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A Study of the Influence of Slag Alkali Level on the Alkali-Silica Reactivity of Slag Concrete

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Abstract

Ground granulated blast furnace slag (ggbs), can reduce the alkali load in concrete, despite its relatively high alkali content. Most research has been devoted to the efficacy of slag with an alkali content of less than 1.0% and this is reflected in guidance documents. A comparative assessment was made of the effect, if any, of the alkali level of ggbs on potential alkali-silica reactivity. Expansion tests were performed on a matrix of concrete mixes using Irish normal Portland cement, two slags of differing alkali content, three aggregates and alkali loads of 5 and 6 kg $Na_2O_{eq.}/m^3$. A replacement level of 50% was used throughout. No significant difference in behaviour was apparent, irrespective of aggregate type or alkali load, indicating that the alkali level of the slag is not a contributory factor at the 50% replacement level.

Keywords: ASR, ggbs, mortar bar expansion test

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INTRODUCTION

No cases of damaging alkali-silica reaction have been reported to date in Ireland despite the fact that the bedrock of Ireland incorporates significant quantities of chert in the Carboniferous limestones. Chert has given rise to concern internationally in the context of ASR, primarily due to the potential presence of reactive silica [1]. In this context, control of alkali load in concrete be considered desirable. In such cases the use of cement replacement materials may ameliorate the risk of ASR, if used at adequate replacement levels.

Ground granulated blast furnace slag (ggbs) has not been a significant feature of Irish concrete practice to date, in part because of a lack of an indigenous source and a lack of research on the properties of Irish slag concrete mixes. This is likely to change in the future and many specifiers may take note of experience of slag in the United Kingdom in advance of data becoming available from Irish concrete practice. However economical sources of imported slag may on occasion have higher alkali levels than those used in the United Kingdom. Specifically the U.K. guidance [2] is limited to slags with alkali levels below 1%. International research has to date largely studied the effect of ggbs on concrete durability parameters [3, 4], with little focus on the effect of increased alkali content. The need therefore exists to research the properties of Irish concrete made with slags of different alkali levels.

The objective of the study reported in this paper was to determine the relative performance, in the context of alkali-aggregate reactivity, of Irish NPC concrete and slag concretes made with two slags, which had alkali levels below and above the 1% level.

MATERIALS AND METHODS

Materials

Concrete prism expansion tests were performed on a matrix of concrete mixes using three aggregates that had exhibited low, medium and high expansion in standard tests. The aggregates were selected based on the results of previous research in Ireland by McNally and Richardson [5]. These included combinations that had exhibited higher than average expansions in standard expansion tests, an argillaceous limestone aggregate and a greywacke aggregate sourced from outside the Republic of Ireland. Details of the aggregates are presented in Table 1.

The binders were Portland cements and Portland cement / slag combinations (Irish NPC; Irish NPC & higher alkali slag; Irish NPC & lower alkali slag) Three sources were employed to provide:

- Portland cement typical of Irish practice (NPC);
- Slag of alkali level <1% (Slag 1);
- Slag of alkali level >1% (Slag 2).

Control concretes were based on Portland cement mixes with the addition to the mix water of potassium sulfate (K_2SO_4) to bring the concrete to the required alkali load. The slag mixes were similar but 50% of the cement was replaced by slag. The alkali level of the slag did not influence the mix design because the hypothesis under test was that the slag did not contribute alkalis at the high replacement level.

Methodology of Test

The test method was a modified version of the British Standard [6] concrete prism test, BS 812 Part 123. The standard test employs an alkali load of 7 kg Na_2O_{eq}/m^3. This was modified to allow testing of aggregate combinations at different alkali levels and the incorporation of slags.

The first objective was to compare the performance of slag and Portland cement concrete at the worst case alkali load achievable using current Irish cement production. The mixes were brought to the highest possible value of alkali load using potassium sulfate at the highest practical solution level. This led to a load of 6 kg $Na_2O_{eq.}/m^3$. The following combinations were cast: NPC, NPC/Slag1 in proportions 50/50, and NPC/Slag 2 in proportions 50/50 using the following aggregate combinations: N-1/H-1, L-1/H-1 and R-1/N-2 (Reference Numbers CP-11 to CP-19).

