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**Recommendation of RILEM TC 189-NEC: 'Non-destructive evaluation of the concrete cover'**

# Comparative test – Part II - Comparative test of "Covermeters"

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The text presented hereunder is a general draft for general consideration. Comments should be sent to the TC Chairman Dr. Roberto Torrent, HOLCIM Group Support Ltd., Concrete and Aggregates Division, Im Schachen, CH-5113 Holderbank, Switzerland; Tel: +41 58 858 67 14; Fax: +41 58 858 67 09; Email: roberto.torrent@holcim.com, by 30 June 2006.



## 1. NON-DESTRUCTIVE ASSESSMENT OF COVER DEPTHS

This paper, which summarises Part II of the Comparative Test, deals with the NDT assessment of the actual cover depth to reinforcement in recently built structures, using commercially available covermeters, in a completely non-destructive manner.

## 2. COMPARATIVE TEST OF "COVER-TO-REINFORCEMENT" METHODS

Cover depth has an important effect on the processes that lead to the corrosion of steel in concrete. The object of Part II of the Comparative Test was to determine the suitability of some commercial covermeters to assess the cover depth to reinforcement, in a completely non-destructive manner, *i.e.*, without any damage to the concrete.

The capability of different covermeters to assess the cover to reinforcement was checked by using them in different environmental conditions (Temperature and Relative Humidity) and for different steel bar arrangements, embedded in concretes of 2 different w/c ratios.


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## 3. SPECIMENS AND MATERIALS

Two groups of cover depths were included: usual cover, in the range 25-35 mm and deep cover, in the range 70-80 mm. The latter, less usual, represents situations where long service lives are required in very aggressive environments.

Four slabs, 0.3 x 0.9 x 0.12 m, with conventional reinforcement bars were cast, according to the detailing shown in Fig. 1. Nominal covers (in mm) of each bar are shown in brackets and the distances from the left margin of the slab to the centre of the bar (in mm) are indicated below each nominal cover.

Table 1 shows the actual covers and distances from the left margin for slabs M, R, S and T, as they were informed by Empa by direct measurement on the saw-cut slabs.

These slabs correspond to concretes made with two w/c ratios, tested in dry and wet condition, and also at normal and low temperature, as can be seen from Table 2; more details about the mixes, curing and storage of the slabs (test conditions) can be found in Annex A of Part I of the report, for the corresponding test condition.

In a first round of measurements (Case A), no information whatsoever was given to the participants regarding position or diameter of the bars.

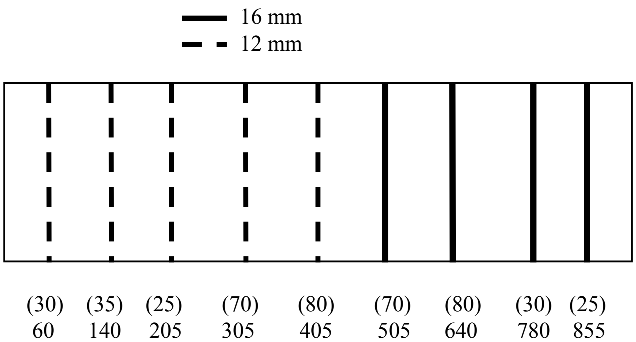


Fig. 1 - Layout of slabs M, R, S and T.

**Table 1 - Actual cover and position of the bars, in mm**

| **slab R** | **Position** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|---|
| cover thickness [mm] | | 29 | 35 | 24 | 69 | 80 | 72 | 80 | 34 | 28 |
| distance from edge [mm] | | 61 | 140 | 208 | 307 | 405 | 510 | 640 | 784 | 855 |
| **slab S** | | | | | | | | | | |
| cover thickness [mm] | | 31 | 36 | 26 | 68 | 80 | 72 | 80 | 32 | 27 |
| distance from edge [mm] | | 59 | 140 | 208 | 304 | 406 | 510 | 638 | 782 | 858 |
| **slab M** | | | | | | | | | | |
| cover thickness [mm] | | 30 | 34 | 25 | 70 | 81 | 71 | 81 | 32 | 26 |
| distance from edge [mm] | | 58 | 138 | 205 | 306 | 404 | 506 | 638 | 778 | 856 |
| **slab T** | | | | | | | | | | |
| cover thickness [mm] | | 30 | 34 | 24 | 69 | 81 | 73 | 83 | 29 | 24 |
| distance from edge [mm] | | 57 | 136 | 205 | 302 | 407 | 498 | 630 | 777 | 855 |

