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Concrete Cover to Reinforcement – or Cover-up

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ABSTRACT:

Cover to reinforcement is the shortest distance between the surface of a concrete member and the nearest surface of the reinforcing steel. My earliest contact with the problem of cover to reinforcement was when I was a young engineer in charge of construction of drilling pits in which well-heads were to be located.

The four reinforced concrete sides of the pit were 150 mm thick; the main reinforcement consisted of vertical bars 25 mm in diameter. When I came to inspect the reinforcement prior to concreting, I noticed that is was located about 75 mm from the inner face of the finished pit. From the structural point of view this seemed a strange position, given that the earth on the outside would exert pressure on the pit walls and put their inner face in tension.

I spoke to the foreman who produced a drawing that clearly read: minimum cover 25 mm. “If the minimum is to be 25 mm”, he said,” I thought I would do better than that and make it 75mm”. This taught me an important lesson: the designer or detailer must not assume that the steel fixer (ironworker) or the operative, necessarily understands the rationale of the instructions on the drawing or in the specification, or that an operative interprets these instructions on the basis of personal knowledge of structural behaviour. Indeed, all instructions must be self-standing and self-explanatory.

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Concrete Cover to Reinforcement – Or Cover-up

TECHNICAL PAPER

Adam Neville

Cover to reinforcement is the shortest distance between the surface of a concrete member and the nearest surface of the reinforcing steel. My earliest contact with the problem of cover to reinforcement was when I was a young engineer in charge of construction of drilling pits in which well-heads were to be located. The four reinforced concrete sides of the pit were 150 mm (6 in.) thick; the main reinforcement consisted of vertical bars 25 mm (1 in.) in diameter. When I came to inspect the reinforcement prior to concreting, I noticed that it was located about 75 mm (3 in.) from the inner face of the finished pit. From the structural point of view, this seemed a strange position, given that the earth on the outside would exert pressure on the pit walls and put their inner face in tension.

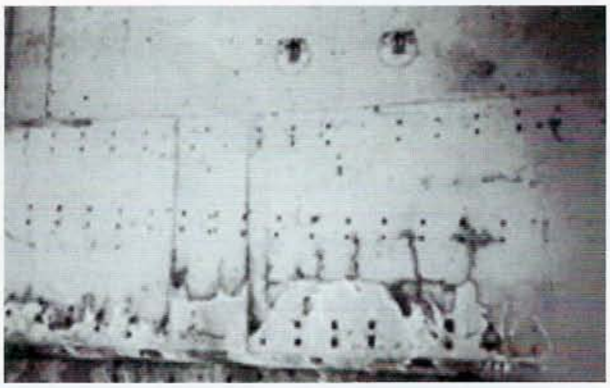
I spoke to the foreman, who produced a drawing, that clearly read: minimum cover 25 mm (1 in.). "If the minimum is to be 1 inch," he said, "I thought I would do better than that and make it 3 inches." This taught me an important lesson: the designer or the detailer must not assume that the steel fixer (ironworker) or the operative necessarily understands the rationale of the instructions on the drawing or in the specification, or that an operative interprets these instructions on the basis of personal knowledge of structural behaviour. In deed, all instructions must be self-standing and self-explanatory.

PURPOSE OF COVER TO REINFORCEMENT

It may be appropriate to remind ourselves of the reasons for providing the cover. There are several reasons, and at times we become so preoccupied with one of them that we tend to forget the importance of the others. For example, in the last decade, prevention of corrosion of reinforcement has reached such importance that we sometimes specify a large cover, without considering all the consequences of doing so. Let me, therefore, briefly list the purposes of cover.

TENSILE FORCE: Historically, the primary purpose is to put concrete around the reinforcing steel in a beam so that the strain in concrete in flexure is transferred to the steel which can then develop a tensile force. This is how reinforced concrete works and, if tension does not develop in the steel, it does not work! In other words, this purpose of providing cover to the reinforcing steel is essential and all-important. However, for this purpose, the cover can be very small; but what happens if the cover is excessive? The further the reinforcement from the tensile face of the beam the smaller its contribution to the carrying moment. In the extreme, if the cover is grossly excessive, the steel may develop no tension. This would be the case in a cantilever in which the cover from the top is so large that the steel is no longer on the tension side in flexure. This, too, would have been the situation in the walls of "my" drilling pit in service.