The second objective was to study the relative performance of Irish NPC concretes and slag concretes at alkali levels closer to those that might be

encountered in practice in adverse conditions. The aggregate combinations used were the same, as was the basic mix design, but the alkali load was lowered to 5 kg $Na_2O_{eq.}/m^3$ (Reference Numbers CP-21 to CP-29). This also allowed exploration of the potential existence of an alkali threshold at which initiation of expansion due to ASR may become evident as reported by McNally and Richardson [7]. Constraints on oven capacity resulted in the tests being limited to 3 prisms per variable rather than the 4 required in standard tests. Details of mix series and their constituents are presented in Table 2.

The mix design was based on the proportions (% by volume) published in the BCA Testing Protocol [8] for greywacke aggregate concretes.

RESULTS AND DISCUSSION

Results

The average expansions recorded at 52 weeks are presented in Table 3.

The results are based on three prisms per test series. There was little variation between individual prisms of each set.

It is normal to report average expansions to the nearest 0.005% but the values have been reported in Table 3 to an accuracy of 0.001%. This does not infer confidence in this level of accuracy but it has been used to highlight the very low levels of expansion recorded in certain cases, especially in the slag concrete specimens.

Discussion

Comparative expansion trends at alkali loads of 6 kg Na_2O_{eq}/ m^3 for the three aggregate combinations are illustrated in Figures 1 to 3. Similar comparative trends at alkali loads of 5 kg Na_2O_{eq}/ m^3 are illustrated in Figures 4 to 6.

The slag concretes had very low expansion levels. The Slag 2 concrete specimens generally expanded more than the Slag 1 concretes but the difference is marginal and is not considered significant. It appears therefore that the alkali content of the slag is not a factor at 50% replacement level.

These trends are supported by comparison with published results, for example by Arano and Kawamurai [9]. They carried out similar tests to those described on one aggregate combination at replacement levels of 5%, 10%, 20%, 30%, and 60%. The degree of expansion decreased as the replacement level increased, as shown in Table 4. They measured the concentration of hydroxyl ions in the pore solution of the Portland cement concrete and the 20% replacement level Portland cement/ slag concrete. There was very little difference in the OH^- ion concentration and their hypothesis is that the mobility of the ions may be reduced in the pore solution of the slag concrete, thereby delaying or reducing the extent of expansion.

It was apparent from the results that the partial replacement of Portland cement with slag significantly reduces the expansion of the concrete in tests for potential reactivity. This trend holds irrespective of aggregate type or alkali

load. The trend of reduced expansion through incorporation of slag was most discernible at the higher alkali load (6 kg $Na_2O_{eq.}/m^3$) and in the greywacke aggregate concrete. It may be speculated that at high replacement levels the incorporation of slag inhibits the mobility of hydroxyl ions to such a degree that it counteracts the potentially damaging effect of increased alkalinity.

The Portland cement mixes exhibited potentially significant behaviour at the higher alkali load of 6 kg $Na_2O_{eq.}/m^3$. The guidance for interpreting expansive behaviour is that innocuous materials should not reach expansion levels of 0.05% at 12 months and that expansion levels of 0.15% and above are a cause for concern. A comparison of Fig. 2 and Fig. 5 may indicate that some Irish aggregate combinations trigger a potentially deleterious reaction at alkali loads in excess of 5 kg $Na_2O_{eq.}/m^3$. Fortunately this high alkali level is rarely found in practice.

CONCLUSIONS

The partial replacement of Portland cement with slag at a replacement level of 50% significantly reduced the expansion of the concrete in expansion tests.

No significant difference in behaviour was apparent between the slag concrete specimens, indicating that the alkali level of the slag is not a contributory factor at the replacement level used in the tests.