**Table 2 - Test conditions for Slabs M, R, S and T**

| | w/c | Temperature (°C) | Moisture condition | Test condition |
|---|---|---|---|---|
| Slab M | 0.55 | 20 | Dry | 2 |
| Slab R | 0.55 | 10 | Dry | 10 |
| Slab S | 0.40 | 20 | Dry | 1 |
| Slab T | 0.55 | 20 | Moist | 8 |

*Note: Test conditions are described in Part I, Annex A*

**Table 3 - List of equipment used**

| **Institute or Company** | **Instruments used** |
|---|---|
| TNO | HILTI FS10 |
| HILTI (*) | HILTI FS10 |
| ELCOMETER INSTRUMENTS Ltd. | PROTOVALE CM 52<br>PROTOVALE CM9 |
| PROCEQ | PROFOMETER 5 |
| LNEC | PROFOMETER 4 |

*(*) HILTI could not complete the test for Case C, therefore its results are not considered.*

In a second round (Case B) the participants were told that the bars had 12 or 16 mm diameter, but not where they were located.

In a third round (Case C) the participants were told the approximate location of the bars and their respective diameters.

For the 3 cases, the participants had to assess the cover depth of the bars.

For the scope of this TC, the interest focuses in verifying the compliance of new construction with performance-based specifications. Then, the steel-bar diameter and approximate position will be known and so, Case C is the most representative of that situation. Therefore, this report is concerned essentially with the analysis of the results for Case C.

## 4. TESTING EQUIPMENT APPLIED

Only commercial covermeters were evaluated, using standard heads, suitable for common (shallow) covers (exception in 5.1).

Table 3 shows the covermeters used and the institution or company that performed the tests.

### 4.1 Criteria to evaluate the results

The analysis of the results is restricted to Case C, i.e. the assessment of the cover depth when there is knowledge of the diameter and of the approximate location of the bars.

Nevertheless, to consider the effect of lack of knowledge on the location and diameter of the bars (Cases B and A), a separate analysis is presented at the end of this document (see 6.2).

Three levels of analysis are performed: Shallow (cover < 40 mm), Deep (cover > 40 mm) and All (shallow + deep).

Two sets of values resulted from the tests:

$t_r$= real cover depth (mm), measured directly on the saw-cut slabs by Empa

$t_e$= estimated cover depth (mm), reported by the different participants

The error $d = t_e - t_r$ is calculated for each bar at the centre of the slab.

#### 4.1.1 Successful assessments

An assessment is considered successful when:

a) a value has been reported and

b) the absolute value of "d" does not exceed 10% of $t_r$, rounded to the next integer value.

#### 4.1.2 Assessment of accuracy and precision

A measure of the bias of the NDT estimates is given by the mean value of d; therefore, the closer to zero the mean value of d, the higher the Accuracy of the measurements.

A measure of the variability of the NDT estimates is given by the mean quadratic error E, calculated as:

$$E = (\Sigma(d)^2/n)^{[1/2]}$$

where n is the number of measurements considered

**Table 4a - Actual and assessed cover (mm) data for Case C, slab M**

| | Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 | Position 7 | Position 8 | Position 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Bar Ø (mm)** | 12 | 12 | 12 | 12 | 12 | 16 | 16 | 16 | 16 |
| **Arrangement** | Single | Single | Single | Single | Single | Single | Single | Single | Single |
| **Cover (actual)** | 30 | 34 | 25 | 70 | 81 | 71 | 81 | 32 | 26 |
| ***Case C*** | | | | | | | | | |
| HILTI FS10 (TN0) | 31 | 36 | 26 | U.r. | > 90 | 75 | 78 | 32 | 27 |
| PROTOVALE CM52 | 29 | 32 | 24 | 68 | 77 | 68 | 77 | 31 | 27 |
| PROTOVALE CM9 | 31 | 36 | 26 | 72 | 78 | 72 | 82 | 33 | 28 |
| PROFO 5 (Proceq) | 30 | 35 | 25 | 68 | U.r. | 68 | 78 | 32 | 26 |
| PROFO 4 (LNEC) | 30 / 30 | 34 / 36 | 26 / 26 | U.r. / 65 | U.r. / 65 | U.r. / 78 | U.r. / 81 | 32 / 30 | 27 / 25 |