CRACKING: Cover is also important from the standpoint of shrinkage cracking. Unreinforced concrete, if restrained (and restraint can be avoided only in some situations) will allow concentrations of tensile strain to develop. If this strain exceeds the strain capacity of the concrete, shrinkage cracking will develop. To prevent the development of such concentrations of tensile strain, it is necessary to provide reinforcement, spaced fairly closely, and located sufficiently near the exposed drying



surface of the concrete member. Otherwise, cracking may occur. This is objectionable on aesthetic grounds if the concrete surface is apparent, and on durability grounds if an attacking medium can penetrate through the cracks toward the reinforcement.

The corollary of the above is that the thickness of cover must not be excessive; otherwise, the outer part of the concrete member would be, in fact, unreinforced and liable to shrinkage cracking. I shall come back to the issue of the maximum thickness of cover that we should use despite the occasional clamor for thicker and thicker cover by those seeking to provide protection of the reinforcement from corrosion.

CORROSION: This brings us to the need for cover for the purpose of protection of steel. Bare steel undergoes corrosion, that is, it rusts. However, when embedded in concrete, the surface of the steel is passivated and protected by the alkaline environment of the pore liquid in the hydrated cement paste. Continuation of this protection over the life of the structure requires that the alkalinity of the cement paste is not reduced. A common cause of such reduction is by carbonation, mainly of calcium hydroxide in the hydrated cement paste in the cover right up to the vicinity of the surface of the steel. Carbonation is progressive from the outer surface of the concrete: the progress is more rapid the greater the penetrability of the concrete, and this process effectively decreases the protective cover. Hence, the need for adequate cover.

Embedded steel becomes liable to corrosion, also in the absence of carbonation, if aggressive ions reach the surface of the steel. The most common ion is chloride, either from seawater (splashed or airborne) or from chloride salts used as deicing agents. The penetration of cover concrete by these agents is governed by the same factors as the progress of carbonation.

FIRE: There is one more important reason for the provision of adequate cover to reinforcement and fire protection of the steel. Fire endurance of reinforced concrete elements is a complicated topic because it involves structural action, which may be impaired by flame penetration and heat transmission. However, in essence, design codes specify the minimum cover of various types of structural elements (beams, floors, ribs, and columns) necessary to ensure a fire resistance over a certain number of hours; this specification is sometimes known as fire rating.

THREE TYPES OF PROBLEMS WITH COVER

A problem with cover means that it is unsatisfactory. There can be three reasons for it. First, the cover may be incorrectly specified. Secondly, the specification can be incorrectly formulated. Thirdly, the actual cover "as built" can be different from what was specified.

COVER INCORRECTLY SPECIFIED

As discussed in the preceding section, the requirements for cover include the development of the appropriate tensile force in the reinforcement, considerations of durability, fire resistance, and shrinkage distribution or restraint. As I have already intimated, the fire resistance requirements are too complex, as well as specialized, for inclusion in this article.

Let us now look at the consequences of incorrectly specified cover on the behaviour of concrete elements.

To develop the calculated tensile force, the reinforcement must be in the position assumed in the calculation of the moment of resistance of the beam or its ultimate strength. If the cover is larger than assumed in the calculations, large cracks will open under a lower applied load than should be the case. Under an overload, failure may occur prematurely. If the position of the reinforcement is structurally correct but an excessive cover was achieved by an additional depth of concrete, the self-weight of the beam is greater than assumed in the design calculations. This additional weight has adverse structural consequences also.

From the standpoint of durability, the protection of the reinforcement is a function of the thickness of cover and of the quality of concrete in it. It is believed that these two factors can be offset one against the other, and some codes of practice provide tables of alternative combinations of thickness of cover together with the quality of concrete to ensure durability under given conditions. The quality is described by minimum compressive strength or water-cement ratio or cement content. This is not the place to discuss which of these parameters is most appropriate. However, it is important to point out that a combination of a very large cover and a very poor concrete is entirely unsatisfactory: no matter how large the cover, if the concrete is porous and permeable, aggressive agents will rapidly penetrate through it to the surface of the steel reinforcement.

In other words, in my opinion, when concrete is to be exposed to conditions generally called severe or very severe, let alone extremely severe, the quality of concrete must be high or very high. Indeed, it is only the concrete in the cover zone that matters as far as the durability problems discussed here are concerned; the quality of the concrete in the interior of the member is almost irrelevant. The quality of concrete that is necessary is discussed fully in Properties of Concrete.1 What is not discussed in that book, but must be considered here, is that the thickness of the cover must be adequate but it must not be excessive.

