ELSEVIER

Cement and Concrete Composites **19** (1997) 367–372

0958-9465/97/$17.00

PII:S0958-9465(97)00034-6

The Effectiveness of Palm Oil Fuel Ash in Preventing Expansion Due to Alkali–silica Reaction

A. S. M. Abdul Awal & M. Warid Hussin

Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor Bahru, Malaysia

(Received 2 April 1997; accepted 1 August 1997)

Abstract

Laboratory tests were conducted to evaluate the performance of palm oil fuel ash (POFA), a recently identified pozzolanic material, in reducing the expansion of mortar bars containing Tuff as a reactive aggregate where ordinary Portland cement (OPC) was replaced, mass for mass, by 0, 10, 30 and 50% POFA. The South African NBRI Accelerated Test method was used in the experimental investigation, which revealed that palm oil fuel ash has a good potential in suppressing expansion due to alkali–silica reaction.

Keywords: Alkali–silica reaction, palm oil fuel ash, pozzolanic material, reactive aggregate, expansion.

INTRODUCTION

The use of supplementary cementing materials, such as fly ash, slag and silica fume, is one of the most popular solutions proposed to suppress the expansion due to alkali–silica reaction. Dating back some 50 years ago, Stanton[1] was the first to explain the possibility of reducing the expansion due to alkali–aggregate reactions by using pozzolanic cement containing finely ground 'Monterrey Shale' or by replacement of 25% high-alkali Portland cement with pumicite. Subsequent tests by the same author confirmed the beneficial effect of a wide range of natural pozzolans.[2] A decade later, similar studies by the US Army Crops of Engineers [3] showed that artificial pozzolans such as fly ash were also effective in reducing expansion.

The extent of research on fly ash and alkali–aggregate reaction has proliferated in the past 50 years, and there are now several hundred published references dealing with this subject. Despite the considerable research effort, there are still conflicting sources of evidence concerning the effectiveness of fly ash in controlling the reaction and subsequent expansion.[4–6] Much of the conflict arises from inherent differences in the materials (type of cement, aggregates and fly ash) used and the methods of assessment (type and conditions of test). However, fly ash itself is an extremely variable material, and its effectiveness in controlling alkali–silica reaction has been shown to depend on its physical, mineralogical and chemical properties.[7]

Research on various aspects of durability of concrete utilising palm oil fuel ash (POFA), a recently identified pozzolanic material, as a partial replacement of ordinary Portland cement (OPC) has been in progress at the University of Technology, Malaysia since the early 1990s. This paper aims at evaluating the effectiveness of POFA at various replacement levels of 0, 10, 30 and 50% of OPC in reducing the expansion of mortar bars due to alkali–silica reaction using Tuff as a local reactive aggregate.

MATERIALS AND TEST DETAILS

Palm oil fuel ash

Palm oil fuel ash is a waste material obtained by burning of palm oil husk and shell as fuel in palm oil mill boilers. At present, some 200 palm oil mills are in operation in Malaysia where thousands of tons of ash are produced annually and are simply disposed of without any commercial return. However, it has been found that this ash has pozzolanic properties that not only enable the replacement of cement but also play an active role in making strong and durable concrete.[8–10]

In the present study, ash was collected from a mill at Bukit Lawang, in the State of Johor, West Malaysia and was sieved through a 300-μm sieve in order to remove any foreign materials and larger size ash particles. It was then ground in a Los Angeles abrasion machine using mild steel bars (12 mm in diameter and 800 mm long), instead of balls, inside.

Like other fly ashes, palm oil fuel ash is greyish in colour, becoming dark with increasing proportions of unburnt carbon. Table 1 shows the physical properties and chemical analysis of POFA. One of the most important properties that is to be noted is the fineness of the ash. Fineness, as measured in specific surface area, shows that POFA is much finer than OPC. The chemical analysis suggests that this ash, in general, satisfies the requirement to be pozzolanic, and may be grouped in between Class C and Class F pozzolana as specified in ASTM C618-92a.[11] Details of the effects of POFA on setting time and other properties of concrete have been presented elsewhere.[12,13]

Table 1. Physical properties and chemical analysis of OPC and POFA

Tests	*OPC*	*POFA*
Physical properties:		
Fineness–specific surface area (m^2/kg)	314	519
Specific gravity	3.28	2.22
Chemical analysis (%)		
Silicon dioxide (SiO_2)	20.2	43.6
Aluminium oxide (Al_2O_3)	5.7	11.4
Ferric oxide (Fe_2O_3)	3.0	4.7
Calcium oxide (CaO)	62.5	8.4
Magnesium oxide (MgO)	2.6	4.8
Sulphur trioxide (SO_3)	1.8	2.8
Sodium oxide (Na_2O)	0.16	0.39
Potassium oxide (K_2O)	0.87	3.5
Loss on ignition (LOI)	2.7	18.0
28-day strength activity index with OPC	—	115

Cement

Ordinary Portland cement (ASTM Type I) from a single source was used throughout the investigation. The physical properties and chemical analysis of the cement are also summarised in Table 1.

