Case Studies in Construction Materials 3 (2015) 78–82

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Analysis of total chloride content in concrete

Saleh A. Al-Saleh*

Al Imam Mohammad Ibn Saud Islamic University, College of Engineering, Civil Engineering Department, PO Box 88800, Riyadh 11672, Saudi Arabia

ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 7 May 2015
Accepted 19 June 2015
Available online 13 July 2015

Keywords:
Total chloride
Mixing water
Aggregate
Concrete
Corrosion
Durability

ABSTRACT

This research paper presents an analysis of total chloride contents in concrete. The concrete mixtures that were approved by the municipality of Riyadh city in Saudi Arabia for a main ready mix concrete plant were considered in this study. The analysis was based on an experimental investigation of chloride levels in mixing water, aggregates, and concrete. The analysis also used the maximal total chloride limits of British Standards for the concrete in conjunction with other ingredients required for the mix.

The results obtained suggest that the effect of chloride content in mixing water has minimal to moderate influence upon the chloride content of concrete up to *w*/*c* equal to 0.4. It also shows that aggregate is the critical ingredient in terms of determining the presence of chloride in concrete. Critically, the limits of chloride content in any concrete mix could be violated even though the limits of chloride content still meet some standards for their content within concrete ingredients. The proportions of any mix design are also an important factor to be considered when attempting to specify the limits of chloride content of the ingredients of concrete mixtures for any type of concrete. It is vital to investigate empirically the relationship between total chloride and chloride contents in ingredients in order to precisely define the limits of chloride content in concrete mix ingredients. Mix design that has the lowest *w*/*c* ratio is preferable as far as the chloride content is concerned. Finally, water chloride content could be higher than ASTM specified limits with mix designs that have low water cement ratios and should be lower than the ASTM limits with high water cement ratios.

1. Introduction

Concrete structures that are constructed according to the required specifications and standards show excellent durability and perform well over their service life. Deterioration of concrete may occur due to a number of mechanisms. Corrosion of steel reinforcement is the most destructive form of damage affecting serviceability and strength of concrete structures (Page and Treadaway, 1982). The chemical environment in concrete normally passivates the steel reinforcement in which a tenacious oxide passive film is formed on the surface of embedded reinforcing steel under high alkaline condition of concrete which protects steel reinforcement against corrosion (Barkey, 2004).

The condition of passivity can be destroyed due to the process of absorbing chloride ions (Crentsil et al., 1992). This is considered as the most aggressive and most wide spread corrosive ion since it contributes to corrosion of steel reinforcement (Barberon et al., 2005). Fraczek (Fraczek, 1987) suggests that chloride contamination is probably the most critical as it is

* Fax: +966 12759943.
E-mail address: alsalehsam@gmail.com (S.A. Al-Saleh).

http://dx.doi.org/10.1016/j.cscm.2015.06.001
2214-5095/$ – see front matter

observed to initiate the form of corrosion that is much more severe and detrimental to the integrity of concrete structure. Chloride acquires different forms in concrete which include chemically bound, physically absorbed, and free chloride. Only free chloride is responsible for rebar corrosion in concrete (Tutti, 1982). Chlorides may be incorporated into the concrete through mixing water, chloride contaminated aggregates or chloride containing admixtures (Saricimen et al., 2002; Arya and Xu, 1995; Hussain et al., 1996; Dehwah et al., 2002). Therefore; this research is aimed to analyze total chloride content in concrete in conjunction with other ingredients required for the mix according to total chloride standardized limits in concrete and its ingredients and by considering actual concrete mix designs.