What is considered adequate cover is prescribed in design codes. Many codes in more-or-less temperate climates underestimate the fact that in some other climates the severity of exposure can be much more acute than what is labelled "very severe" in Great Britain or in many parts of the United States. The Middle East, and especially the Gulf area, is a prime example of truly extreme conditions. Here, the temperature of the concrete is high and the insolation is severe, so that a considerable depth of concrete becomes very dry and "thirsty". At some later stage, the seawater, carried by wind in the form of droplets or aerosol, or salt-laden dust, wetted by dew, is deposited on the surface of the concrete and imbibed to a considerable depth. The process is cumulative and chloride ions reach the surface of the reinforcement (Fig. 1). The irregularly placed reinforcing is now visible.

This article is not concerned with what happens next, but it is clear that an adequate thickness of cover is necessary. Codes of practice give advice on what is adequate but, as I have already pointed out, under extreme conditions the advice may be too optimistic. This has led some engineers to recommend a greater thickness of cover: 100 mm (4 in.) or even 120 mm (5 in.). In my view, this is wrong because such a large cover means that a considerable thickness of concrete is unreinforced; consequently, shrinkage cracks can open or flexural cracks can develop under load. Such cracking would allow ingress of aggressive agents so that the alleged remedy of a very thick cover is, in fact, detrimental. To quantify my opinion, I would say that cover should not exceed 80 mm (3 ¼ in.), or perhaps 90 mm (3 ½ in.). If this is still inadequate for the desired durability, a better quality of concrete, possibly containing some special ingredients, must be used. It is also possible that reinforced concrete is inappropriate for the given conditions. We sometimes forget that, at least in a particularly exposed part of a structure, unreinforced concrete masonry could be used. When there is no reinforcement, carbonation is not harmful and chlorides do not represent serious danger.

Fig 1: Catastrophic delamination of soffit of a slab due to inadequate cover for extreme exposure conditions

SPECIFICATION INCORRECTLY FORMULATED

Let me now turn to problems arising from an unsatisfactory formulation of the specification. First, all embedded steel, not just structural reinforcement, is subject to corrosion. It follows that the specified minimum cover must apply to links (stirrups) and, indeed, to other embedded steel. This is sometimes forgotten; more often, the drawing states: "cover to steel, so much." The person on site cannot be blamed for interpreting this to mean "cover to main steel" – never mind bits and pieces.

A more serious problem arises with the precise meaning of the term "cover". To say 'cover to 40 mm (1 ½ in.)' and expect the cover everywhere to be exactly that is entirely unrealistic. In reality, cover, here and there, must vary from the specified value. The issue is then how to interpret that value. For example, the British approach[2] is to operate in terms of what is called "nominal cover," that is the value of cover used in the structural design calculations and indicated on the drawings. To allow for the variability in the thickness of cover in reality, the British code[2] says: "The actual cover to all reinforcement should never be less than the nominal cover minus 5 mm (¼ in.)." The code is silent on how much more than specified is tolerated. So, our aforementioned foreman was not wrong to exceed the cover by 50 mm or 2 in.

The ACI Building Code,[3] section 7.5, uses a similar approach: the tolerance on mini mum cover is -10 mm (-⅜ in.) for members up to 200 mm (8 in.) deep, and for deeper members, -13 mm (-½ in.). The important point here is that the American tolerance is -10 or -13 mm (depending on the depth of the member) while the British tolerance is only -5 mm (-¼ in.) in all cases.

I am not arguing which code is right, but in my view they are both inadequate in that they do not lay down a positive tolerance. Some other codes do give both a negative and a positive tolerance, and many job-specific specifications do so likewise. I shall return to the issue of specifying the cover in an unambiguous and adequate manner later in my article. At this stage, I should consider two potential questions: How does cover vary in reality? Is the cover in actual structures too large as well as too small?

ACTUAL COVER NOT AS SPECIFIED

The underlying reason for writing this article is the fact that, in a number of actual structures, the cover varies, often considerably, from the specified value. This fact is not widely known and, even when the existence of improper cover is known, this is not considered to be a problem; certainly, nothing is done about it. It is only when a given structure has shown signs of serious deterioration, involving the corrosion of the reinforcement, that detailed inspection reveals the fact that the cover as executed was not as specified. It is this belated discovery, or uncovering, that has prompted me to refer in the title of this article to a "cover-up".