Aggregate

Over the years, there have been several reports of occurrences of alkali–silica reactivity in Malaysia where the most reactive aggregates identified so far are andesite, rhyolite, tuff and quartzite.[14,15] The reactive aggregate used in this study was a tuff obtained from Pengerang Quarry in the southern part of Johor. A non-reactive fine aggregate of granitic composition with a fineness modulus of 2.4 was used. The specific gravity and the water absorption of the fine aggregate was 2.59 and 1.34%, respectively.

Preparation of test specimen

A number of accelerated mortar bar tests[16–18] have been proposed for determining the alkali reactivity of aggregates. In this study, the South African NBRI test method[17] was adopted. Earlier studies[18–20] have shown a good correlation exists between the expansion in the test and that observed in the ASTM mortar bar expansion test.[21]

To prepare mortar bars, the reactive aggregates were crushed and sieved to the gradation described also in ASTM C227-90.[21] In order to find the pessimum content of reactive aggregate, mortar bars were made with different proportions of 0, 25, 50, 75 and 100% tuff with sand as fine aggregate. On obtaining the pessimum content, based on expansion behaviour, mortar bars were cast in the second stage of the experiment with POFA as a supplementary cementing material at various replacement levels of 0, 10, 30 and 50% of OPC to assess the effectiveness of POFA in suppressing ASR. In all mixes, bars were cast in triplicate, and the average of three expansion values is reported.

Measurement of expansion

The mortar bars, prepared in accordance with NBRI test method,[22] were demoulded after 24 h and immersed in water, while maintaining a temperature of 80°C for 24 h. The lengths of the bars, referred to as 'zero reading', were measured before immersion in a 1 N NaOH solution maintained at the same temperature. The length measurements were continued for 14 days where the average expansion after 12 days was taken as the reference value for assessing potential alkali reactivity.

In order to obtain the benefit from pozzolanic reaction, mortar bars with POFA, together with the control one prepared for the second set of experiments, were cured in water (27°C) for 28 days before placing them into an immersion tank at 80°C.

TEST RESULTS

Determination of pessimum content of reactive aggregate

The maximum expansion due to alkali–silica reaction depends on a certain proportion of the reactive material in the aggregate known as 'pessimum' content. This proportion may be as low as 3–5% in the case of 'opal' or much higher, even up to 100%, with less reactive materials.[23] It was mentioned earlier that for the purpose of obtaining pessimum content, mortar bars with five different mixes of 0, 25, 50, 75 and 100% tuff with sand as fine aggregate, were tested; the measured expansions are shown in Fig. 1.

Figure 1 reveals that the larger the amount of tuff, the higher was the expansion at all ages. The value of expansion for the control specimen, i.e. with 0% tuff after 12 days of exposure was very small. At the same age, a relatively higher amount of expansion occurred for the mortar bars with 25% tuff. However, the value still remains less than the value considered to be deleterious, i.e. 0.1%.[17] It is interesting to note that close values of expansion (between 0.15 and 0.20%) were obtained for the mixes with 50, 75 and 100% tuff. This means that at larger aggregate contents, i.e. beyond 50% of reactive rocks in aggregates, relatively smaller expansions were produced.

Except for no-fines concrete, concrete, in general, consists of fine and coarse aggregates. Considering the nature of expansion obtained and for a practical reason (i.e. a combination of reactive coarse aggregate with non-reactive sand), the pessimum content of tuff in this study was, thus, taken as 50% of the total aggregate.

Effect of POFA on expansion

Figure 2 illustrates the graphs of expansion of mortar bars, plotted against time, in which OPC was replaced with various amounts of POFA. It is evident from the figure that a reduction in expansion occurred with an increase in the amount of ash content. After 12 days of exposure, a maximum expansion of 0.166% was recorded for the control specimen (0% POFA). By replacing 10% POFA, about 25% reduction in expansion was obtained, i.e. the value of expansion measured at the same age was 0.126%.