2. Research data

The materials and mix designs used in this research were from one of the main ready mix plants in Riyadh city which supplies concrete to many big public and private projects. The compositions of the most used mix designs that have been approved by the municipality of Riyadh city for the selected ready mix concrete plant are shown in Table 1. The water cement-ratio (w/c) is specified according to the desired strength which is between 0.31 and 0.48. Chemical analyses were performed on aggregate and mixing water according to BS 812-117 (BS 812-117, 1988) and ASTM D512 (ASTM D512-04, 2004), respectively, to define the chloride contents. The amount of chloride in the cement is controlled during the manufacturing process and is defined as 0.01% or less by weight of cement and also specified in the literature as 0.01% (Neville, 2004). Total chloride in concrete is measured for each concrete mix according to BS 1881-124 (BS1881 Part 124, 1988 BS1881 Part 124, 1988). The results of chloride measurements are presented in Table 2.

3. Measured total chloride

Total chloride or acid-soluble chloride in concrete depends on the chloride content in concrete mix ingredients. The precise amount of chloride that is contributed by each element of the concrete mix compositions is hard to be defined because the chloride contents in aggregate and in concrete mixture as a whole are not equally distributed.

The total chloride by weight of cement contributed by all mix ingredients was measured experimentally based on different concentration of chloride ions in mixing water which were 250 ppm, 750 ppm, and 1250 ppm. The measurements were also based on actual mix proportions and chloride content in aggregate shown in Tables 1 and 2. The results are presented in Fig. 1. It can be seen in Fig. 1 that the BS 8500 (BS 8500-1, 2006) total chloride limit for reinforced concrete that is non-heat curing and made with sulphate resistance cement (0.2) is nearly violated at mix M4 (w/c = 0.48) even though the chloride content is less than BS 882 (BS 882, 1992) standardized limits for aggregate and ASTM C 94 (ASTM C 94, 2013) standardized limit for mixing water. It is clear from the figure that the BS total chloride limit of non-heat curing and made with sulphate resistance cement is going to be violated at mixtures with higher w/c ratios. Hence, the limits of total chloride content in concrete could be violated even though the limits of chloride content for mix ingredients are satisfied. Therefore, it can be stated that chloride limits of concrete ingredients and total concrete could not be consistent, especially with mix designs that have water cement ratios higher than 0.48. The figure shows that the measured total chloride is affected by the proportions of concrete mix. Also, the amount of total chloride is directly proportional to water cement ratio or inversely proportional to cement content. Therefore, the proportions of any mix design are an important factor to be considered in

Table 1
Concrete mix compositions.

Mix no.	w/c Ratio	Cement (kg/m^3) Water (kg/m3) Aggregate 20 mm Aggregate 10 mm	Water (kg/m^3)	Aggregate 20 mm(Kg/m^3)	Aggregate 10 mm (Kg/m^3)	Coarse sand (kg/m^3)	Fine sand (kg/m^3)	Mira 19 (liter)	Daracem 217 (liter)	% of cement
M1	0.31	470	144	660	440	240	457	1.6	2.5	19.46
M2	0.35	440	152	660	440	245	458	2.35	1.5	18.34
M3	0.40	410	163	660	440	245	458	1.6	1.8	17.23
M4	0.48	350	168	750	400	241	452	1.4	0	14.82

Table 2
Chloride content in concrete mix materials.

Mix no.	Chloride content				
	Cement (1)	Combined aggregate (1)	Water (ppm)	Mira 19 (liter)	Daracem 217 (liter)
M1	0.01	0.02636	(2)	0	0
M2	0.01	0.02642	(2)	0	0
M3	0.01	0.02642	(2)	0	0
M4	0.01	0.02581	(2)	0	0

(1) Percentage by weight of ingredient.
(2) Different concentrations: 250, 750, 1250 ppm.

order to specify the limit of chloride content of the ingredients of any concrete mix design. Also, it is hard to define precise chloride limits in aggregate because the chloride content is not equally distributed in aggregate and in concrete as a whole.