My first personal observation of improper cover was when external signs of large-scale corrosion of reinforcement (rust, cracking along the position of the reinforcement, spalling, and delamination) led to a detailed investigation of the position of the reinforcement. This was in several major structures in the Middle East, but the problem is certainly not limited to that part of the world. For example, in a high-rise building in Australia, described as prestigious (which translates into high rent), I observed what I call "negative cover" (Fig. 2). This term should be introduced into the ACI vocabulary to describe a situation where the reinforcement can be actually seen by the naked eye and felt by a finger. It is only fair to add that inadequate cover was not the sole cause of corrosion in all those cases, but it is a vital element in the deterioration of many structures.

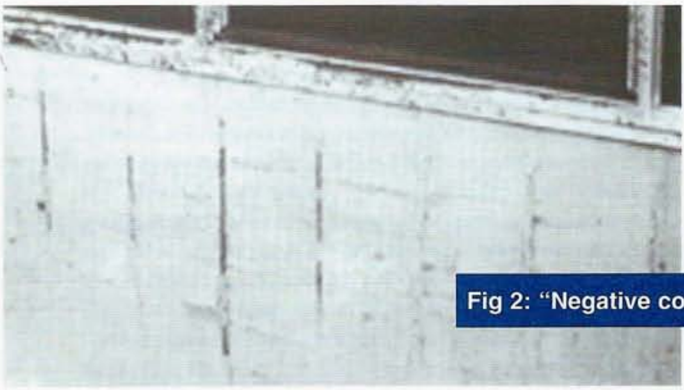


Fig 2: "Negative cover"

Fig 3: Leaning on the shovel is not enough; the operative must stand on something, and reinforcing steel must be supported.

In passing, I could add that the members, some of which had a negative cover, were cladding units without interior lining, 75 mm (3 in.) thick. The reinforcing bars were 25 mm (1 in.) in diameter, with a specified cover, front and back of 20 mm (¾ in.). Can this be achieved in real life? What happened in the event is that chloride ingress occurred from outside and carbonation from inside the building. This must be the classical case of reinforcement suffering from the worst of both worlds.
Those familiar with construction may wonder how woefully improper cover can exist, given that, on most well-regulated sites, the position and fixing of reinforcement is checked by the engineer, or his representative, prior to authorization of the actual concreting. There is a delightful story, I am assured not

apocryphal, about the construction of a multi-story building. When the reinforcement for a given floor was in position, the engineer verified it, ordered concreting to proceed, and depart ed. On the occasion of concreting the tenth floor, he happened accidentally to leave his briefcase behind but did not discover its loss until several hours later. When he returned to retrieve his briefcase, the concreting had been finished. To his astonishment, he observed a large number of reinforcing bars stacked to one side. The explanation was simple: after the engineer's inspection, the building owner ordered the removal of half the reinforcement at every floor level. He was going to sell the building as soon as it had been completed, so economy took precedence over safety.

In reality, fraud or malpractice is not the cause of improper cover, but there are several reasons for it. One of the main ones is a lack of appreciation of the importance of achieving the specified cover. In this respect, as in many others, some of the operatives are inadequately trained and knowledgeable about reinforced concrete. It has to be admitted that they often work under physically demanding conditions and under considerable pressure. Tying up the bars may be skimped, fixing may be inadequate, chairs, spacers and other supports may become damaged or displaced. Standing on the reinforcement by the operatives (Fig. 3) can temporarily displace it, but the weight of concrete makes the displacement permanent. These problems can become aggravated when the shrinkage reinforcement is relatively light.

The use of well-made reinforcement cages should minimize the above problems, but then whole cages have been known to be wrongly placed or to shift bodily when their support is too weak. The real trouble is that all the means of fixing the reinforcement are minor, small or flimsy, so that they do not attract major attention of those involved in concreting.

But the causes of improper cover are not limited to site operations. The design and detailing of reinforcement sometimes makes for serious practical difficulties on site. Occasionally, there is more steel than can actually be fitted into the space available, especially when lapping or cranking is necessary. The drawing often does not show how to achieve this, there being a simple instruction of the type: "laps to be 460 mm (18 in.)." In some types of structures, the amount of reinforcement required for structural reasons is so large that there are great difficulties in fitting it in, without shoving and pushing. On one occasion, the amount of steel was so large that the foreman was moved to ask the engineer: Do you want me to concrete it or to paint it?

The reason for the practical difficulties of placing the reinforcement as specified may lie in the fact that some designers (of course, not all) lack site experience and are simply not aware of how hard, if not impossible, it is to execute their designs and sketchy detailing. The use of computers should help in this respect but sometimes detailing is taken care of too far down the line.