Further reduction, although not significant, occurred in the specimens with 30% POFA, which suggests that this replacement level is inadequate to reduce ASR strain to the recommended acceptable level. With 50%

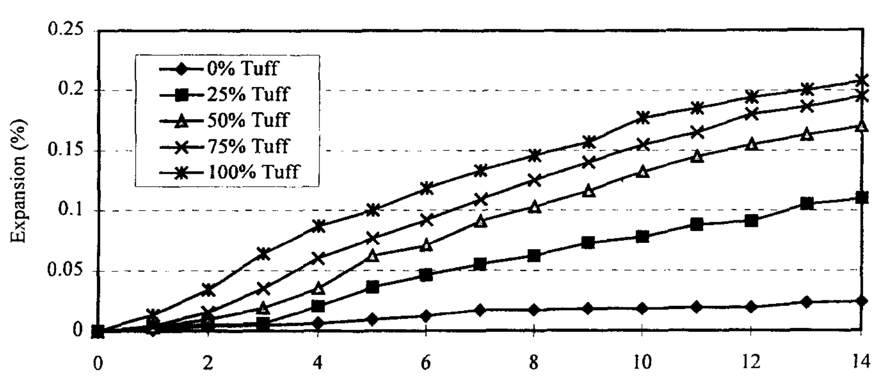

Fig. 1. Effect of the reactive aggregate (tuff) content on the expansion of mortar bars.

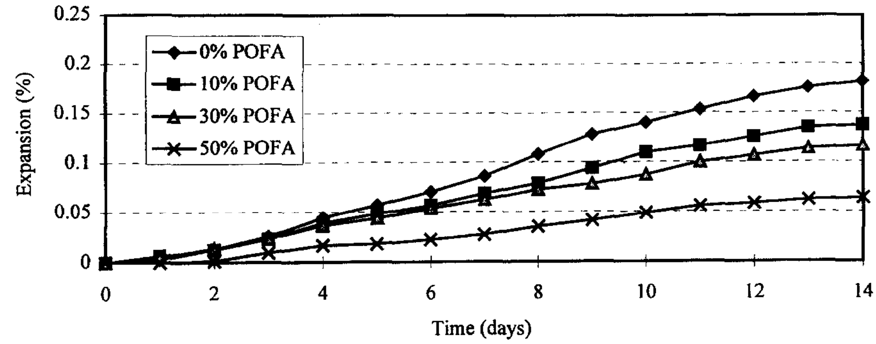

Fig. 2. Influence of palm oil fuel ash on the expansion of mortar bars

replacement, however, a substantial reduction in expansion (0.058%) was recorded, which is much lower than the value to be deleterious. It is worth noting that the bars containing 50% POFA also showed a delay in the start of expansion.

DISCUSSION OF TEST RESULTS

The effect of pozzolanic materials on expansion due to ASR has been known to depend variously on their alkali content, calcium content, pozzolanicity and fineness. It is also generally agreed that greater expansion results from higher alkali contents, though it does not mean that increasing the alkali content progressively increases the alkali expansivity.[24]

The alkali content of fly ash varies considerably (typically from 1.0 to 8.0% Na_2O equiv.) but, generally, higher than that of normal Portland cement (0.2–1.4% Na_2O equiv.). Most of these alkalies are originally bound in the glassy phase of the ash, and the soluble alkali content is usually less than 0.1% Na_2O equivalent[7]. This means that the whole amount of alkali does not take part in the alkali–silica reaction. Only a fraction, popularly designated as 'available alkali' remains effectively available for ASR, though the opinion on the amount of available alkali for reaction is divided.[25,26]

Table 2 summarises the alkali content of OPC and POFA used in this investigation. The total alkali as Na_2O equivalent of POFA is 2.69%, which is much higher than the maximum limit of 1.5% prescribed in the ASTM standard.[11] Despite the higher alkali content, POFA has been found to be effective in reducing expansion.

