermeter devices was not significantly affected by the temperature, moisture condition or the water: cement ratio of the encapsulating concrete. In addition, the study showed that generally most commercial covermeters presented very good accuracy, measured in terms of both bias and precision parameters; while the accuracy decreased for large covers and with lack of information about the reinforcement bar diameters.

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However, the operating manuals of most covermeters recommend appropriate techniques for locating buried reinforcing bars and placing the search head in the correct position for an accurate depth measurement. Generally, to check reinforcing bar locations, the search head is moved slowly across the surface of the concrete perpendicular to the principal direction(s) of the reinforcement. The read-out is observed until a minimum is reached and the position of the head is noted - usually by marking the position on the concrete surface (The Concrete Society 2000).

However there are no generally accepted methods to define either a representative sample for cover measurements or how a cover survey should be carried out. Purvis et al (1994) recommended a minimum number of 40 cover measurements per member or per 465 square meters of bridge surface area, whichever results in the greater number of cover measurements. The South African data presented in this paper were collected using a minimum of 30 individual cover readings per m^2 and approximate cover survey area of 1,5 to $2m^2$, i.e. cover surveys typically comprised in excess of 45 readings, and the arithmetic mean number of measurements per cover survey was 63.

Variability of Cover

The variability of cover originates from allowances for permissible tolerances for bending reinforcement and for formwork placement, as well as commitment to quality assurance during design and construction (SARCEA 1989). Numerous authors have studied cover from a statistical point of view and determined that cover typically follows a Gaussian (or normal) distribution. Sharp (1997) observed that the mean cover achieved is usually quite close to the specified nominal figure, except where gross errors occur due to incorrect initial placing or significant movement of the formwork or reinforcing cage, in which case a skew distribution may result. Others have noted significant variation of the achieved cover with elements on each site, as well as between sites (Clark et al 1997; Samples & Ramirez 2000(a) and Samples & Ramirez 2000(b)). This variation about the mean can be wider than expected and usually exceeds accepted

