INNOVATION BASED ON TRADITION: BLAST FURNACE SLAG CEMENT FOR DURABLE CONCRETE STRUCTURES IN NORWAY?

Rob B. Polder[1, 2], Timo Nijland[1], Mario de Rooij[1], Claus K. Larsen[3], Bård Pedersen[3]

[1]TNO Technical Sciences/Structural Reliability, P.O.Box 49, 2600 AA Delft, The Netherlands
Email: rob.polder@tno.nl
[2]Delft University of Technology, Civil Engineering and Geosciences, Delft, The Netherlands
3Norwegian Public Roads Administration, P.O.Box 8142 dep, 0033, Oslo, Norway

ABSTRACT

Blast furnace slag cement (BFSC) has been used to build reinforced concrete structures in marine and road environment in The Netherlands for nearly a century. The experience is good and structures with long service lives can be obtained, as has been shown by several field studies. This is caused by a high resistance against chloride penetration and a high electrical resistivity, demonstrated both in the field and in the laboratory. Due to the high slag content, related CO_2 emission and embedded energy are lower than for Portland cement.

In many countries including Norway, BFSC is a novelty and long term experience is lacking. In order to study the potential for use of BFSC in Norway, a desk study was carried out, reporting on many aspects. The resistance against chloride induced corrosion stands out positively, whereas neither carbonation nor frost are problems in practice. However, the Dutch experience is mainly based on CEM III/B with 65-75% of slag by mass of binder. Such a cement is not available on the Norwegian market. The introduction of CEM III/A with c. 48% slag in Norway is anticipated. Consequently, an experimental program was drawn up to study the properties of concrete made with CEM III/B and CEM III/A (with 48% slag), with and without addition of silica fume. The ultimate goal is to provide a basis for evaluation of use of slag cement in Norway for durable coastal and marine structures.

This paper describes the history and performance of slag in concrete in The Netherlands, the outline of the experimental program and expected results from the study.

Key words: service life; reinforcement corrosion; blast furnace slag cement; chloride penetration; new structures

INTRODUCTION

In many countries including Norway, BFSC is a novelty and long term experience is lacking. In The Netherlands, however, blast furnace slag cement (BFSC), nowadays called CEM III/B with at least 65% slag, has been used to build reinforced concrete structures in marine and road environments for nearly a century. The experience is good and structures with long service lives can be obtained, as has been shown by several field studies [1,2,3,4,5]. Particularly coastal bridges could benefit from using a cement type with an inherent high chloride penetration resistance. In order to study the potential for use of BFSC in Norway, a desk study was carried out, reporting on many aspects [1]. The resistance against chloride induced corrosion stands out positively. This is caused by a high resistance against chloride penetration and a high electrical resistivity, demonstrated both in the field and in the laboratory [6,7]. Under exposure conditions relevant to The Netherlands, neither carbonation nor frost-thaw damage are problems in practice, whereas the use of CEM III/B has, also in practice proven to be an effective preventive measure against deleterious alkali-silica reaction [1 and references therein]. Due to the high slag content, related CO_2 emission and embedded energy are lower than for Portland cement.

However, Dutch experience is mainly based on CEM III/B with 65-75% of slag by mass of binder. Such a cement is not available on the Norwegian market, but the introduction of CEM III/A with c. 48% slag is anticipated in Norway. In order to compare performance of this cement with that of CEM III/B and binders currently used in Norway, an experimental program was drawn up to study the properties of concrete made with classical Dutch CEM III/B; CEM III/A (with 48% slag), CEM I (Portland cement) and CEM II/A-V (fly ash cement), the latter three with addition of 5% silica fume. This program is aimed at determining basic chloride transport properties of mortars prepared with the binders, from early age up to several years. The ultimate goal is to provide a basis for evaluation of use of slag cement in Norway for durable marine structures. This program will start in 2014 and will run for three years.

This paper will report on the desk study to set a baseline for properties that can be obtained with slag cement concrete and will present expectations for the results of the experimental program. The expected results will be discussed.