It is clear from Fig. 1 that the BS 8500 (BS 8500-1, 2006) total chloride limit as a percentage by weight of cement for reinforced heat curing concrete and prestressed concrete (0.1) are easily violated with concrete mix designs that have *w*/*c* greater than 0.4. Also, the figure shows that BS total chloride limit for this type of concrete is not violated in mix M1 and M2 even though the BS limits for mix ingredients are violated. This result supports the outcome stated above in which the chloride limits in concrete and its mix ingredients are not consistent. Moreover, the figure shows that the percentage of chloride by weight of cement in mix M4 is much higher than in mix M3 even though the amount of chloride in combined aggregate of mix M4 (0.0264) is less than in mix M3 (0.0258). Therefore, it can be stated that mix design that has the lowest *w*/*c* ratio or has the highest percentage of cement is preferable as far as chloride is concerned. Finally, it can be seen in the figure that the effect of chloride content in mixing water on total chloride is minimal to moderate up to a *w*/*c* equal to 0.4. The critical amounts are the amounts of aggregates; therefore, it is essential to precisely control the presence of chloride in aggregates.

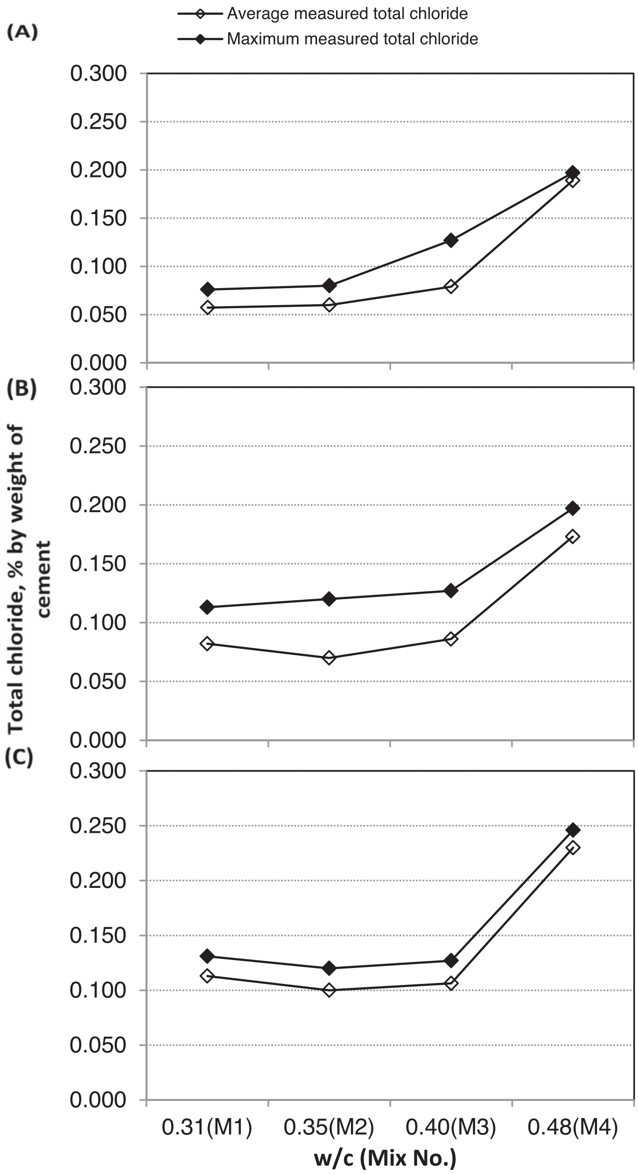

Fig. 1. Total chloride in the actual concrete mixtures: (A) water chloride content is 250 ppm, (B) water chloride content is 750 ppm, and (C) water chloride content is 1250 ppm.

4. Comparison of theoretical and measured total chloride

It is widely assumed in concreting practices that total chloride is the sum of chloride that comes from each element of the concrete compositions. In this way of total chloride calculations, the chloride content in each element and in concrete as a whole are assumed to be equally distributed. Hence, the total chloride in concrete can be expressed by the following general equation:

$$cl_{tm} = cl_c + \frac{w}{c}(cl_w) \times 10^{-4} + \frac{1}{c}(ca \times cl_{ca} + fa \times cl_{fa}) + \frac{1}{c}\left[\sum_{i=1}^{n} ad_i \times cl_i\right] \quad (1)$$

where cl_{tm} is the maximum total chloride content in concrete in percentage by weight of cement, cl_c is the cement chloride content in percentage by weight of cement, $^w/_c$ is the water–cement ratio, cl_w is the chloride content in mixing water in ppm,