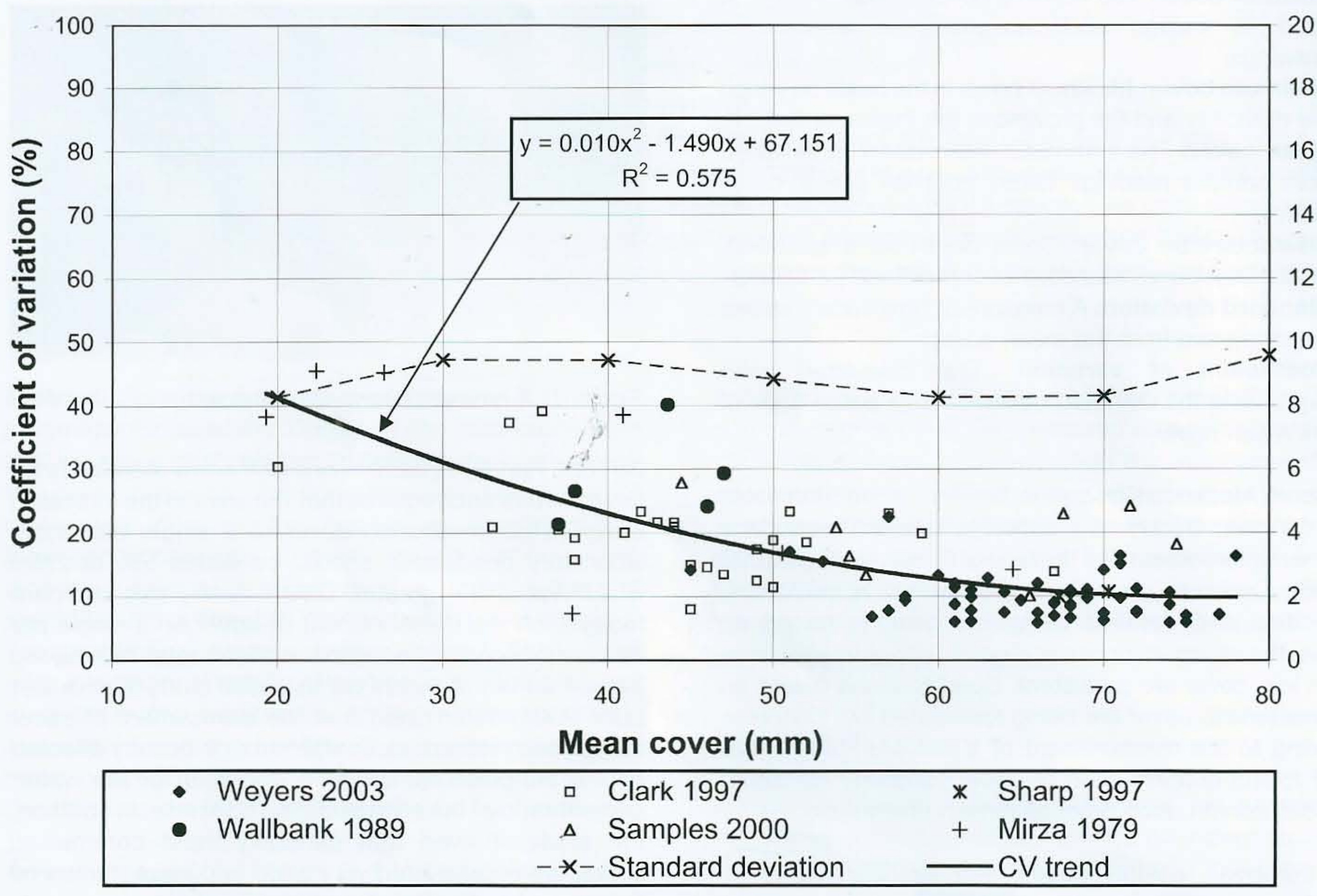

Figure 2: Variation of internationally published cover data (after Weyers et al 2003; Clark et al 1997; Sharp 1997; Wallbank 1989; Samples & Ramirez 2000a; Samples & Ramirez 2000b and Mirza & MacGregor 1979).

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tolerances (Sharp 1997 and Gee 1995).

Sharp (1997) introduced the coefficient of variation (CV) concept to gauge the degree of manufacturing control as a quality control aid in performing as-built cover surveys, provided that a minimum of 35 cover measurements were determined for each cover survey. The following table recommends typical CV values for various standards of control based on British experience.

Table 1: *Suggested CV values for various standards of control for typical British construction practice (Sharp 1997).*

Standard of control	Coefficient of variation (%)
Near-laboratory precision	10
Good	15
Moderate	20
Poor	30

In order to evaluate the relationship between cover variability and mean cover, international data (Weyers et al 2003; Clark et al 1997; Sharp 1997; Wallbank 1989; Samples & Ramirez 2000a; Samples & Ramirez 2000b and Mirza & MacGregor 1979) representing cover surveys of more than 45 readings and detailing both the mean cover and standard deviation were used. The coefficient of variation was calculated and plotted in relation to the mean cover for the international data, shown in figure 2.

A clear relationship is established between the mean cover and the coefficient of variation (CV) for the international data. CV was found to decrease with increasing mean cover depth. This implies that any variation in cover is more significant at low covers than at high covers. The CV decreased from 42% to 23%, and further to 12% at 20mm, 40mm and 60mm mean cover respectively, which represents poor, moderate, and good standards of control. For mean cover between 65mm and 80mm, the CV was approximately constant at 10% representing good control. Further analysis of the international data shows that a polynomial best fit trend with a correlation coefficient of 0,758 (R^2 = 0,575) was established. The trend is considered to be good, given the large variety of cover survey methods, covermeter devices, structural member types and

