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Factors Affecting Steel Corrosion in Concrete Bridge Substructures

Facteurs influant sur la corrosion de l'armature des structures porteuses de ponts en béton

Einflussfaktoren zur Bewehrungskorrosion in Brückenunterbauten aus Stahlbeton

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SUMMARY

Some 45 different areas of concrete on 15 bridge substructures were selected for detailed survey. Some were sound, others showed corroding reinforcement. Both site survey measurements and laboratory analysis of cores were made. Bridges less than 25 years old were of better concrete and had better cover than those more than 50 years old, but showed more serious reinforcement corrosion because the modern bridges were more susceptible to chloride from de-icing salt. The relationship between carbonation and concrete quality is shown by the survey.

RÉSUMÉ

Plus de 45 endroits différents de la structure porteuse de ponts en béton ont été choisis pour une inspection détaillée. Certains étaient sains, d'autres révélaient une armature corrodée. Les analyses ont été effectuées aussi bien in situ qu'en laboratoire. Les ponts de moins de 25 ans présentent un meilleur béton et un meilleur enrobage, mais une plus forte corrosion de l'armature, car ils sont plus sensibles aux chlorures des sels de déverglaçage. L'examen montre aussi la relation entre carbonation et qualité du béton.

ZUSAMMENFASSUNG

Um die 45 verschiedene Stellen von Brückenunterbauten aus Beton wurden für eine detaillierte Inspektion ausgewählt. Einige waren intakt, andere wiesen korrodierte Bewehrungen auf. Es wurden sowohl an Ort als auch im Labor Analysen vorgenommen. Brücken von weniger als 25 Jahren wiesen besseren Beton und bessere Ueberdeckungen auf, zeigten aber stärkere Bewehrungskorrosion, da sie auf Chloride von Tausalzen anfälliger sind. Die Untersuchung zeigt auch den Zusammmenhag zwischen Karbonatisierung und Betonqualität auf.

1. INTRODUCTION

1.1 Standards for the specification of concrete to make durable structures are founded on long experience. However, the evolution of modern cements and cement blends, and changes in the required performance of modern concrete to cope with changed environments and construction methods, suggest that traditional standards are not necessarily adequate for concrete for contemporary and future structures. There have already been suggestions that the changes, particularly of cement, have resulted in less durable concrete, and there is no doubt that corrosion of steel in structures only a decade or so old is all too common. To design concrete which will be adequately durable for present and future conditions it is necessary to understand the basic factors that control durability, and the work described in this paper is a contribution to that understanding.

1.2 This paper is based on a survey made for the Bridges Department of the Transport and Road Research Laboratory of Great Britain. The details of that investigation are reported in Reference [1].

1.3 For this study 15 bridges were selected from a broad survey of over 100. The bridges ranged in age from 11 to 68 years. On each bridge a number of areas of concrete, usually on the substructure and about $4m^2$, were chosen for detailed study. There were 45 areas in all. Some areas included corroding reinforcement (evidenced by spalling, cracking or rust stains) and others were apparently corrosion free. As well as visual examination of each area, the depth of cover was measured and corrosion activity assessed by half-cell survey. Core samples were taken and from these the depth of carbonation and the chloride profile in each area determined. Core samples were also used to assess the quality of the concrete (porosity, permeability and so on) and to estimate the original mix proportions.

2. RESULTS OF SURVEY

2.1 Durability and age of bridge

2.1.1 The structures surveyed tended to fall into two groups; those more than 50 years old and those between 22 and 11 years old. For a first analysis it is convenient to group the different measurements into two blocks, 'old' and the 'modern', and compare these to see what quantitative changes have happened over the more than 30 years between them.

2.1.2 The minimum depth of cover in each area tended to be less for old than modern bridges, with more than half the 'old' areas having cover of 20mm or less and less than a quarter of the 'modern' areas with this range.

2.1.3 The concrete quality was measured in a number of different ways, and these may be grouped broadly into estimates of original mix proportions, and material properties. For mix proportion the analyses give the modal values for cement content as 250 to 300 kg/m^3 for concrete from 'old' areas and 300 - 350 kg/m^3 for 'modern' ones, with distributions such that whilst over half the old areas had less than 300 kg/m^3, only one of the 18 'modern' concretes was in that range. Clearly, modern concretes generally have a higher cement content than older ones. As would be expected from this, estimates of water/cement ratios show lower values for modern concretes.

2.1.4 The material properties tend to conform to expectation from the estimated mix proportions. Capillary porosity and water absorption are less for modern concrete, and although the modal values for permeability are about the same for old and modern concretes the ranges of results are such that the very high permeabilities are associated with old, not modern material.