HISTORY AND PERFORMANCE OF SLAG IN CONCRETE

This brief historical overview is based on [1,2,8]. The regulations issued between 1912 and 1962 reflect the changing attitude towards slag use in concrete. In Dutch Reinforced Concrete Regulations (GBV) 1912, slag was prohibited in concrete; in the GBV 1918, the use of slag cement comparable to current CEM II/B-S or blast furnace slag cement, comparable to CEM III/A and CEM III/B, was explicitly forbidden for reinforced concrete. In the 1920's, slag cement imported from Germany was nevertheless used for building the North Sea canal locks at IJmuiden after testing had shown the good resistance to sea water. In 1931 slag cement production started at IJmuiden in collaboration between steel and cement producers. Since 1930, using BFSC was only allowed if client and contractor agreed so in advance; this remained the position in the 1930, 1940 and 1952 regulations. In the 1962 code, the choice of cement type was free; it was explicitly stated that BFSC has better characteristics in aggressive environments than ordinary Portland cement. In 1984, blast furnace slag cement was recommended and Portland cement was discouraged for use in aggressive environments. The 1986 concrete technology standard, in which environmental (exposure) classes were introduced, recommended using BFSC with high sulphate resistance, i.e. with at least 65% slag, for marine environment. What is now called CEM III/B 42.5 LH HS (or most recently: SR), with typically about 70% slag, became the dominant cement type in the 1970s with a market share of more than 50%. In The Netherlands, about 10 million cubic metres of slag cement concrete are produced annually, in particular for concrete cast in situ. The low heat of hydration is seen as a big advantage with regard to early age cracking. Fly ash has been used since the 1980s in CEM II/B-V with typically 27% replacement level of clinker or mixtures of CEM I and fly ash with comparable replacement levels. Addition of silica fume is rare in The Netherlands.

Traditionally, slag and fly ash were intermixed with clinker in the cement plant and the combined product was sold as “cement”. The manufacturer would carefully compose these products to have similar 28 day strength as Portland cement, typically with 32.5 or 42.5 MPa of (mortar) compressive strength. In the 1990s, CEM III/A 52.5R with increased early strength was introduced, with 52-57% slag, aimed at the precast industry. BFSC contain typically 0.6% of Na_2O_{eq}. Recently, separate slag for addition to Portland cement in the concrete mixing plant has become available, but its use is not common.

Since the 1980s, Ministry of Infrastructure regulations require concrete based on cements with at least 50% slag or 25% fly ash (the latter for precast concrete only), among others for preventing deleterious ASR [9]. For reference to concrete technology practice in other countries, Dutch traditional concrete compositions for aggressive environments (XD, XS) involve about 340 kg cement per cubic meter, a target w/c of 0.43 and rounded siliceous aggregate of 32 mm maximum size; typical slump would be 125 mm and 28 day compressive strength c. 50 MPa [10].

Field studies of concrete in marine environment on structures up to 60 years of age and several decades of laboratory work have shown that concrete made with cement that contains about 70% of blast furnace slag (nowadays termed CEM III/B LH SR) shows excellent behaviour with respect to chloride penetration and reinforcement corrosion [5]. This was supported by exposure and laboratory studies [3,10,11]. In comparative studies, it was observed that chloride penetration in Portland cement concrete was deeper and faster than in BFSC concrete. Chloride profile analysis revealed that chloride surface contents were similar, but diffusion coefficients were consistently lower for slag cement than for Portland cement. The decrease over time of apparent diffusion coefficients in slag cement is stronger than in Portland cement concrete. In addition, slag cement concrete has a higher electrical resistivity and lower corrosion rate after depassivation [6,7,12,13]. Slag cement hydration is slower than Portland clinker hydration, but from about seven days age on, chloride migration is slower in the former than in the latter [14]. Similarly, cement with moderate fly ash replacement of Portland clinker shows lower diffusion coefficients and higher resistivities than Portland cement, in particular from a few months of hydration on [7,15]. Composite cements with slag and fly ash at about 50% clinker replacement behave similarly to fly ash cements. Critical (corrosion initiating) chloride contents appear comparable for all cement types mentioned [16]. Summarising, replacement of clinker by slag at high levels (50 – 70%) and fly ash at intermediate levels (20 – 30%) produces high chloride penetration resistance and high electrical resistivity, overall decreasing the risk of corrosion in chloride contaminated environments.