Table 2. Alkali contents (%) in OPC and POFA

Type	*Na_2O*	*K_2O*	*Total alkali as Na_2O equiv.*
OPC	0.16	0.87	0.73
POFA	0.39	3.50	2.69

The reason for this, as Vivian[27] explained, is that the pozzolan particles react very rapidly with alkalies in cement because of their reactive nature and fineness, thus leaving little unreacted alkali for later reaction with aggregate. The work by Diamond[28] suggests that ashes with low calcium generally reduce the alkalinity of a pore solution in proportion of the level of replacement, i.e. the ashes act as an inert diluent. Studies by Chen and Suderman,[29] and Bérubé and Duchesne[30] may be cited as examples for quantifying the safe limit of alkali content. Their work with ashes of various amount of alkali reveal that a total alkali content of 5% or more may be too high for fly ash in the presence of natural aggregates, whereas 3% or less proved to be satisfactory, even with very reactive aggregates. Considering the above safety limit of 3%, undoubtedly, the fineness of POFA and its pozzolanic activity, illustrated in Table 1, are both in favour of its effectiveness in controlling expansion due to ASR.

CONCLUSION

No other research findings on the use of POFA in preventing expansion due to ASR are yet available to compare with the performance data obtained in this investigation. However, the results summarised above are very promising. The main consensus from the available literature as well as from the data obtained in this study is that the effectiveness of POFA, like that of other fly ashes, increases as the level of replacement level increases. The higher replacement level of cement by 50% POFA may, however, affect the strength development of concrete, as an early investigation[12] has shown that a reduction in compressive strength occurs with the amount of ash content beyond 40%. Careful design with an adequate amount of ash should, therefore, be chosen, and future investigations should include a long-term study in the laboratory as well as in the field condition to establish the total benefit.