2.1.5 A simple comparison of the depth of carbonation of old and modern concretes shows, as expected, that the old ones generally have carbonated to greater depths. It is commonly assumed that depth of carbonation is proportional to the square root of age and this rule was used to 'normalise' the data to a standard age of 55 years. When this is done, it is found that, while 40% of the old concretes exceed 5-15mm depth, only 10% of modern concretes do. The performance of modern concrete is, then, generally better than old, and this conforms with the mix proportions and material property observations.

2.1.6 One core sample from each area was used to establish the chloride profile from the surface into the concrete. In this survey, where appreciable chloride was found, there was always a gradient from the surface inwards, indicating the chloride came from de-icing salt. The distribution of surface chloride levels for old and modern bridges are shown in Figure 1. Only 10% of modern areas showed less than 0.15% Cl^- by mass of cement compared with 60% of the old areas. On modern bridges 45% of the areas showed more than 0.5% Cl^- by mass cement compared with 15% of old ones.

2.1.7 This finding is sufficient to account for the relatively poor durability reputation of modern concrete bridges: the problem is not in the material being less durable but because the exposure conditions are more harsh for modern than for old bridges. While the reasons for this are not fully understood, two factors undoubtedly have a major influence:

a) Modern bridges tend to be on motorways which in Britain are heavily salted.
b) Modern construction tends to favour simply supported spans which require movement joints at the supports. These joints do not behave well but frequently leak, leading to salt water pouring over the substructure. The majority of cases of damage studied could be associated with such leaks. Older structures, which were generally of in-situ and more continuous forms of construction tended not to have such joints.

2.2 Depth of carbonation and concrete quality

2.2.1 Although in the U.K. the most severe durability problems result from exposure to chloride, carbonation must not be forgotten. In this survey there were a number of areas where corrosion was not the consequence of chloride penetration, and in general these were areas where the depth of carbonation had reached the reinforcement. The depths of carbonation were very variable but if they can be related simply to concrete quality some progress will have been made to understanding and control of carbonation related durability problems.

