Paper No. 6450

# Pulverized fuel ash as a constructional material †

by

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## *Discussion*

**Mr Stanley Raymond** (Reader in Civil Engineering, Royal Technical College, Salford) observed that the Author stated, quite rightly, that properly compacted P.F. ash gave a very satisfactory fill material. One of the chief reasons for this was the property possessed by moist compacted ashes of hardening with time, this property being significant since it gave flexibility to the handling and laying of a material which by its nature was somewhat variable. The hardening, which might be observed qualitatively in old ash tips, gave an increase in shear strength which could only be accounted for by some form of cementitious action. A laboratory investigation into this phenomenon had been carried out in the Royal Technical College, Salford, together with field investigations on trial embankments, and it was intended to report on these in the near future.

57. The hardening with some ashes was considerable. One trial embankment when constructed had given mean CBR values from in-situ tests of approximately 20%. After a month values of more than 100% had been obtained, and the material in the bank had had the consistency of a soft rock such as loess. After standing for 14 months it had had to be demolished by explosives, being too hard to be removed by mechanical diggers.

58. It was likely that the hardening was a pozzolanic one (initiated by small quantities of free calcium oxide present in the ash), and that the material was not quite so chemically inert as the Author suggested. There was indeed, from its mode of origin, no reason why it should not be relatively active compared with rock detritus of similar grading.

**Mr Arthur Bannister** (Reader in Civil Engineering, Royal Technical College, Salford) and **Mr James Ridyard** (Senior Lecturer in Civil Engineering, Royal Technical College, Salford) observed that Table 2 showed that the concrete made with a cement and P.F. ash mixture had reasonable equality in strength throughout with the control. Many writers, including Jordan[20], Brink and Halstead[21], and Fulton and Marshall[1], had shown that the strengths of such concretes steadily approached those of the concretes with no P.F. ash added. During investigations at the Royal Technical College, Salford, into the strength of concretes made with cement and P.F. ash mixtures and having a water/cement ratio of 0·63 and aggregate/cement and P.F. ash ratio 6·5, the average results shown in Table 4 had been noted (based on no added P.F. ash as 100%).

60. The beams tested were 4 in. × 4 in. in cross-section, had an effective span of 16 in., and were reinforced by two ¼-in.-dia. bars placed with 1-in. cover. With 20% P.F. ash and varying water/cement ratios and ashes, the comparable figures for the compressive strength were 71% and from 85 to 105% at 7 days and 1 year respectively.

61. Table 2 could well indicate some special factor applicable to that site.

62. The site engineer could now feel confident on statistical methods of quality control of concrete on the site, and it seemed that when using a material which varied

† Proc. Instn civ. Engrs, vol. 16, p. 419 (Aug. 1960).
References 20–26 are given on p. 425.

between generating stations and with time, mix design might have to be based on the minimum expected performance. Alternatively, the control ratio, as defined by Erntroy[22], might have to be decreased. Perhaps the C.E.G.B. could collect and issue data which were not readily available and so allow a statistical analysis for mix design with P.F. ash and cement mixtures.

TABLE 4

| | Compressive strength | | Load at appearance of first tension cracks in beams | |
|---|---|---|---|---|
| | 7 days | 1 year | 7 days | 1 year |
| 25% P.F. ash . . . . | 66% | 85% | 81% | 83% |

63. P.F. ash could readily replace gypsum plaster in the manufacture of certain types of building block, particularly the non-load-bearing types. Compressive strengths of the order of 480 lb/sq. in. were obtainable[23] for 1-in. cubes in a saturated condition made of a mixture of 60% gypsum plaster, Class A, 40% P.F. ash, and a water/plaster ratio of 0·833.

**Mr D. P. O'Sullivan** (Senior Assistant Civil Engineer, Transmission Project Group, Central Electricity Generating Board) referred to the use of P.F. ash as a fill and road material at Whitson, Newport.

65. At this site the Central Electricity Generating Board were constructing a substation to provide an electricity supply to the new strip mills being constructed by Messrs Richard Thomas & Baldwin at Newport.

66. The site of the substation was on low-lying land and as a result it had been decided to raise the level of the area by 4 ft. P.F. ash had been used as a fill material and had been obtained from Rogerstone Power Station near Newport.