**Table 4b - Actual and assessed cover (mm) data for Case C, slab R**

| | Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 | Position 7 | Position 8 | Position 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Bar Ø (mm)** | 12 | 12 | 12 | 12 | 12 | 16 | 16 | 16 | 16 |
| **Arrangement** | Single | Single | Single | Single | Single | Single | Single | Single | Single |
| **Cover (actual)** | 29 | 35 | 24 | 69 | 80 | 72 | 80 | 34 | 28 |
| ***Case C*** | | | | | | | | | |
| HILTI FS10 (TN0) | 30 | 37 | 27 | 75 | U.r. | 80 | 83 | 36 | 32 |
| PROTOVALE CM52 | 29 | 33 | 23 | 67 | 81 | 71 | 81 | 33 | 28 |
| PROTOVALE CM9 | 30 | 36 | 25 | 70 | U.r. | 74 | 82 | 36 | 29 |
| PROFO 5 (Proceq) | 30 | 35 | 25 | 67 | U.r. | 67 | 74 | 35 | 28 |
| PROFO 4 (LNEC) | 29 / 28 | 35 / U.r. | 25 / 24 | U.r. / 76 | U.r. / 62 | U.r. | U.r. / 74 | 32 / 42 | 27 / 32 |

**Table 4c - Actual and assessed cover (mm) data for Case C, slab S**

| | Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 | Position 7 | Position 8 | Position 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Bar Ø (mm)** | 12 | 12 | 12 | 12 | 12 | 16 | 16 | 16 | 16 |
| **Arrangement** | Single | Single | Single | Single | Single | Single | Single | Single | Single |
| **Cover (actual)** | 31 | 36 | 26 | 68 | 80 | 72 | 80 | 32 | 27 |
| ***Case C*** | | | | | | | | | |
| HILTI FS10 (TN0) | 31 | 36 | 27 | > 90 | U.r. | 80 | 90 | 35 | 30 |
| PROTOVALE CM52 | 30 | 33 | 26 | 67 | 78 | 71 | 78 | 34 | 28 |
| PROTOVALE CM9 | 32 | 37 | 27 | 72 | U.r. | 74 | 82 | 33 | 28 |
| PROFO 5 (Proceq) | 31 | 36 | 26 | 65 | 72 | 70 | 77 | 33 | 28 |
| PROFO 4 (LNEC) | 30 / 30 | 35 / U.r. | 26 / 25 | U.r. | 60 / 70 | U.r. | 70 / U.r. | 31 / 32 | 27 / 28 |

**Table 4d - Actual and assessed cover (mm) data for Case C, slab T**

| | Position 1 | Position 2 | Position 3 | Position 4 | Position 5 | Position 6 | Position 7 | Position 8 | Position 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Bar Ø (mm)** | 12 | 12 | 12 | 12 | 12 | 16 | 16 | 16 | 16 |
| **Arrangement** | Single | Single | Single | Single | Single | Single | Single | Single | Single |
| **Cover (actual)** | 30 | 34 | 24 | 69 | 81 | 73 | 83 | 29 | 24 |
| ***Case C*** | | | | | | | | | |
| HILTI FS10 (TN0) | 30 | 35 | 27 | > 90 | U.r. | 78 | 75 | 28 | 25 |
| PROTOVALE CM52 | 29 | 32 | 23 | 66 | 82 | 71 | 82 | 29 | 23 |
| PROTOVALE CM9 | 31 | 35 | 25 | 70 | 78 | 74 | 82 | 30 | 25 |
| PROFO 5 (Proceq) | 30 | 34 | 24 | 67 | U.r. | 68 | 79 | 29 | 24 |
| PROFO 4 (LNEC) | 30 / 29 | 33 / 32 | 24 / 24 | 68 / U.r. | 68 / 64 | 59 / U.r. | 67 / 78 | 29 / 27 | 24 / 23 |

The closer E is to zero, the higher the precision of the measurements.

#### 4.1.3 Influence of test condition (slabs M, R, S and T)

The influence of testing condition (M, R, S and T) was assessed by comparing the variability of the ND assessment of the cover depth for each instrument (see Table 2).