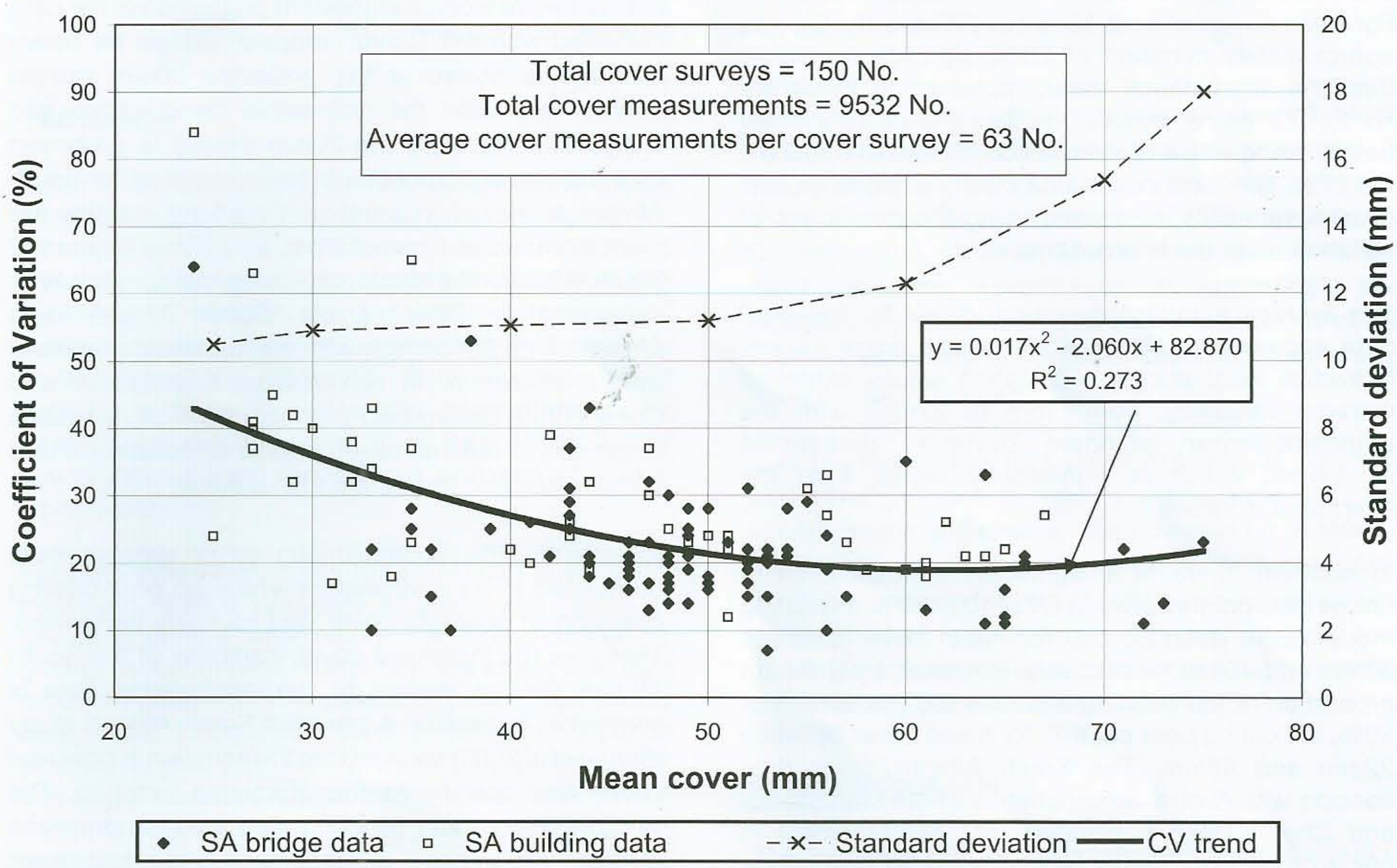

Figure 3: Variation of South African cover data.

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construction practice represented by the international data.

In addition, a statistically significant relationship could not be defined for standard deviation in relation to mean cover values for the international data. The average standard deviation values were confined between 8mm and 10mm, while individual values varied greatly from 4mm to 18mm. The arithmetic mean standard deviation for the international data was determined as 8mm.

In comparison, South African cover survey data for both bridge and building structures representing various elements for each structure type are presented in figure 3.

The relationship between the mean cover and the coefficient of variation is confirmed for the local data and CV decreases with increasing mean cover depth. The South African data reaffirms that the consequences of variation are more significant at low cover depths than at greater cover depths. The CV decreased from 48% to 27%, and further to 19% at 20mm, 40mm and 60mm mean cover respectively. The CV represents poor to moderate standards of control, and is higher and more variable overall than the international trend. For mean cover between 55mm and 80mm, the CV was approximately constant at 20%, significantly higher than the international trend, representing moderate control. Further analysis of the data gives a polynomial best fit trend with a correlation coefficient of 0,523 (R^2 = 0,273). The local cover data clearly exhibits greater relative variability, measured using the coefficient of variation, than the international data.

