

CARBONATION OF REINFORCED MASONRY

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ABSTRACT Corrosion of reinforcement is a problem in concrete structures. A cause of the corrosion is loss of alkalinity due to carbonation from the atmosphere. The resistance of a structure to corrosion can be assessed from the rate of carbonation from the exposed surface.

A theoretical model is developed to calculate the depth of carbonation in typical forms of reinforced masonry, including those with face shells of mortar, concrete and clay brick overlying the grouted cavity containing reinforcement.

Laboratory specimens simulating typical reinforced masonry composites are subjected to a concentrated atmosphere of carbon dioxide, and the depths of carbonation measured over a period of time. The results confirm the theoretical model.

The implications with regard to design and allowable limits for regulatory purposes are discussed.

1. INTRODUCTION

Reinforcement corrosion in concrete is an issue of concern in the building industry at the present time (1). The efforts of many research organisations throughout the world are directed towards a better understanding of the environmental and material factors which influence the corrosion of steel in reinforced concrete, and the production of information for design which will ensure the durability of structures. However, an aspect which has not been adequately considered is the corrosion of steel reinforcement in masonry construction.

Reinforced masonry is a composite. Steel bars are placed into cavities in the masonry and the cavities are then filled with grout or concrete. The masonry can be of various types, common forms being hollow concrete masonry units laid with continuous core cavities or parallel leaves of clay brick masonry around a central reinforced cavity.

In reinforced concrete, the degree of protection that is provided to the reinforcement is a function of the thickness and quality of the covering layer of concrete. Carbon dioxide slowly penetrates the concrete exposed to the atmosphere, progressively lowering the alkalinity of the material to a level at which steel is liable to corrode. This carbonation front advances at a rate decreasing with time. From the time it arrives at the steel, rusting may develop and lead to cracking, spalling and eventual failure of the structure. The rate of development depends upon environmental factors, in particular the availability of moisture.

It is generally accepted that the rate of progress of the carbonation front can be defined, for practical purposes, by an equation of the form:

$$D = AT^{1/2}$$

where D = depth of carbonation front from the surface,
 A = carbonation coefficient, and
 T = time.

Thus the initiation of corrosion can be assessed given knowledge of A , which can be determined experimentally, and the thickness of cover over the reinforcement.

The study of reinforced masonry is complicated by there being more than one, usually dissimilar, layers between the reinforcement and the exposed face. These layers may be clay brick, the face shell of a concrete block, or a mortar joint as well as the grout or concrete surrounding the steel. Opinions vary as to the allowance that can be made for the resistance to carbonation of such materials in combination.

This paper essays to clarify the situation. A theoretical model is firstly established as a means of predicting the time at which the carbonation front may reach the steel for a given combination of cover materials. The results of a planned experimental program serve to examine the validity of the theory, and conclusions are drawn as to the allowance that might be made in design rules for such combinations of materials.

2. THEORETICAL MODEL

2.1 Cementitious face shells

Consider the case where the grout concrete, c , is covered by a facing of another type of concrete or mortar, f .

The carbonation behaviour of the individual materials can be represented by the equations:

$$D_f = A_f T^{1/2} \quad (1)$$

$$D_c = A_c T^{1/2} \quad (2)$$

When the carbonation front has passed through the full depth of the face material, at a time T_{fo} , carbonation will then continue into the grout, following the curve represented by equation (2), but from a point on that curve which depends upon the characteristics of the face. It may be postulated that the face has an effective depth D_e and an effective time for full carbonation T_e , which allows the following equation (3) to identify the depth of carbonation inwards from the exposed surface after the front has reached the interface of the two materials.

$$D = A_c [T + T_e - T_{fo}]^{1/2} - D_e + D_{fo} \quad (3)$$

where D_{fo} is the actual face shell thickness.

Figure 1 illustrates the curves of equations (1), (2) and (3).