Carbonation of CEM III/B concrete is faster (in particular in accelerated laboratory experiments) than CEM I concrete and results in a more open microstructure. In practice, however, carbonation depths are shallow en pose no problem with respect to reinforcement corrosion for cover depths in the usual range for civil engineering structures [1]. Freeze-thaw + de-icing salt resistance of CEM III/B concrete is slightly lower than that of CEM I concrete. Under Dutch climate conditions, any freeze-thaw + de-icing salt damage of concrete is very small and the performance of CEM III/B and CEM I concrete are considered to be similar with regard to this aspect. However, freeze-thaw + de-icing salt damage is expected to be worse in Norway due to harsher winter climate, and is one of the main concerns related to the use of slag cements. Bad curing (resulting in higher carbonation and a more open microstructure of the cover concrete) increases the susceptibility for freeze-thaw + de-icing salt damage of CEM III/B, especially in the form of scaling, at young age. The need for sufficiently long wet curing is therefore the main concern with slag and in particular fly ash based blended binders.

EXPERIMENTAL PROGRAM

The program includes the following:

- Binders CEM III/B (no silica fume), CEM III/A (48% slag, with 5% silica fume), CEM II/V-A (with 5% silica fume), CEM I (with 5% silica fume)
- Testing mortar with w/b 0.40
- Testing for rapid chloride migration (RCM [17]) at ages 2, 7, 28, 90, 180 and 360 days, and at two and three years
- Testing for electrical concrete resistivity (using 120 Hz AC) at ages 2, 7, 14, 28, 56, 90, 180, 270 and 360 days, and then every three months up to three years.
- Carbonation depths at one, two and three years age.

EXPECTED RESULTS

At the moment of writing this paper, no results are available of the intended testing program. However, it is thought interesting to predict expected results based on previous data and supposed effects of binder compositions. Data are available of the development of chloride migration coefficients of CEM I and CEM III/B mortars with w/c 0.50, from ages of one until 28 days [14]; and data on concrete with w/c 0.35, 0.45 and 0.55 from 28 days until three years [18]. Concrete and mortar may have different migration coefficients, even for the same w/c and at the same age. Nevertheless, it is possible to match the values at 28 days, correct concrete values at later ages and compare the results over time. Figure 1 shows the results.

Also shown in Figure 1 are simple power models for both cement types. These were obtained by fitting the equation $y = A\ x^{-n}$ with A a constant representing the (modelled) one day value, x time in days and n an exponent as typically used in time dependent diffusion coefficient modelling [19,20]. Early age development deviated significantly from a simple power model, so data for one and two days were neglected for CEM I and data for 1 – 7 days were neglected for CEM III/B. The resulting fits are quite acceptable from either 3 or 7 days up to three years; exponent and one day values were n=0.23 and A=37 for CEM I and n=0.38 and A=10 for CEM III/B. Consequently, we have a reasonable prediction for RCM values for the mortar made with CEM III/B in the program. However, CEM I is not used pure but with 5% silica fume added; and the other binders contain either less slag than CEM III/B or no slag but fly ash; and both contain silica fume. So the next step in predicting results should address the effect of silica fume, and those of the other binders.

Silica fume is expected to accelerate the hydration, thus producing lower early values; whether it produces low values at higher age in the mixes to be investigated remains to be seen, although exposure testing has suggested so, possibly depending on silica fume dosage [15]. Slag produces lower values than CEM I at about 28 days, that continue to decrease. Fly ash produces higher values at early age and at 28 days, but lower values on the long term. Fly ash and silica fume combined can produce rather low diffusion coefficients [10]. Consequently, the predictions for RCM at 28 days would have the following order with values decreasing from 17 to about $3*10^{-12}$ m^2/s:
CEM I ≈ CEM II/A-V + 5% silica fume > CEM I + 5% silica fume > CEM III/A + 5% silica fume ≈ CEM III/B.

Predicting early age values and/or time dependency for the mixes to be tested is considered too speculative at this moment. However, correcting for w/c ratio would be possible. As analysis of large numbers of RCM values for different binders and w/c ratios has shown, the RCM = f(w/b) depends on the binder type [1,21,22,23], with a much stronger dependency (at 28 days) for Portland cement than for slag cement. The ranking order remains the same. Predictions have been collected in Table 1. Previous testing of various concrete composition in Norway up to ten years generally would suggest similar values at 28 days as predicted here [15].