ACKNOWLEDGEMENTS

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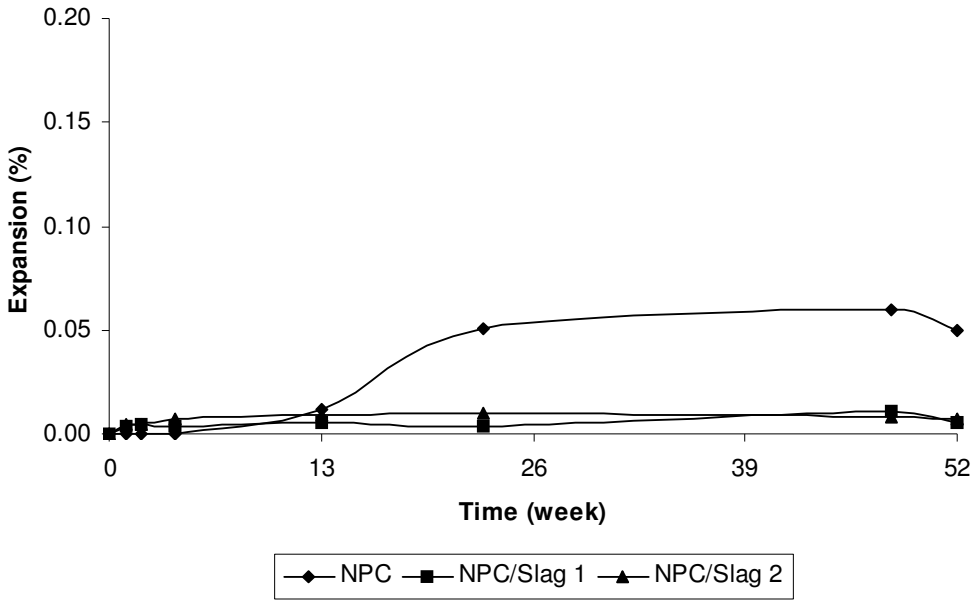

Fig. 1. Comparison of binders for the aggregate combination N-1 and H-1 at an alkali load of 6.0 kg Na_2O_{eq}/m^3

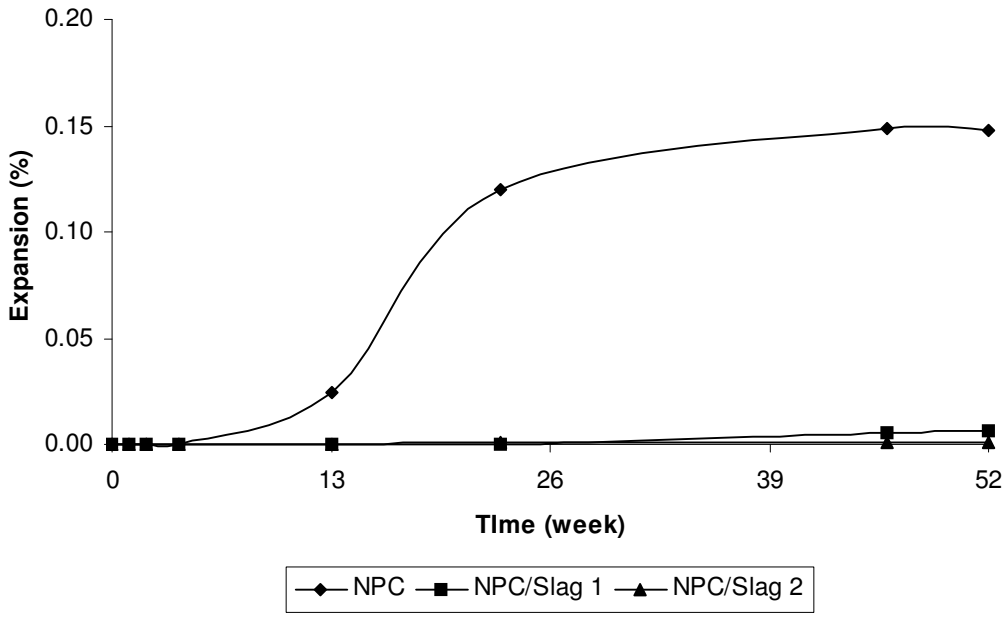

Fig. 2. Comparison of binders for the aggregate combination L-1 and H-1 at an alkali load of 6.0 kg Na_2O_{eq}/m^3