## 5. RESULTS

### 5.1 Assessment of cover to reinforcement

The data reported by the participants were grouped by testing condition (M, R, S and T) and testing equipment. These data, corresponding to Situation C, shown in Tables 4a to 4d, are the basis for the analysis of the results.

Cases of uncertain measurements, where the cover depth was not reported, are identified as "U.r." (uncertain reading). These cases are included in the qualitative evaluation as "non success" (see Section 5.2), but they were not included in the estimation of accuracy and precision (see 5.3).

LNEC (PROFOMETER 4) used a small head (spot reading) and a big head (depth reading). When Tables 4a to 4d show both values as spot/depth, only the former is considered for the analysis.

### 5.2 Successful assessments

The percentage of successful assessments of the different covermeters for slabs M, R, S and T for Shallow, Deep and All covers is shown in Fig. 2.

### 5.3 Accuracy and precision (Bias and variability)

Bias and variability of the cover assessment for all slabs (consolidated values) are indicated in Fig. 3.

### 5.4 Influence of test conditions

The influence of test condition (M, R, S and T) on the variability of the ND assessment of the cover depth for each instrument is shown in Fig. 4. In most cases, the influence of temperature, moisture and w/c ratio on the assessment of the cover depth was negligible, except in one case (HILTI FS-10) for which no explanation could be found.

### 5.5 Comparison between Cases A, B and C (effect of previous knowledge)

Fig. 5 shows the effect of previous knowledge on the percentage of successful assessments of the cover depth for shallow covers, while Fig. 6 illustrates the same effect for deep cover depths.

The effect of lack of information on the actual bar diameter is stronger for deep covers, while it is not so relevant for shallow covers.

## 6. DISCUSSION

Three aspects of the measurements are commented: success rate, bias and variability.

Fig. 2 shows that for Case C and for covers below 40 mm, all the instruments showed a 100 % success in assessing the cover depth within the adopted tolerance (± 10 % $t_r$). When all covers are considered, the degree of success varied with the instruments, with some of them achieving over 90% success rates.

Regarding Bias, as shown in Fig. 3, the average bias of all

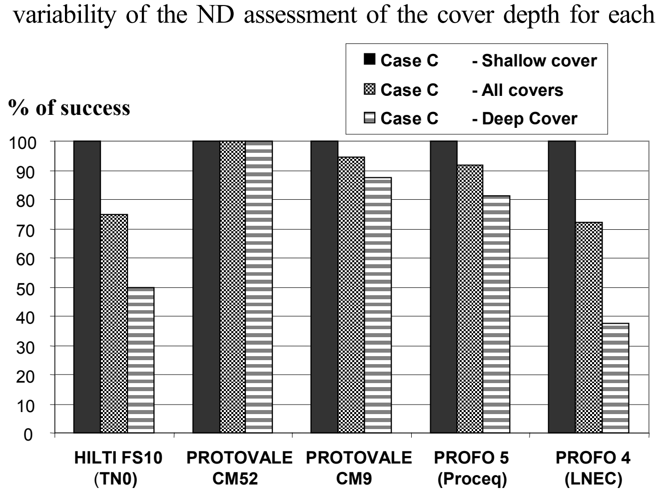


Fig. 2 - % of success in the assessment of cover to reinforcement.

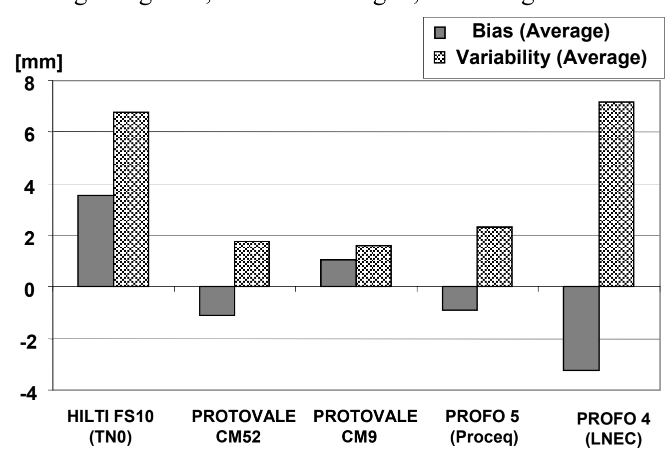


Fig. 3 - Bias and Variability (all slabs, all covers), consolidated for Slabs M, R, S and T.