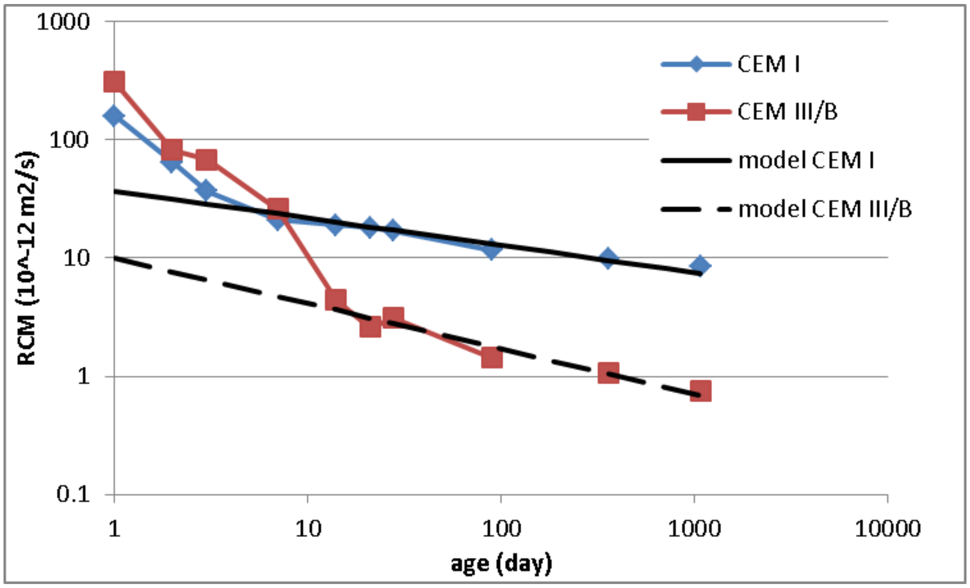

Figure 1 - Development of chloride migration coefficient for CEM I and CEM III/B mortars over time.

Table 1 - Predictions for RCM values at 28 days age for mortars with different binders

binder	Mortar w/c 0.50 A (10^{-12} m^2/s)	n (-)	RCM @ 28 day (10^{-12} m^2/s)	Mortar w/c 0.40 RCM @ 28 day (10^{-12} m^2/s)
CEM I	37	0.23	17	6.8
CEM III/B	10	0.38	3.1	2.1
CEM I + 5% silica fume	?	?	10	5
CEM III/A + 5% silica fume	?	?	3	2
CEM II-V/A + 5% silica fume	?	?	17	10

CONCLUSIONS

Reinforced concrete structures made with blast furnace slag cement with a high percentage of slag, CEM III/B, have shown consistently good durability in aggressive environments under marine and de-icing salt exposure in The Netherlands. This is related to a high chloride diffusion resistance and high electrical resistance for slag cement. The Norwegian Public Roads Administration have expressed their interest in slag cement for their project Durable Structures. Using BFSC in Norway would be innovative. Improved durability of coastal bridges would be expected. However, Dutch CEM III/B experience cannot be transferred directly, as no such cement is available on the Norwegian market. Presently, CEM III/A with about 48% slag is being considered for the Norwegian market. Moreover, Norwegian concrete technology for aggressive environment includes addition of silica fume at c. 5% and using low water-to-binder ratios of 0.40 or lower. In order to study the potential of slag cements an experimental program was set up. The program concentrates on determining chloride diffusion coefficients and electrical resistivity between two days and three years of age. At the moment of writing this paper, no results are available yet. However, previous experience allows prediction of the behavior of mortars made with the investigated binders. The first results of the program will be presented.