2.2.2. The complicating effect of age can be avoided for this analysis by

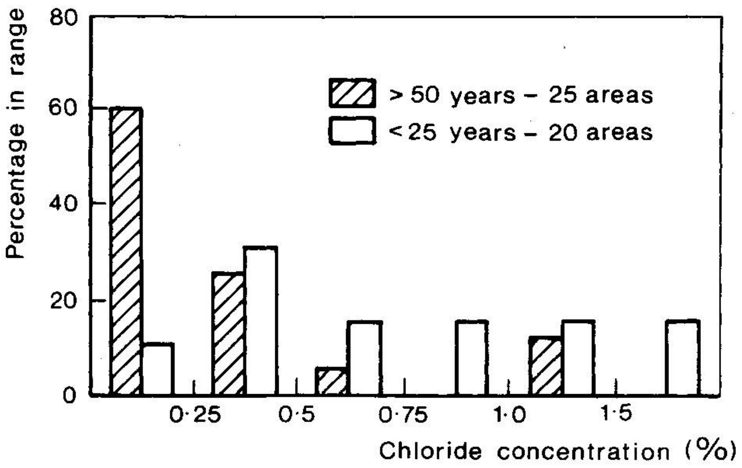

FIGURE 1

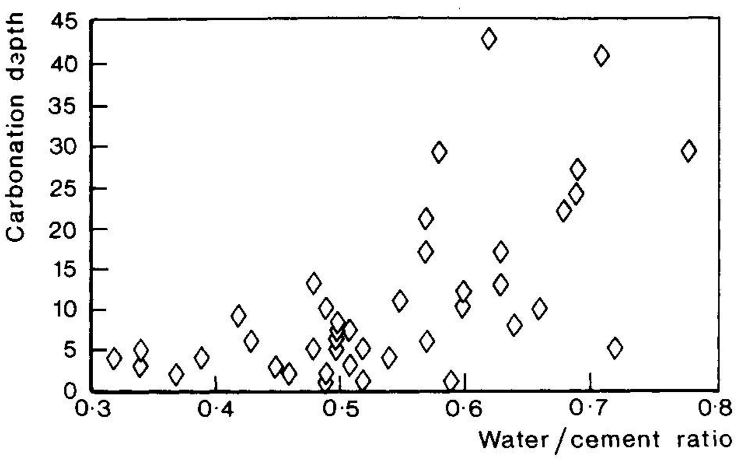

FIGURE 2

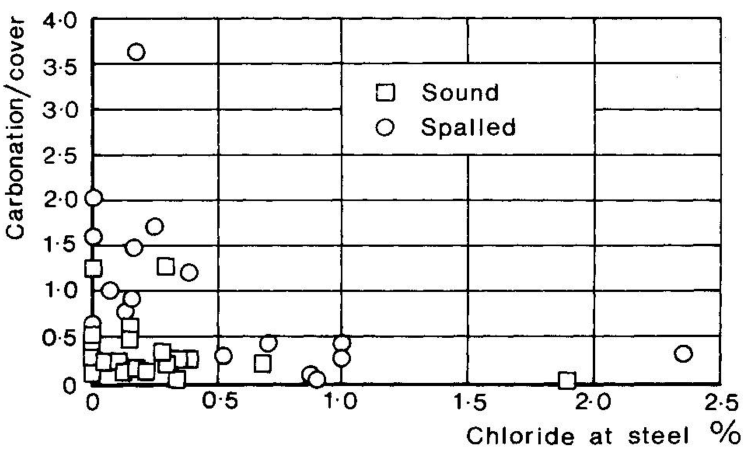

FIGURE 3

considering only the old concrete samples - their range of age is negligible compared with their starting age of 50 years. Figure 2 shows the typical depth of carbonation and the water/cement ratio for this group. There is a clear tendency for high carbonation depths to be associated with high water cement ratios and no concrete with less than 0.55 w/c showed more than 15mm carbonation. The values shown are 'typical' depths and are the mean value from all samples in the area. 'Maximum' values, the highest value in each area, were also noted and these show more variability than the typical ones but, as with the typical values, the mean depth of carbonation for areas with more than 0.6 water/cement ratio is about 10mm more than those areas below this ratio. At all ages there are a significant number of areas with effectively zero carbonation, and the wide scatter of results within the carbonated area of Figure 2 suggests that some factor additional to concrete quality is present. Since it is well recognised that carbonation rate is very moisture dependent, this factor is likely to be the micro-environment of the concrete.

2.3 Corrosion

2.3.1 Figure 3 shows that concrete is usually sound unless the carbonation depth is more than about 0.8 of the cover or the chloride level at the steel is more than 0.5% Cl^- by mass cement. In view of the uncertainty of the inferred depths on spalled concrete the carbonation/cover ratio of 0.8 is not incompatible with the expected value of 1. The critical chloride level of 0.5 compares with the maximum of 0.4% Cl^- by mass cement in British Standard 8110.

2.3.2 The effect of factors such as age or concrete quality cannot be deduced from this survey since all but two areas corroded when chloride was above the threshold. It is interesting, however, that the two areas which did not show spalling despite the high chloride level had better cover (48 and 70mm) than most of the spalled areas.

3. DISCUSSION

3.1 Carbonation induced corrosion need not be a problem with bridges. In this survey only two areas were found with depths of carbonation more than 30mm, and that after 50 years. Carbonation should not be forgotten, however. If carbonation depth increases proportionally to the square root of age then the modern concretes sampled in this report will have carbonated to a range of 5 to 40mm in the 120 year design life time of a bridge, and this is greater than many of the minimum covers found. Whilst most areas of bridges will be protected, the probability of areas of poor cover coinciding with poor concrete must increase if there is any deterioration in the general quality of the concretes specified or of the standards for achieving adequate cover. For confidence in the future there is a need for more information on the interelationship between micro-climate, bridge design and carbonation of concrete.

3.2 Chloride is a much more difficult problem. The simple conclusion from this survey is that if the chloride level is more than 0.5% Cl^- by mass cement, corrosion is very likely; and these high levels can be achieved at the depth of the reinforcement in little more than a decade. The survey does suggest, however, that since high chloride levels occurred primarily where surfaces do not drain well, and where cover was not very high, a combination of design for drainage and protection of areas susceptible to de-icing run off could increase service life significantly. A study of the interelationship between the structural details, the micro-climate, and the chloride levels and their rate of build up would be valuable both for new design and to assess maintenance needs on existing bridges.

4. CONCLUSIONS

4.1 A comparison of the performance of concretes more than 50 and concretes less than 25 years old shows that modern concretes give better protection to reinforcement than do the old ones. The corrosion which does occur on modern bridges is almost always the consequence of chlorides from de-icing salt: modern bridges seem to have a higher exposure to salt than do old ones.

4.2 Carbonation is not a problem in the short term for bridges. Concretes of reasonable quality will not carbonate more than 40mm in 120 years, and average carbonation would be less than 15mm in this time.

4.3 If chloride is present at the steel with more than 0.5% Cl^- by mass cement then corrosion is almost certainly occurring. Chloride from de-icing salt can penetrate the concrete very quickly: From this survey more than 30mm in two decades is not exceptional. The durability of bridges is likely to be improved more by changes of design to keep chloride levels low and cover high than by improvements in the quality of the concrete.

REFERENCES

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