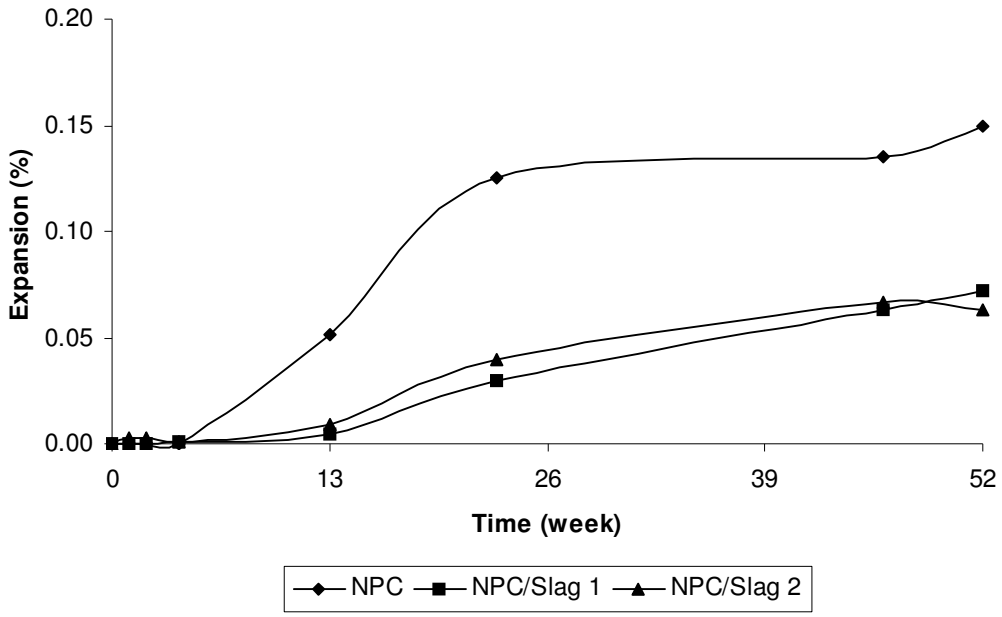

Fig. 3. Comparison of binders for the aggregate combination R-1 and N-2 at an alkali load of 6.0 kg Na_2O_{eq}/m^3