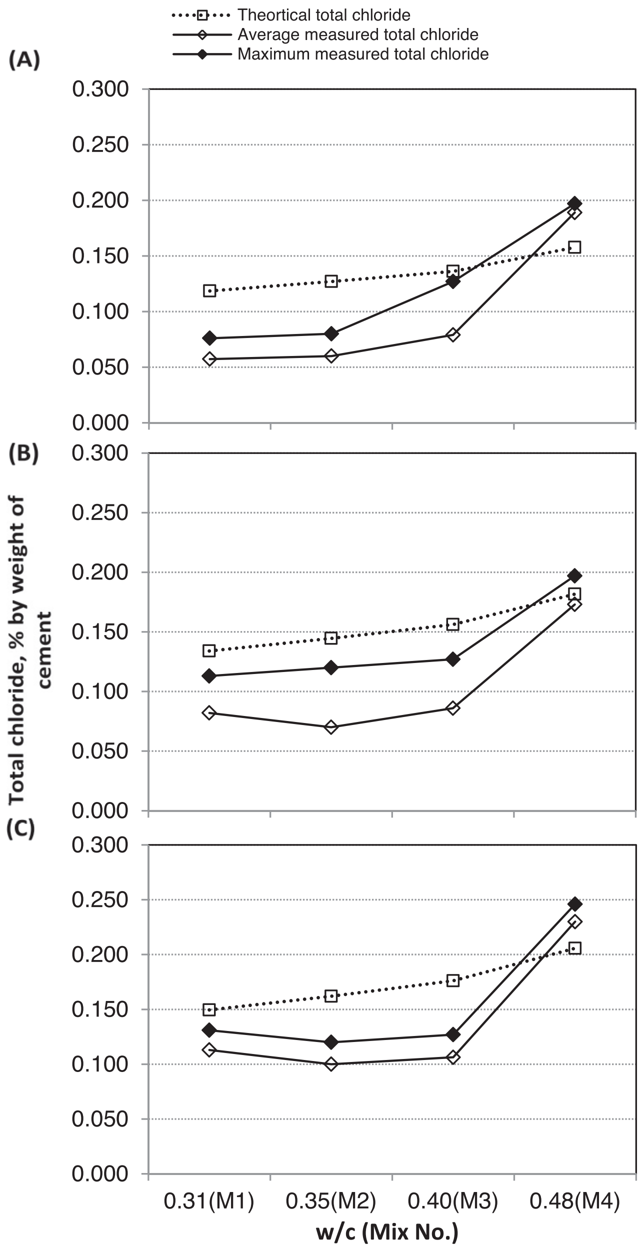

Fig. 2. Theoretical and measured total chloride in the actual concrete mixtures: (A) water chloride content is 250 ppm, (B) water chloride content is 750 ppm, and (C) water chloride content is 1250 ppm.

c is the cement content in the concrete mixture in kg/m^3,ca is the coarse aggregate content in the concrete mixture in kg/m^3, fa is the fine aggregate content in the concrete mixture in kg/m^3, cl_{ca} is the chloride content in coarse aggregate in percentage by weight of coarse aggregate, cl_{fa} is the chloride content in fine aggregate in percentage by weight of fine aggregate, cl_i is the admixture content in the concrete mixture in kg/m^3, ad_i is the chloride content in the admixture in percentage by weight of admixture.

The theoretical total chloride by weight of cement contributed by all mix ingredients was calculated using Eq. (1) based on different concentration of chloride ions in mixing water which were 250 ppm, 750 ppm, and 1250 ppm. The calculations were also based on actual mix proportions and chloride content in aggregate shown in Tables 1 and 2. The results are presented in Fig. 2. It can be seen in Fig. 2 that the calculated total chloride is more than the measured total chloride in mixtures with low *w*/*c* ratios or have higher percentages of cement content. Therefore, assuming total chloride to be the sum of chloride comes from all ingredients of a concrete mix is misleading. However, this way of estimating total chloride can be safe in concrete mixtures with *w*/*c* ratios equal or less than 0.4. Also, it is recommended to consider the highest measured values of chloride content in aggregate and concrete when comparing such values to standardized limits.