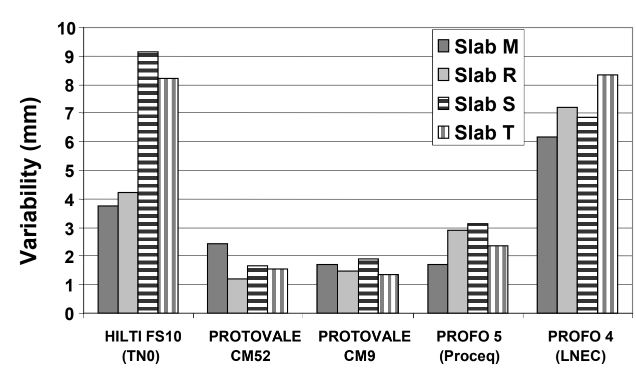


Fig. 4 - Variability for each slab (M, R, S and T), Case C.

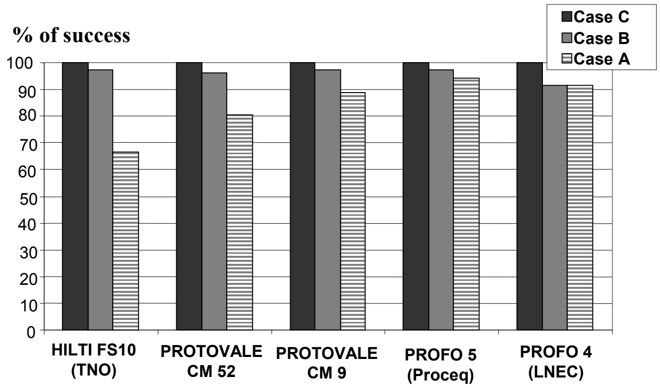


Fig. 5 - Percentage of success (average for all slabs) for Cases C, A and B and shallow cover.

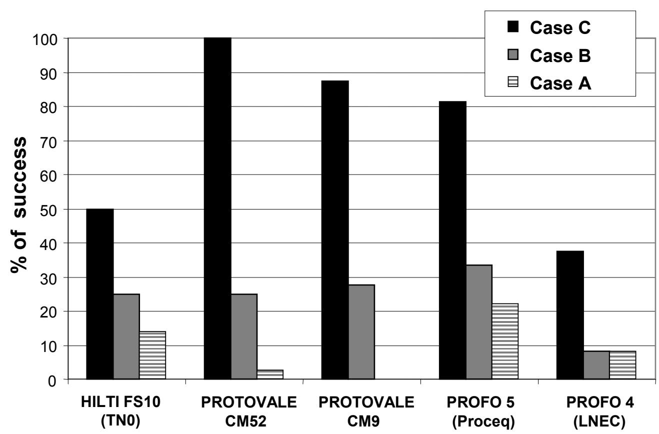


Fig. 6 - Percentage of success (average for all slabs) for Cases C, A and B and deep cover.

measurements is between ±1 and ±4 mm. These biases might eventually be corrected by an internal adjustment of the instrument or by proper calibration procedures.

Regarding Variability (Fig. 3) the average ranges between 2 mm and 7 mm.

Under the conditions of the experiment, for shallow covers all instruments showed the same good performance; on the other hand, for deep covers, Protovale CM 52, Protovale CM 9 and Profometer 5 performed better than the other two.

## 7. CONCLUSIONS AND FURTHER WORK

The Comparative Test proved that all the instruments are capable to measure with 100 % success the depth of the concrete cover within an accuracy of ± 10 %, under the following conditions:

- The nominal diameter of the bars is known
- The cover depth is below 40 mm.

For all covers (25 – 85 mm), three instruments are still capable to measure with more than 90 % success the depth of the concrete cover within an accuracy of ± 10 %.

The ability of the instruments to assess the cover depth decreases with the depth of the bars, especially for small diameters, and with the lack of information about their diameters.

In general, the assessment of the cover depth was not significantly affected by the temperature and moisture conditions under which the measurements were made, nor by the w/c ratio of the concrete.

Three instruments presented very good accuracy (bias below 1 mm) and precision (variability around 2 mm).

It was agreed to run a further comparative test on actual - size prototype elements, under more realistic steel arrangements and field conditions.