It can be readily shown that

$$T_e = (D_e/A_c)^2 \text{ and } T_{fo} = (D_{fo}/A_f)^2$$

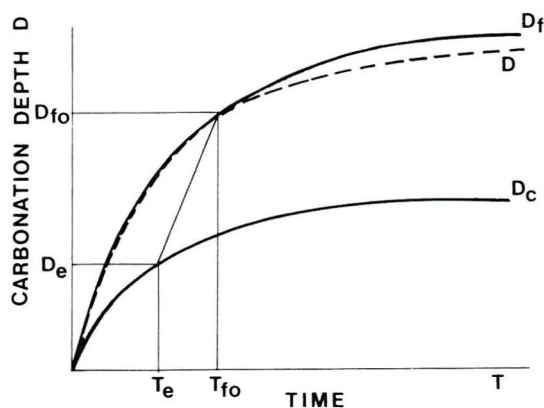


Figure 1 Carbonation versus time for facing (D_f), concrete (D_c) and composite (D).

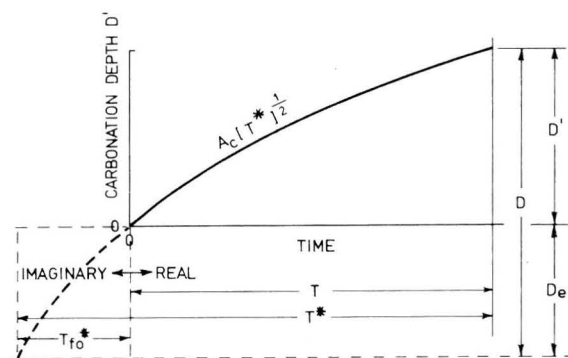


Figure 2 The imaginary concept for clay brick facings.

For practical purposes, it is necessary to make some assumptions in regard to T_e and D_e so that a working expression is created.

The dashed line curve D in Figure 1 follows the form of part of curve D_c after the facing is carbonated at time T_{fo} . The part of the curve D_c selected is the subject of the assumptions. Three idealised cases have been considered.

- (a) 'Thickness equivalence' - it is assumed that $D_e = D_{fo}$, and the dashed curve then follows that for D_c after the intercept with D_{fo} .
- (b) 'Time equivalence' - $T_e = T_{fo}$ is assumed, and the form follows D_c after the intercept with T_{fo} .
- (c) 'Complete exposure' - $D_e = T_e = 0$. After T_{fo} , the complete form of D_c from zero time is followed.

Previous studies by one author (AB) have indicated the most appropriate assumption to be (b) 'time equivalence', i.e. $T_e = T_{fo}$.

In this case

$$D = A_c T^{1/2} + \left(1 - \frac{A_c}{A_f}\right) D_{fo} \quad (4)$$

$$D_e = (A_c/A_f) D_{fo} \quad ; \quad T_e = (D_{fo}/A_f)^2$$

which can be further simplified to

$$D = D_{fo} + A_c (T^{1/2} - R) \quad (5)$$

where $R = D_{fo}/A_f$ is a parameter which represents the resistance of the face to continuing carbonation in the grout.

With A_f and A_c determined, say, by experiment, and D_{fo} available, the required depth of placement of steel in the grout for corrosion protection over a specified lifetime can be established.

2.2 Non-cementitious face shells

The case of a clay brick or other non-carbonating face shell is adaptable to the theory. With some degree of permeance to gases, the carbonation may commence in the grout soon after exposure, but at a reduced rate to that indicated by equation (2). This is accommodated by assuming that the face shell has imaginary carbonation properties expressed as a carbonation coefficient A_f^* , and exposure time for full carbonation T_{fo}^* .

Thus, again adopting the 'time equivalent' assumption,

$$D^1 = A_C [T^*]^{1/2} - \frac{A_C}{A_f^*} D_{fo} \quad (6)$$

$$D_e = (A_C/A_f^*) D_{fo} \quad ; \quad T_{fo}^* = (D_{fo}/A_f^*)$$

where D^1 is the depth of carbonation from the interface, and T^* is an imaginary exposure time which can be related to the real exposure time by equation 7,

$$T = T^* - T_{fo}^* \quad (7)$$

Figure 2 illustrates these relationships.

Again, the expression can be simplified by the use of a parameter R .

$$D^1 = A_C [(T + R^2)^{1/2} - R] \quad (8)$$

where $R = D_{fo}/A_f^*$.

3. EXPERIMENTAL PROCEDURE

3.1 General

To assess the validity of the model, laboratory specimens were made and subjected to accelerated carbonation in a chamber where the concentration of carbon dioxide was controlled at 4 per cent and the relative humidity at 50 per cent. (Normally, the atmosphere contains a concentration of carbon dioxide of about 0.03 per cent). At intervals of time up to 112 days, specimens were removed from the chamber, split open, and the depth of carbonation measured by spraying the broken surface with a solution of phenolphthalein in alcohol, which makes the carbonated part clearly visible.