The average standard deviation values for the local data appeared to increase with mean cover values. Individual local standard deviation values exhibited extreme variability, from 3mm to 22mm, with the arithmetic mean standard deviation determined as 11mm, which is significantly higher than the international values.

In addition, there is a significant concentration of bridge data points between CV of 10 to 30%, indicating moderate to good control for mean cover between 60mm and 40mm respectively. However, a significant proportion of the building data has a CV in excess of 30%, indicating poor control, for mean cover between 22mm and 48mm. The South African cover data concurs with Australian experience where Marosszeky and Chew (1990) concluded that reinforcement is placed to a significantly higher standard on bridges and that the quality is more consistent on bridge sites than on building sites.

Appropriate tolerance limits for South African conditions

The margin, or reduction from nominal cover, originates from allowances for permissible tolerances for bending reinforcement and for formwork placement, as well as commitment to quality assurance during design and construction (SARCEA 1989). Wallbank (1989) reported that the specified nominal cover should be 15mm to 20mm greater than the required minimum on bridge supports and 5mm to 10mm greater on bridge deck soffits, while the European design codes suggest that the margin for surfaces cast against formwork is typically in the range 5 to 15mm. Sharp (1997) noted that in order to achieve 50mm mean cover, for a designed 95% compliance, the margin needs to be about 17mm; while if 99% compliance were required, the margin would have to be about 23mm. The suggested European values have been superimposed on South African cover data as shown in figure 4.

No South African cover data presented complied with the 5mm European margin for precision work, while only 10 data points, representing 6% of the data sample, complied with the 10mm European margin for normal in-situ work. A significant proportion of the data complied with the 15mm European margin for heavy civil works. Moreover the projected 20mm margin closely resembles the polynomial trend established in figure 3, therefore the 20mm margin is proposed as a realistic and acceptable tolerance level for South African construction practice. Proposed margins are recommended at 10mm, 15mm, and 20mm for current South African standards of workmanship. However, approximately 30% of the South African data presented do not comply with the maximum proposed margin of 20mm. In comparison, Morosszeky and Chew (1990) determined that only 50% of Australian cover survey data achieved a 95% compliance with a 20mm reduction from the nominal cover.

Importantly, the South African cover surveys were conducted in an environment where no post-casting checking of concrete cover was routinely performed. Therefore the increased cover variability of the South African data in relation to the international data is somewhat expected. A previous South African study (Ronné et al 2002) showed that the variation in concrete cover was specific to manufacturing practice. The variable margin can be controlled using appropriate quality assurance procedures, and significant improvements resulted once routine checking of concrete cover was implemented.