5. Conclusions

The following conclusions can be drawn from the results and analysis:

1. The limits of total chloride could be violated even though the limits of chloride content in concrete ingredients are satisfied.
2. The effect of chloride content in mixing water on total chloride is minimal to moderate up to a *w*/*c* equal to 0.4.
3. Aggregate is the critical ingredient on total chloride.
4. Mix design that has the lowest *w*/*c* ratio is preferable as far as chloride is concerned.
5. The proportions of any mix design are an important factor to be considered in order to specify the chloride limits in mix ingredients.
6. It is important to investigate empirically the relationship between total chloride and chloride content in mix ingredients to define precise chloride limits in mix ingredients.
7. Chloride content in mixing water could be higher than the ASTM limits with low water cement ratios and should be lower than the ASTM specified limits with high water cement ratios.

References

ASTM C 94, 2013. Standard Specification for Ready-mixed Concrete. American Society for Testing and Materials, Philadelphia, Pennsylvania.

ASTM D512-04, 2004. Standard Test Methods for Chloride Ion in Water. American Society for Testing and Materials, Philadelphia, Pennsylvania.

Arya, C., Xu, Y., 1995. Effect of cement type on chloride binding and corrosion of steel in concrete. Cem. Concr. Res. 25, 893–902.

BS 812-117, 1988. Method for Determination of Water-soluble Chloride Salts. British Standards Institution, London.

BS 8500-1, 2006. Concrete—Complementary British Standard to Bs En 206-1—Part 1: Method for Specifying and Guidance for the Specifier. British Standards Institution, London.

BS 882, 1992. Specification for Aggregates from Natural Sources for Concrete. British Standards Institution, London.

BS1881 Part 124, 1988. Method for Analysis of Hardened Concrete. British Standards Institution, London.

Barberon, F., Bouny, V.B., Zanni, H., Bresson, B., Caillerie, J.B., Malosse, L., Zehong, G., 2005. Interactions between chloride and cement-paste materials. Magn. Reson. Imag. 23, 267–272.

Barkey, D.P., 2004. Corrosion of steel reinforcement in concrete adjacent to surface repairs. ACI Mater. J. 101 (4), 266–272.

Crentsil, K.K.S., Glasser, F.P., Irvine, J.T.S., 1992. Electrochemical characteristics concrete corrosion as determined by impedance spectroscopy. Br. Corros. J. 27 (2), 113–118.

Dehwah, H.A.F., Maslehuddina, M., Austinb, S.A., 2002. Long-term effect of sulfate ions and associated cation type on chloride-induced reinforcement corrosion in Portland cement concretes. Cem. Concr. Compos. 24, 17–25.

Fraczek, J., 1987. A Review of Electrochemical Principles as Applied to Corrosion of Steel in a Concrete or a Grout Environment. ACI SP-102, pp. 13–24.

Hussain, S.E., Al-Gahtani, A.S., Rasheeduzzafar, M., 1996. Chloride threshold for corrosion of reinforcement in concrete. ACI Mater. J. 93 (6), 534–538.

Neville, A.M., 2004. Properties of Concrete. Pearson Education, Essex, UK.

Page, C.L., Treadaway, K.W.J., 1982. Aspects of electrochemistry of steel in concrete. Nature 297, 109–115.

Saricimen, H., Mohammad, M., Quddus, A., Shameem, M., Barry, M.S., 2002. Effectiveness of concrete inhibitors in retarding rebar corrosion. Cem. Concr. Compos. 24, 89–100.

Tutti, K., 1982. Corrosion of Steel in Concrete. Swedish Cement and Concrete Research Institute, Stockholm, Sweden.