3.2 Specimens

The overall dimensions of the specimens were 75 x 300 x 75 mm high. Face shells were made to a height of 75 mm, either of uniform 15 mm thickness or tapering in thickness from 5 to 25 mm over the height. These were positioned at the sides of the mould and the resultant cavity filled with grout.

Figure 3 illustrates the general form of the specimens. Further specimens of similar dimensions were completely filled with the various materials to establish carbonation coefficients.

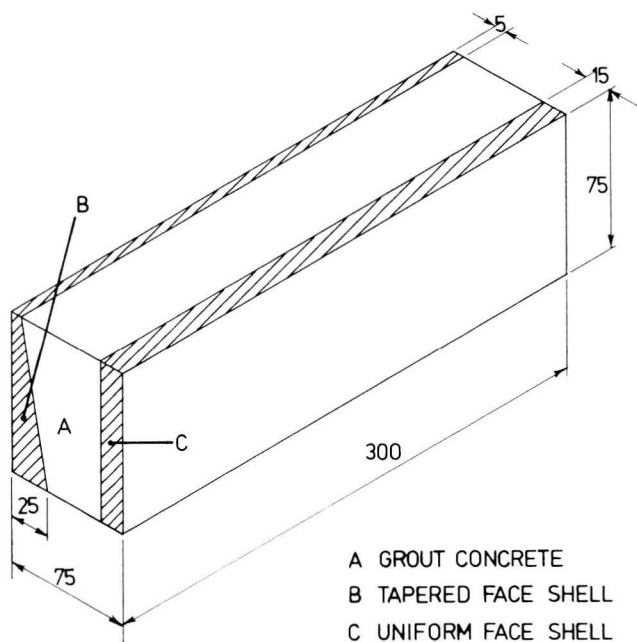


Figure 3 General form of test specimens

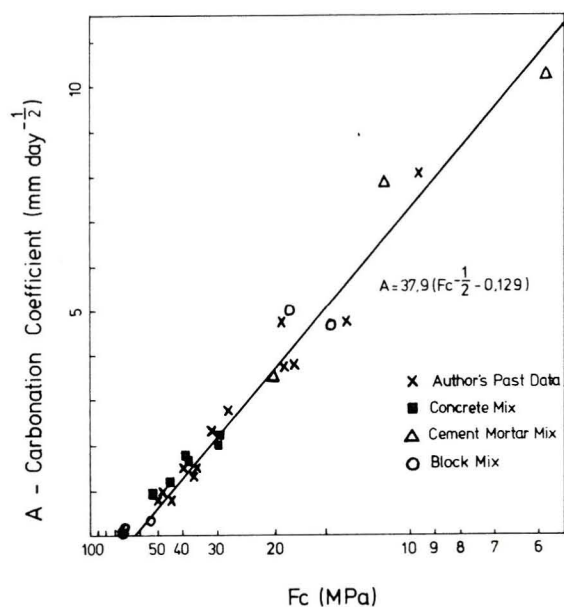


Figure 4 Relationship of carbonation coefficient to compressive strength

TABLE 1 Material proportions and properties

Code	Material	Mix proportions				Compressive strength (MPa)
		Cement	Lime	Sand	Stone	
B1	Facing shell	1	0	2	8	71.4
B2	"	1	0	2.5	5	69.9
B3	"	1	0	3	0	52.4
B4	"	1	0	6	0	18.2
B5	"	1	0	9	0	14.3
M1	Mortar	1	0	3	0	19.6
M2	"	1	1	6	0	10.9
M3	"	1	2	9	0	5.7
C25	Grout	1	0	3	2	29.0
C35	"	1	0	2.4	1.6	37.1
C45	"	1	0	2	1.33	51.4
CL1	Clay brick					87.1
CL2	"					46.6
CL3	"					51.6
CL4	"					15.3

3.3 Materials

Table 1 lists the mix proportions and compressive strengths for the various materials used in the experiments.

Ordinary portland cement, washed silica sand, hydrated lime and crushed basalt aggregate were used for the cementitious materials. The maximum aggregate size used for the facings was 7 mm, and for the grout 12 mm.