REFERENCES

1. Polder, R.B., Nijland, T.G., Rooij, M.R. de, “Experience with the durability of blast furnace slag cement concrete with high slag content (CEM III/B) in the Netherlands since the 1920’s”, TNO report 2013 R10100, 2013, 72 pp.
2. Bijen, J.M.J.M., “Blast Furnace Slag Cement for Durable Marine Structures”, Stichting Betonprisma, Den Bosch, The Netherlands, 1996, 62 pp.
3. Bamforth, P.B., Chapman-Andrews, J., “Long term performance of RC elements under UK coastal conditions”, Proceedings, International Conference on Corrosion and Corrosion Protection of Steel in Concrete, ed. R.N. Swamy, Sheffield Academic Press, 24-29 July, 1994, pp. 139-156.
4. Wiebenga, J.G., “Durability of concrete structures along the North Sea coast of the Netherlands”, Performance of concrete in marine environment, ASTM special publication SP-65, 1980, paper 24, pp. 437-452.
5. Polder, R.B., Rooij, M.R. de, “Durability of marine concrete structures – field investigations and modelling”, *HERON*, 50 (3), 2005, pp. 133-143.
6. Polder, R.B., “Effects of Slag and Fly Ash on Reinforcement Corrosion in Concrete in Chloride Environment – Research from The Netherlands”, *HERON*, 57 (3), 2012, pp. 197-210.
7. Polder, R.B., Peelen, W.H.A., “Characterisation of chloride transport and reinforcement corrosion in concrete under cyclic wetting and drying by electrical resistivity”, *Cement & Concrete Composites*, Vol. 24, 2002, pp. 427-435.
8. Gaal, G.C.M., “Prediction of Deterioration of concrete bridges”, Ph.D. thesis, Delft University Press, Delft, 2004, 146 pp.
9. Rijkswaterstaat, ROK 1.0, “Regulations for design of infrastructure”, RTD 1001:2011, Ministry of Infrastructure, , 2011, 218 pp. (In Dutch).
10. Polder, R.B., “The Influence of Blast Furnace Slag, Fly Ash and Silica Fume on Corrosion of Reinforced Concrete in Marine Environment”, *HERON*, Vol. 41, No. 4, 1996, pp.287-300.
11. Polder, R.B., Larbi, J.A., “Investigation of Concrete Exposed to North Sea Water submersion for 16 Years”, *HERON*, Vol. 40, No. 1, 1995, pp. 31-56.
12. Osterminski, K., Polder, R.B., Schiessl, P., “Long term behaviour of concrete resistivity”, *HERON*, 57 (3), 2012, pp. 211-230.
13. Polder, R.B., Ketelaars, M.B.G., “Electrical resistance of blast furnace slag cement and ordinary Portland cement concretes”, Proceedings, International Conference Blended Cements in Construction, Sheffield, ed. R.N. Swamy, Elsevier, 1991, pp. 401-415.
14. Caballero, J., Polder, R.B., Leegwater, G.A., Fraaij, A., “Chloride penetration into cementitious mortar at early age”, *HERON*, 57 (3), 2012, pp. 185-196
15. Larsen, C.K., “Influence of concrete composition on long term chloride ingress”, SECON, Dubrovnik, 2006.
16. Polder, R.B., “Critical chloride content for reinforced concrete and its relationship to concrete resistivity”, *Materials and Corrosion*, 60 (8), 2009, pp. 623-630.
17. Tang, L., Nilsson, L.-O., “Rapid determination of chloride diffusivity of concrete by applying an electric field”, *ACI Materials Journal,* Vol. 49, No. 1, 1992, pp. 49-53.

18. Visser, J. H.M., Polder, R.B., "Concrete Binder Performance Evaluation in Service Life Design", Proceedings, ConcreteLife'06 - International RILEM-JCI Seminar on Concrete Durability and Service Life Planning: Curing, Crack Control, Performance in Harsh Environments, March 14 - 16 2006, Dead Sea, Israel, Ed. K. Kovler, RILEM, 2006.
19. DuraCrete R17, "DuraCrete Final Technical Report", Document BE95-1347/R17, The European Union – Brite EuRam III, DuraCrete – Probabilistic Performance based Durability Design of Concrete Structures, CUR, Gouda, 2000, 139 pp.
20. Gehlen, C., "Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken", Deutscher Ausschuss für Stahlbeton, Vol. 510**,** Berlin, 2000, 106 pp.
21. Wegen, G. van der, Polder, R.B., Breugel, K. van, "Guideline for Service Life Design of Structural Concrete – a performance based approach with regard to chloride induced Corrosion", *HERON*, 57 (3), 2012, pp. 153-168.
22. Polder, R.B., Wegen, G. van der, Breugel, K. van, "Guideline for service life design of structural concrete – a performance based approach with regard to chloride induced corrosion", Proceedings, *fib* Workshop Performance-based Specifications for Concrete, Leipzig June 14-15, Eds. F. Dehn, H. Beushausen, 2011, pp. 25-34.
23. Frederiksen, J.M., Sorensen, H.E., Andersen, A., Klinghoffer, O., "The effect of the w/c ratio on chloride transport into concrete – immersion, migration and resistivity tests", HETEK report no. 54, Danish Road Directorate, Copenhagen, ISBN 87-7492-735-8, 1997, 93 pp.