REFERENCES

1. Stanton, T. E., Expansion of concrete through reaction between cement and aggregate. In *Proc. of the American Society of Civil Engineers*, Vol. 66, 1940, pp. 1781–1811.
2. Stanton, T. E., Studies of use of pozzolans for counteracting excessive concrete expansion resulting from reaction between aggregates and the alkalies in cement. In *Pozzolanic Materials in Mortars and Concretes*, American Society for Testing and Materials, STP 99, 1950, pp. 178–203.
3. Buck, A. D., Houston, B. J. & Pepper, L., Effectiveness of mineral admixtures in preventing excessive expansion of concrete due to alkali-aggregate reaction. *U.S. Army Corps of Engineers, Waterways Experiment Station*, Technical Report No. 6-481, U.S. Army Engineer Waterways Experiment Station, Vicksburg, 53 pp., 1953.
4. Hobbs, D. W., Deleterious expansion of concrete due to alkali-silica reaction: Influence of PFA and Slag. *Mag. Concrete Res.*, **38** (1986) 191–205.
5. Kollek, J. J., Effective alkalies from pulverised fuel ash, granulated blast furnace slag and natural pozzolana deduced from mortar bar expansion results. In *Proc. of the 3rd Int. Conf. on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, ed. V. M. Malhotra, ACI Special Publication SP-114, Vol. 1, 1989, pp. 373–401.
6. Swamy, R. N., Alkali-aggregate reactions — The bogeyman of concrete. In *Proc. of V. M. Malhotra Symposium on Concrete Technology: Past, Present and Future*, ed. P. K. Mehta, ACI Special Publication SP-144, 1994, pp. 105–139.
7. Thomas, M., Fly ash and alkali-aggregate reaction. In *Proc. of an Engineering Foundation Conference on Advances in Cement and Concrete*, ed. M. W. Grutzeck & S. L. Sarkar, American Society of Civil Engineers, 1994, pp. 362–376.
8. Tay, J.H., Ash from oil-palm waste as concrete material. *J. Mater. Civil Eng. ASCE*, **2** (1990) 94–105.
9. Salihuddin, R. S., Relationship Between Engineering Properties and Microstructural Characteristics of Mortar Containing Agricultural Ash, Ph.D. thesis, Universiti Teknologi Malaysia, 1993.
10. Hussin, M. W. & Awal, A. S. M. A., Influence of palm oil fuel ash on strength and durability of concrete. In *Proc. of the 7th Int. Conf. on the Durability of Building Materials and Components*, Stockholm, ed. C. Sjöstrom, E & FN Spon, London, vol. 1, 1996, pp. 291–298.
11. ASTM C618-92a, Standard specification for fly ash and raw or calcinied natural pozzolan for use as a mineral admixture in Portland cement concrete, *Annual Book of ASTM Standards*, 04.02, American Society for Testing and Materials, Philadelphia, 1992, pp. 306–308.
12. Awal, A. S. M. A. & Hussin, M. W., Properties of fresh and hardened concrete containing palm oil fuel ash, In *Proc. of the 3rd Asia pacific Conf. on Structural Engineering and Construction*, ed. M. W. Hussin, Universiti Teknologi Malaysia, Johor Bahru, 1996, pp. 359–367.
13. Hussin, M. W. & Awal, A. S. M. A., Palm oil fuel ash: A potential pozzolanic material in concrete construction, In *Proc. of the Int. Conf. on Urban Engineering in Asian Cities in the 21st Century*, ed. T. Tingsanchali & A. C. Wijeyewickrema, Asian Institute of Technology, Bangkok, 1996, pp. D.361–D.366.
14. Hashim, A. R. & Sazali, Y., Assessment of potential alkali–silica reactivity of local aggregates. In *Proc. Int. Conf. Concrete Engineering and Technology*, CONCET '91, Kuala Lumpur, 1991, pp. 2.1–2.15.
15. Ping, T. K., *Alkali–silica reaction in reinforced concrete*, B. Eng. (Civil) Project Report, Universiti Teknologi Malaysia, 1996.
16. Chatterji, S., An accelerated method for the detection of alkali–aggregate reactivities of aggregates. *Cement Concrete Res.*, **8** (1978) 647–650.
17. Oberholster, R. E. & Davies, G., An accelerated method for testing the potential alkali reactivity of siliceous aggregates. *Cement Concrete Res.*, **16** (1986) 181–189.
18. Bérubé, M. A. & Fourier, B., Accelerated test methods for the alkali–aggregate reactivity. In *Advances in Concrete Technology*, ed. V. M. Malhotra, CANMET, Ottawa, 1992, pp. 583–627.
19. Oberholster, R. E., Alkali reactivity of siliceous rock aggregates: diagnosis of the reaction, testing of cement and aggregate and prescription of preventive measures. In *Proc. of the 6th Int. Conf. on Alkalies in Concrete*, Danish Concrete Institute, Copenhagen, pp. 1983, pp. 419–433.
20. Yoshioka, Y. *et al.*, Study on a rapid test method for evaluating the reactivity of aggregates. In *Proc. 7th Int. Conf. Concrete Alkali–Aggregate Reactions*, Ottawa, 1986, pp. 314–318.
21. ASTM C227-90, Standard test method for potential alkali reactivity of cement aggregate combinations (Mortar bar method). In *Annual Book of ASTM Standards*, American Society for Testing Materials, 04.01, Philadelphia, 1990, pp, 128–132.
22. Davies, G. & Oberholster, R. E., Use of the NBRI accelerated test to evaluate the effectiveness of mineral admixtures in preventing the alkali–silica reaction. *Cement Concrete Res.*, **17** (1987) 97–107.
23. Smith, R. L. & Raba, C. F., Jr, Recent developments in the use of fly ash to reduce alkali–aggregate reaction. In *Alkalies in Concrete*, American Society for Testing and Materials, STP930, ed. V. H. Dodson, 1986, pp. 58–68.
24. Ramachandran, V. S., Feldman, R. F. & Beaudoin, J. J., *Concrete Science: Treatise on Current Research*, Heyden & Son, London, 1981.
25. Hobbs, D. W., *Alkali–Silica Reaction in Concrete*, Thomas Telford, London, 1988.
26. Duchesne, J. & Bérubé, M. A., Available alkalies from supplementary cementing materials. *ACI Mater. J.*, **91** (1994) 289–299.
27. Vivian, H. H., In *Proc. 6th Int. Conf. Alkalies in Concrete*, Danish Concrete Association, Copenhagen, 1983, pp. 243–248.
28. Diamond, S., Alkali reactions in concrete — Pore solution effects. In *Proc. of the 6th Int. Conf. on Alka-*

lies in Concrete, Danish Concrete Association, Copenhagen, 1983, pp. 155–166.

29. Chen, H. & Suderman, R. W., Effectiveness of Canadian supplementary cementing materials in reducing alkali–aggregate reactivity, Final Report, DSS Contract No. OSQ83-00215, CANMET/EMR, Ottawa, 1990, 245 pp.

30. Bérubé, M. A. & Duchesne, J., Evaluation of testing methods used for assessing the effectiveness of mineral admixtures in suppressing expansion due to alkali–aggregate reaction. In *Proc. 4th Int. Conf. Fly Ash Silica Fume, Slag and Natural Pozzolans in Concrete*, Istanbul, ACI Special Publication, SP-132, 1992, pp. 549–575.