The compressive strengths were determined by standard procedures for the particular materials.

3.4 Curing and Preconditioning

Concrete and mortar face shells were cured in a fog room (23°C, 100% RH) for 28 days, and then dried for about 14 days in a laboratory (23°C, 50% RH) before being positioned in the mould and the grout concrete cast. Clay brick shells were cut and stored in the laboratory for about 14 days before positioning. The composite specimens sustained a further 28 days moist curing, and a laboratory drying of 28 days, before being subject to the carbonating atmosphere for 112 days.

Before the specimens were placed in the carbonating atmosphere, the top and bottom surfaces were sealed with a resin coating, thus restricting the ingress of carbon dioxide to the side surfaces.

4. RESULTS

4.1 Carbonation Coefficients

When the carbonation coefficient, A , is determined from specimens of the individual cementitious materials, an empirical relationship with the compressive strength can be established, as illustrated in Figure 4. The relationship can be defined as

$$A = 37.9 F_c^{-1/2} - 4.85 \quad (9)$$

when F_c is the compressive strength in MPa and A is in mm day^{1/2}. The Figure includes the materials used in these experiments and a number of results gained by one of the authors (AB) for Japanese materials.

Table 2 sets down the values of A determined from the composite specimens used in the work. Here the values for grout were achieved through the use of equations (5) and (8). It will be noted these values in Table 2 are less than would be determined from Figure 4, and vary for the same grout when used with different facing materials. A most likely reason is absorption of water from the grout into the face shell, thus lowering the water content of the grout, increasing its strength, and lowering the value of A .

4.2 Composite Specimens

In Figure 5(a) and (b), the experimental results are plotted and compared with theoretical curves, using the coefficients of Table 2, for typical sets of uniformly thick face shells of mortar and of clay brick.

TABLE 2 Carbonation coefficients 'A' from composite specimens - mm day^{-1/2}

Facing	Shell	Grout		
		C25	C35	C45
B1	0.083	-	-	-
B2	0.120	-	-	-
B3	0.360	-	-	-
B4	5.00	1.0	0.76	0.36
B5	4.69	1.0	0.71	0.44
M1	3.57	1.48	1.1	0.62
M2	7.89	0.95	0.62	0.36
M3	10.30	1.1	0.70	0.33
CL1	0.10	1.6	1.1	0.80
CL2	0.95	1.1	1.0	0.76
CL3	1.10	1.1	0.94	0.67
CL4	20.0	0.94	0.80	0.62

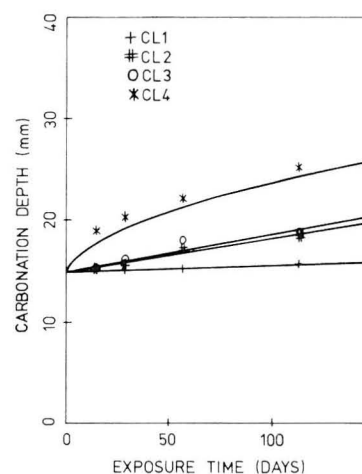
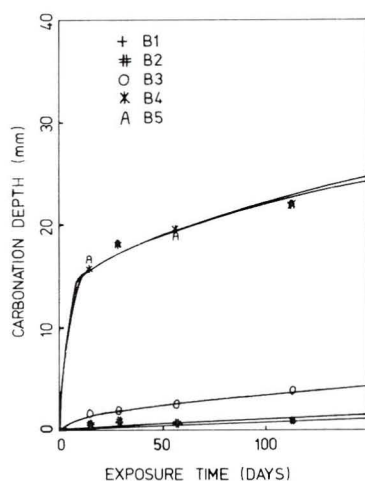


Figure 5

(a) Comparison of theory and experimental results for a 25 MPa concrete faced with materials B1-B5 of uniform thickness

(b) Comparison of theory and experimental results for a 25 MPa concrete faced with clay brick materials CL1-CL4 of uniform thickness

Figure 6 presents similar results for a set of tapered shells using simulated block concrete, while Figure 7 refers to a set of non-cementitious (clay brick) face shells.

The overall correlation between the theoretical model and the experimental results, for the depths of carbonation measured at 112 days in the concentrated atmosphere of carbon dioxide, is illustrated in Figures 8 (cementitious facing shells) and 9 (clay brick facing shells).