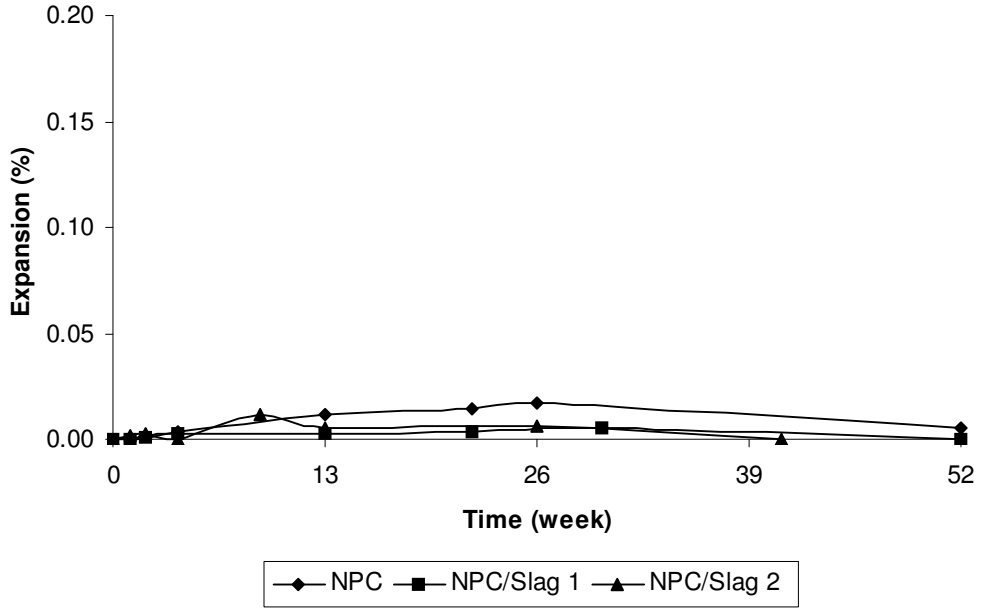

Fig. 4. Comparison of binders for the aggregate combination N-1 and H-1 at an alkali load of 5.0 kg Na_2O_{eq}/m^3

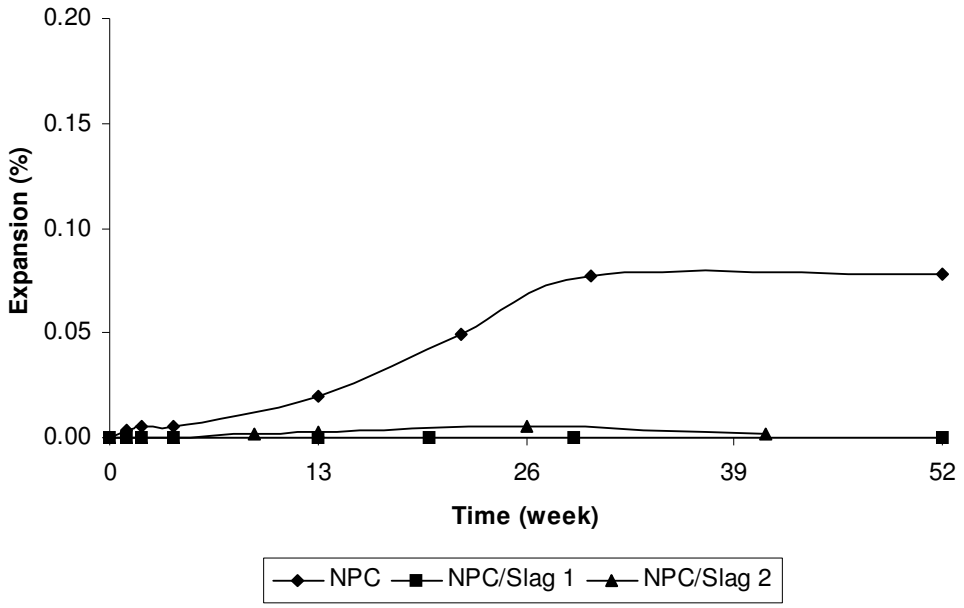

Fig. 5. Comparison of binders for the aggregate combination L-1 and H-1 at an alkali load of 5.0 kg Na_2O_{eq}/m^3