Another source of difficulties is improper or incorrect bending of bars or cutting them to length. Relatively small errors can have serious consequences, given that bar lengths are handled in feet or tenths of a meter, whereas cover is measured in quarters of an inch or in increments of 5 mm.

OBSERVED PROBLEMS WITH COVER

At this stage, I may well be called upon to demonstrate that the various problems with improper cover are real problems, frequently occurring in actual structures, and not just an imaginary or rare occurrence. There are several publications demonstrating the reality of my concern. I propose to refer to four of them, dealing with several types of structures in three countries.

In Canada, Mirza and MacGregor[4] studied the actual cover in a number of slabs, both cast on site and precast. In cast-on-site slabs, they found that the top reinforcement was more often affected than bottom reinforcement. The mean deviation of cover from the specified value was -20 mm (-0.8 in.) for the top reinforcement, and -8 mm (-⅓ in.) for the bottom reinforcement. In precast slabs, with only bottom reinforce ment, the cover was virtually exactly as specified. This is not surprising, given that factory-style mass production can achieve perfection; moreover, in precasting operations, the reinforcement is generally not used to support the operative.

An Australian study[5] is particularly interesting because it combined the determination of actual cover with observations of corrosion; there was a good correlation between the two. This is not surprising because, at 227 "fault locations" in 95 buildings, the average cover had a shockingly low value of 6 mm (¼ in.). This decisive role of inadequate cover with respect to corrosion of reinforcement does not invalidate my earlier argument about the paramount importance of the quality of concrete because, in the elements studied, the quality of concrete was the same and only the thickness of cover varied. The highest occurrence of problem areas in building facades was in beam and slab end faces.5 This is interesting because it suggests that it is the longitudinal displacement of reinforcement, or its excessive length, in a horizontal member that leads to inadequate cover (Photo on title page).

Some other figures from the same study[5] are of interest. In as many as 18 percent of locations in buildings, the cover was less than 0.6 of the specified value. In bridges, the situation was very much better, with only 4 percent of locations having a cover of less than 0.6 of the specified value. Nevertheless, cover that is too small by a factor of 0.4 is a serious matter.

The data on excessive cover are of particular interest in view of my earlier comments on the occurrence of this phenomenon, rarely considered in design codes. It was found that at 62 percent of locations in buildings and 51 percent of locations in bridges, the actual cover exceeded the specified value(5).

A major investigation of the state of 200 bridges in Great Britain provided a considerable amount of information about cover to reinforcement.6 Of these bridges, 77 exhibited rust or spalling associated with low cover. The cover survey was carried out on 500 mm (20 in.) square test areas, and the minimum cover in each area was determined.

The value of the minimum cover in the bridge elements varied widely. For example, in deck soffits of bridges constructed between 1970 and 1980, the lowest value of the minimum cover was 10 mm (0.4 in.) and the highest value of minimum cover was 130 mm (5 in.). For bridges built between 1980 and 1985, the corresponding values were 20 mm (¾ in.) and 75 mm (3 in.) respectively. For abutments and piers, the spread was even larger: in the earlier period, 0 to 115 mm (0 to 4 ½ in.), and for the later period, 10 mm to 100 mm (½ to 4 in.). By way of comparison, I should add that the nominal cover specified for the deck soffits was generally 30 to 45 mm (1 ¼ to 1 ¾ in.), and for abutments and piers, 40 to 55 mm (1 ½ to 2 ¼ in.); a negative tolerance of 5 mm (¼ in.) was usually allowed.

For each period of construction, the mean minimum value was calculated, as well as the modal minimum value (that is, the minimum value most frequently encountered). In all cases, the modal value of minimum cover was lower than the mean value. This means that the low values of cover were more frequent, but the large values of minimum cover were very large. In other words, the distribution of minimum values of cover was skewed to the right.

Data on prestressed concrete decks are difficult to interpret because much depends on the specific method of prestressing. However, generally, the control of cover in prestressed concrete members seems to be better(6).

The final study to be considered in this paper is also British; it is very recent and deals with structures actually under construction on 25 sites(7). The study is limited to vertical members: columns and walls; there was no difference in the pattern of cover between these two types of members. Many of the measurements make dismal reading. For example, in one major bridge with a specified cover of 40 mm (1 ½ in.), in two columns, the measured values of cover were all higher than specified, in some cases with values up to 93 mm (3 ¾ in.). In another bridge, also major, with a specified cover of 50 mm (2 in.) all but three measured values of cover were too small, down to 37 mm (1 ½ in.).