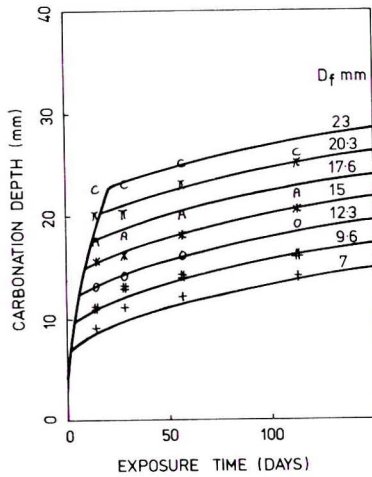


Figure 6 Comparison of theory and experimental results for a 45 MPa concrete faced with material B4 as a tapered shell

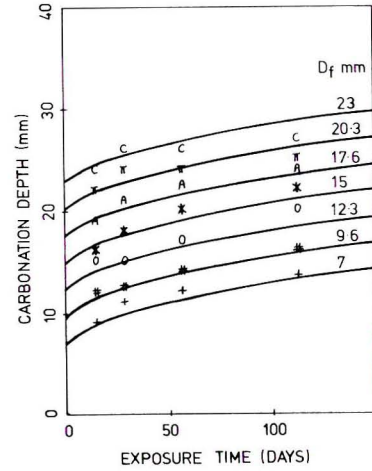


Figure 7 Comparison of theory and experimental results for a 45 MPa concrete faced with clay brick CL4 as a tapered shell

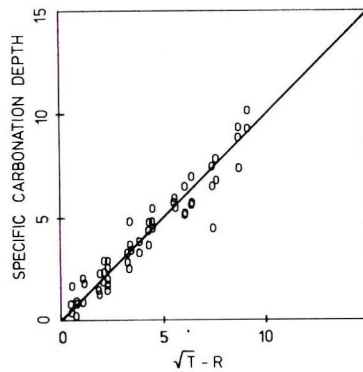


Figure 8 Experimental relationship between specific carbonation depth and $T^{1/2} - R$ for cementitious shells ($N = 57$, Variance = 14.8%)

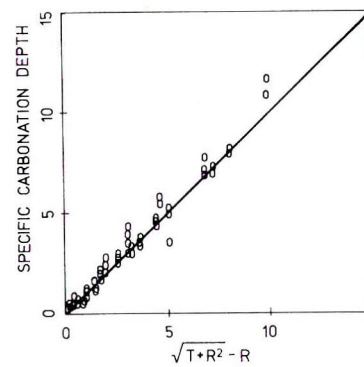


Figure 9 Experimental relationship between specific carbonation depth and $(T + R^2)^{1/2} - R$ for clay brick shells ($N = 71$, Variance = 10.1%)

The model is expressed in the linear equations for specific carbonation depth -

$$\frac{D - D_{fo}}{A_c} = T^{1/2} - R \quad (10)$$

$$(R = D_{fo}/A_f)$$

and

$$\frac{D^1}{A_c} = [T + R^2]^{1/2} - R \quad (11)$$

$$(R = D_{fo}/A_f^*)$$

for the two types of facing.

The general correspondence of the plotted experimental results, each of which is an average of seven measurements, can be compared with the line of equality between the two sides of equations (10) and (11).

For both sets of shells the fit appears reasonable, and thus it is considered that the theory is suitable for practical purposes.

5. DISCUSSION

The experimental results have been gained under accelerated carbonation, because of time considerations. The relationship between these conditions and normal external exposure has been a matter of some debate. Studies on concrete specimens have indicated a time ratio of the order of 60 applies between a standard laboratory atmosphere and the concentrated carbon dioxide chamber (2). In a country like Australia, where the populated areas span over a wide range of conditions, the ratio will undoubtedly vary. However, some limited field observations by one author (FDB) suggest that this ratio could be adopted as a general measure for estimating carbonation times in the field. The values of carbonation coefficient listed in Table 2 might then be divided by 8 ($\approx 60^{1/2}$) for real situations which are exposed but sheltered from rain.

While the time relationship might be utilised to establish appropriate covers for required times of serviceability, a valid comparison with reinforced concrete practice can be made using the values of A established under the concentrated atmosphere. It is useful to consider an example where a face shell of strength 12 MPa, 25 mm thick overlies a grout of 25 MPa strength containing embedded reinforcement. Say that in a normal reinforced concrete member 30 mm of cover is required. What then is the equivalent cover in this situation?