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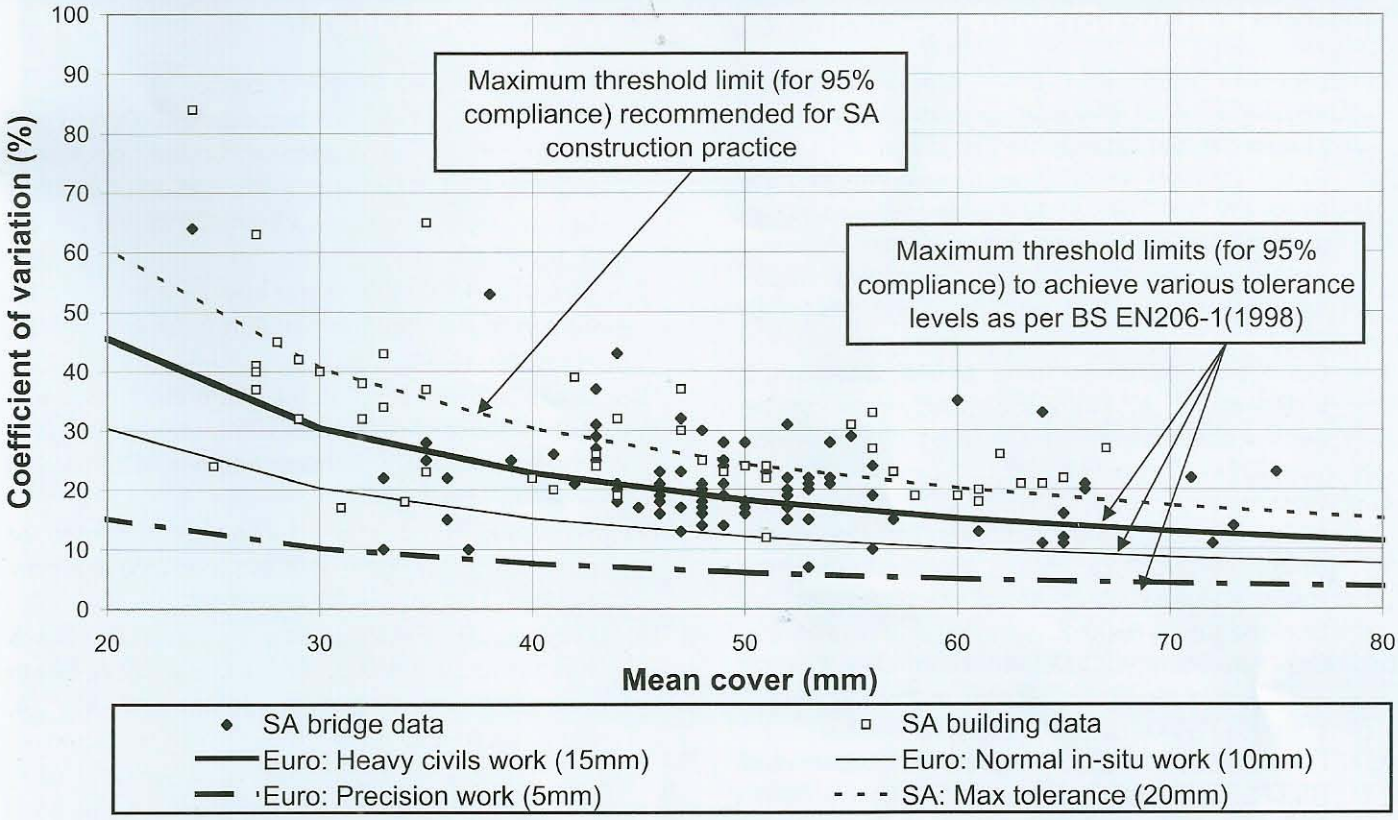

Figure 4: Appropriate tolerance limits for cover for 95% compliance.

Conclusions

Cover to reinforcement is a critical parameter to ensure adequate durability of reinforced concrete structures. Extended service life of reinforced concrete structures and potentially severe economic penalties resulting from reduced durability demand that poor construction quality, particularly the non-achievement of concrete cover, cannot be tolerated. Detailed analyses of data for both South Africa and international cover to reinforcement were performed in order to further quantify the inherent variability as a probable cause of cover problems.

For both international and South African cover data, increased relative variability of cover was found for low cover depths, while relative variability reduced for greater covers depths. In addition, the local cover data exhibited greater absolute variability than international cover data. Qualitatively local building construction practice appears to exhibit more relative variability, and is less consistent, than bridge construction.

Modifications to specifications for concrete cover are required to ensure adequate quality of construction. The inherent variation of the local cover data is related to appropriate tolerance margins for current South African construction practice that are proposed at 10mm for precision work, 15mm for normal in-situ work, and 20mm for heavy civil work (for 95% compliance). Currently 30% of South African cover data does not meet the 20mm margin criterion. Appropriate and reliable specifications that take due cognisance of the inherent variability of concrete cover are required to ensure adequate quality of construction.

It is recommended that cover surveys be routinely performed on site to ensure compliance with the specifications and improve the potential for durability. Importantly, the cover surveys must be conducted using a reliable covermeter and should typically comprise a minimum of 45 individual readings over a survey area of 1,5 to 2 m² per member, in order to reliably quantify the variability of cover to reinforcement.

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