One more set of measurements should be reported because it serves a useful purpose, if only as a horrible example. On a more than a billion dollar building project, with a specified cover of 50 mm (2 in.), the actual cover in one wall ranged from 12 to 75 mm (½ to 3 in.). The incidence of too-small cover and of too-large cover was about equal; what is remarkable is that there were almost no measurements of cover between 43 and 53 mm (1 ⅝ and 2 ⅛ in.), that is, near the specified value.

These four studies, among them, show that the problem of improper cover is not limited to just a few structures or to particular types of structures or only to some countries. I can add from my personal experience the existence of inadequate cover in many major structures in the Middle East.

To demonstrate that I am not a lone crusader against improper cover, I would like to quote from Ref. 7:

"It is evident...that the required cover values and their allowable tolerances [negative and positive] have not been met, by wide margins, on most sites. Hence, it is confirmed that lack of cover is an extensive problem which is of a chronic rather than a sporadic nature."

CONCLUSIONS

The various data in References 4 to 7 can be analyzed further, but this would be of value only to an historian of concrete problems. For my part, I wish to look to the future, and I am sure that ACI is primarily concerned with doing better in the years to come. So what are the lessons?

I believe that there is an endemic problem of improper cover. Does it matter? I believe it does.

Even if, from the structural standpoint, having half the reinforcing bars with an inadequate cover and half with an excessive cover is not critical, this is not true for durability considerations. When one-half of the bars have corroded, major repairs will be necessary, and then even the strength of the structure can become impaired.

We must remember that for the protection of the reinforcing steel, having the appropriate thickness of cover is not enough: the concrete must be of appropriate quality, but it is only the quality of the cover concrete that matters.

Should we increase the specified minimum cover in the knowledge that, even where the actual cover is much less than specified, the actual value will be adequate for durability purposes? If we do so, we shall increase the weight of the structural members (with cost implications in materials, labour, and foundations), as well as in the size of the cross-section of the member required to carry the heavier loads. We shall also produce an unreinforced concrete tension zone, with cracks of considerable width; this will promote ingress of aggressive agents, and vitiate our attempts to minimize corrosion.

Should we shrug our shoulders on the grounds that, as stated in Ref. 7, we live in a world of "contractual terms and conditions and a harsh economic climate which do not foster collaboration"? This may well be true, but it is a hard life for car makers, and aircraft manufacturers, too. I need not ask whether parallel consequences for safety and durability would be acceptable.

So what can we do? I do not presume to offer a recipe, but only to present a few ideas.

In the design office, we should pay much more attention to detailing the reinforcement; this is not a trivial task left to somebody down the line. The designer who has not got the requisite experience under his belt would be well advised to get thoroughly acquainted with site operations and the attendant difficulties of working under inclement conditions. The designer must also make sure that the structure is buildable in so far as fitting in the reinforcement is readily possible.

The chairs, spacers, and supports of the reinforcement are an integral part of the finished structure. Their quality should be assured, and the task of providing them should not be left to an indeterminate operative.

The output of the steel-bending shop should be more care fully verified than is sometimes the case. The approach of "adjusting" the reinforcement on site by a sledge hammer will not do.

The site operatives should be better trained and better aware of what the reinforcing steel does and why its cover matters very much. This theme of the need for training is recurrent whatever aspect of concreting is considered.

At the same time, there should be better cooperation and communication between the supervisory staff and the operatives. I am convinced that exacting supervision is helpful; so is frequent verification prior to concreting and also after. Modern covermeters are highly reliable and can deliver a printed output.

I know that it is easy to say that the pressure of time and the need to proceed with the job should not interfere with the quality. In my view, the quality must take precedence, if we are to continue to build concrete structures in an economic way. Poor quality is very expensive, even though the expense is incurred at a later date. This does not make economic sense.

The required cover should be very carefully specified both on the drawings and in the specification. The meaning of "minimum" should be defined. It could be an absolute minimum or a characteristic (say, 5 percent) value (which, personally, I do not favor because of the difficulty of defining the population to be tested). The tolerances should be defined, both positive and negative, but they should not be unrealistically small. The need for cover to the ends of reinforcing bars should not be ignored. Many more suggestions can be made. But what is really required is recognition that cover does matter. Cover-up will eventually be exposed. ●

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