Consider 25 MPa concrete as typical of reinforced concrete, which can be regarded as having a value of A of $3 \text{ mm day}^{-1/2}$ according to Figure 4.

$$\begin{aligned}\text{Then } T &= (D/A)^2 \\ &= (30/3)^2 \\ &= 100 \text{ days}\end{aligned}$$

It is required to determine the depth, D, that the steel should be embedded in the reinforced masonry for the same value of T.

$$\text{Thus } \frac{D-D_{fo}}{A_o} = T^{1/2} - R$$

$$R = \frac{D_{fo}}{A_f}$$

$$\text{From Table 2 } A_f = 5 \text{ mm day}^{-1/2}$$

$$A_c = 1 \text{ mm day}^{-1/2}$$

$$(D-25)/1 = 100^{1/2} - 25/5$$

$$D = 30 \text{ mm}$$

In this case, the depth of embedment is the same as normal concrete. The deficiency of the face shell has been compensated by the improvement of the grout by water loss to the face material. This effect is quite considerable, as it can be estimated from Figure 4 that the strength of the grout in the block has effectively increased to something like 45 MPa presumably as a result of the reduction in water/cement ratio. It appears that the value of A can be halved as a result of this effect. The most vulnerable location is obviously then the mortar joint, as here A_f is greater, say $8 \text{ mm day}^{-1/2}$ according to Table 2. Then the calculated value of D becomes 32 mm, not greatly different.

Under the Australian Code of Practice for reinforced concrete masonry (3), the minimum strength that might be used for both face shell and grout is 12 MPa.

Here the following values might be used

$$A_f = 5 \text{ mm day}^{-1/2}$$

$$A_c = 2.5 \text{ mm day}^{-1/2}$$

giving a value for D of 37.5 mm.

In general, Codes of Practice do not discriminate cover thickness for quality of the cover. The allowable covers vary in accordance with specified environments and member types. There has been speculation as to the worth of the facing, as to whether it should be included in the specification of cover, or whether only a fraction of its thickness should be included.

This work suggests that the shell plays an important part in protecting the steel. The degree to which it does this can be analysed. However, the Codes seek a simpler expression of cover, which will apply to the minimum specification. The ratio of 37.5/30 may then be appropriate, conservatively taken as 1.3 in view of the laboratory prepared nature of the specimens. Thus it is suggested that covers required for reinforced concrete masonry be taken as 1.3 times those applicable to reinforced concrete, in the absence of a more detailed investigation of a particular design.

When the facing shells of clay brick are considered, and compared with the concrete face shells, it can be seen that generally the material is quite effective in resisting carbonation of the grout infill, as judged by the low values of A_f^* for CL1-3 in Table 2. The high value for CL4 can be disregarded as being gained from a non-typical clay unit of low strength and high porosity.

Considering as before, a required time for carbonation to the depth of the steel of 100 days.

$$A_f^* = 1.10 \text{ mm day}^{-1/2}$$

$$A_c = 2.5 \text{ mm day}^{-1/2}$$

$$D_{fo} = 25 \text{ mm}$$

A value for D^1 of 7.5 mm is obtained.

The governing area would be in the vicinity of the mortar joint, which suggests that the same criterion as proposed for concrete masonry would be applicable to clay brick facings.

The work has shown that a large effect has resulted from the improvement in the carbonation coefficients of grouts due to absorption of water into the shell

materials. While this effect is to be expected in all cases, it must be noted that the experiments used specimens smaller in volume than the practical situation. While the theoretical aspects are seen to be confirmed by the experimental results, the carbonation coefficients so determined may be unrealistic, and this is seen as an aspect meriting further study.

6. CONCLUSIONS

- (a) A theoretical approach to the durability of reinforced masonry has been formulated.
- (b) Laboratory experiments under accelerated carbon dioxide atmospheres support the approach.
- (c) Considerable benefit is gained against carbonation from the improvement of grout quality by absorption of water into facing materials, due to the reduction of water/cement ratio of the grout.
- (d) As the minimum strengths of reinforced masonry components are generally less than structural reinforced concrete, it is suggested that covers to steel in reinforced masonry be taken as 1.3 times the corresponding values for reinforced concrete.

7. REFERENCES

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