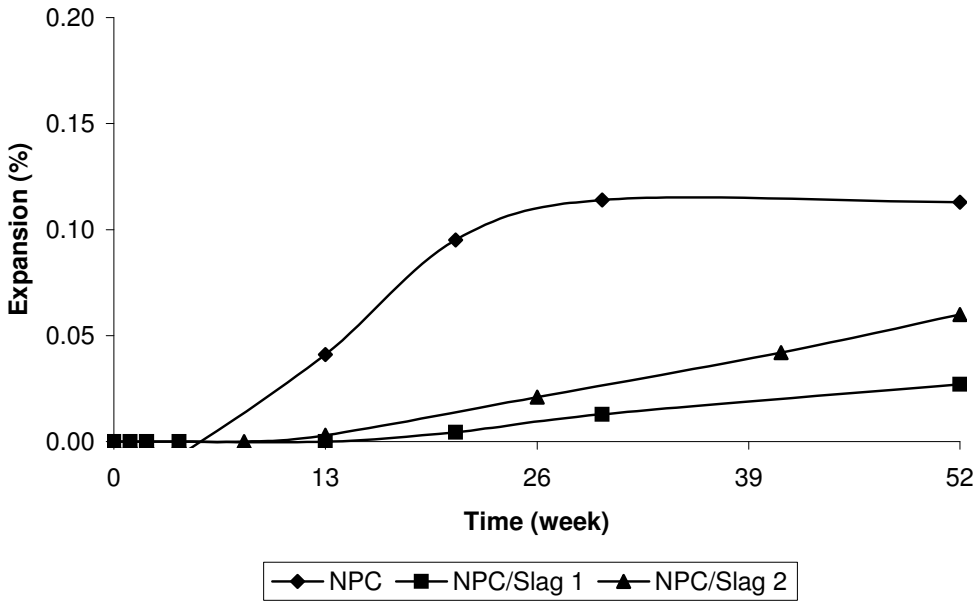

Fig. 6. Comparison of binders for the aggregate combination R-1 and N-2 at an alkali load of 5.0 kg Na_2O_{eq}/m^3

Table 1
Aggregates selected for test programme

Ref.	Type	Geological Description
N-1	Coarse	Pure limestone virtually free of clay. Some traces of dolomite present.
N-2	Fine	97% limestone sand, both clean and clay free. Traces of dolomite and quartz.
L-1	Coarse	Argillaceous limestone with moderate amounts of clay, some quartz silt and organic matter incorporated. 1% chert. 17% argillaceous content.
H-1	Fine	Consists of over 40% limestone, 30% chert and 20% quartz. Also contains about 6% fine greywacke and siltstone. Small amounts of sandstone, quartz and aplite.
R-1	Coarse	Greywacke aggregate, consisting of 65% arkosic greywacke/sandstone. Remainder is lithic greywacke. The arkosic sandstone matrix contains feldspar, quartz, clay minerals and others.

Table 2
Aggregate combinations, binders and alkali loadings

Mix Series Ref. No.	Coarse Aggregate	Fine Aggregate	Binder Composition	Alkali Load (kg Na_2O_{eq}/m^3)
CP-11	N-1	H-1	NPC	6
CP-12	L-1	H-1	NPC	6
CP-13	R-1	N-2	NPC	6
CP-14	N-1	H-1	NPC/Slag 1	6
CP-15	L-1	H-1	NPC/Slag 1	6
CP-16	R-1	N-2	NPC/Slag 1	6
CP-17	N-1	H-1	NPC/Slag 2	6
CP-18	L-1	H-1	NPC/Slag 2	6
CP-19	R-1	N-2	NPC/Slag 2	6
CP-21	N-1	H-1	NPC	5
CP-22	L-1	H-1	NPC	5
CP-23	R-1	N-2	NPC	5
CP-24	N-1	H-1	NPC/Slag 1	5
CP-25	L-1	H-1	NPC/Slag 1	5
CP-26	R-1	N-2	NPC/Slag 1	5
CP-27	N-1	H-1	NPC/Slag 2	5
CP-28	L-1	H-1	NPC/Slag 2	5
CP-29	R-1	N-2	NPC/Slag 2	5

Table 3
Average measured expansions at 52 weeks

Mix Series Ref. No.	Average Expansion at 52 Weeks (%)	Mix Series Ref. No.	Average Expansion at 52 Weeks (%)
CP-11	0.048	CP-21	0.005
CP-12	0.151	CP-22	0.078
CP-13	0.154	CP-23	0.113
CP-14	0.005	CP-24	0.002
CP-15	0.006	CP-25	0.000
CP-16	0.072	CP-26	0.027
CP-17	0.007	CP-27	0.000
CP-18	0.001	CP-28	0.004
CP-19	0.063	CP-29	0.060

Table 4
Expansion test results from a study by Arano and Kawamura [9]

Slag Replacement Level	Expansion (%)
0%	0.18
5%	0.17
20%	0.08
30%	0.02
60%	0.00