67. The ash used had the following chemical and physical properties:—

TABLE 5

| | % |
|---|---|
| Silica ($SiO_2$) . . . . . . . . | 50·4 |
| Alumina ($Al_2O_3$) . . . . . . | 31·1 |
| Ferric oxide ($Fe_2O_3$) . . . . | 3·3 |
| Lime (CaO) . . . . . . . . | 1·1 |
| Magnesia (MgO) . . . . . . | 0·9 |
| Sulphate (as $SO_3$) . . . . . . | 0·3 |
| Titanium ($TiO_2$) . . . . . . | 0·9 |
| Sodium ($Na_2O$) . . . . . . | 0·5 |
| Potassium ($K_2O$) . . . . . . | 2·7 |
| Phosphorus ($P_205$) . . . . . | 0·3 |
| Loss on ignition . . . . . . | 7·9 |
| Total . . . . . . . . . | 99·4 |
| Specific gravity . . . . . . . | 2·0 |
| Specific surface area . . . . | 5,370 sq. cm/g |

| | % |
|---|---|
| Fine sand (0·06 to 0·22 mm) . . | 28 |
| Coarse silt (0·02 to 0·066 mm) . . | 55 |
| Medium silt (0·006 to 0·02 mm) . | 10 |
| Fine silt (0·002 to 0·006 mm) . . | 7 |
| Total . . . . . . . . . | 100 |

68. The method employed to place and consolidate the ash had been as follows. The ash had been obtained from the stockpile at the power station, transported to the

site by road, tipped in position, spread and levelled in 6-in. layers by two D6 tractor-dozers. Since the weather had been mainly dry during the period of filling it had been necessary to sprinkle the material after spreading with water from a 500-gal bowser. Compaction had been achieved by the continual passing of the tractor-dozers over each layer of the levelled material and also by a smooth-wheeled 32-in. tandem vibrating roller.

69. Normal day-to-day control of moisture content had been tested by observing the colour and consistency of the material and by use of a Proctor needle. Laboratory tests had been carried out at frequent intervals to ensure that the material was receiving maximum compaction.

70. The conclusions reached at this site as a result of using P.F. ash fill were as follows:—

(i) The material was suitable for this type of work and provided a cheap and easy method of raising the level of a site, assuming a degree of compaction approaching the maximum was obtained. In this case the surface of the bank had become reasonably impervious after consolidation.

(ii) The most successful compaction had been obtained by using tractor-dozers, followed by a smooth-wheeled tandem vibrating roller.

(iii) Where compaction could not be carried out, for example at the edges, the material had been found to erode and in some places to flow following heavy rainfall. In such places it had been, therefore, necessary to constrain the bank at the edges with a hard-core shoulder containing sufficient hoggin to prevent seepage of the ash through it. From this experience it appeared that the success of embankments built of P.F. ash depended to a large extent on a satisfactory method of retaining the material at the edges.

(iv) During the past few weeks, when exceptionally heavy rainfall occurred in the area, the top surface tended to suffer from excess moisture but this could in the future be prevented by applying a thin sealing coat to the surface of the ash after it had received its final rolling.

(v) Base, trench, and other forms of excavation carried out in the material during the summer months in dry weather proved that the material was ideally suitable for the digging of large and small intricately shaped foundation bases without the use of timber supports. It had been found that the material, although easy to excavate, allowed clean smooth sides to be formed with the minimum of manual effort and was capable of sustaining the weight of large quantities of concrete without deforming.

71. A temporary access road for construction traffic had also been built using a mixture of cement, P.F. ash, and $\frac{3}{8}$-in. limestone aggregate in the proportions 1:6:6. This road had stood up well to heavy traffic and appeared to provide a satisfactory and economic solution for construction of low-cost roads. The result of test cubes taken were given in Table 5.

TABLE 5

| Materials | Mix | Age of cubes when tested | Load: tons | Stress: lb/sq. in. |
|---|---|---|---|---|
| Cement, P.F. ash, and $\frac{3}{8}$-in. limestone aggregate | 1:6:6 volume batched in 5/3$\frac{1}{2}$ mixer | 7 days | 20·5 | 1,291 |
| Ditto | Ditto | 28 days | 35·0 | 2,211 |
| Ditto | Ditto | 3 months | 56·5 | 3,532 |

**Mr J. T. Edwards** (Senior Assistant Engineer, Freeman, Fox & Partners, Consulting Engineers) asked the Author to amplify his remark that placing fill by hydraulic methods would be successful only if the water could get away quickly, because compaction depended entirely on the action of water travelling down through the ash.

73. Much of the ash from power stations was deposited in old gravel workings or similar pits by pumping a water/ash slurry through pipelines. The water-level in the pit might be kept substantially constant and the slurry deposited in the water. The ash settled out under water and compacted to a degree akin to shale. There clearly could be no draining of the water and compaction was due to the superimposing of more ash. Even the top layer, which might or might not be slightly above water-level, would be sufficiently compact to walk upon without appreciable marking.

74. Although the solidity might be partly due to the cementing action, consolidation must also be very high. Would the Author therefore please elaborate on the mechanism of filling consolidation and also on the reason for a division between load-bearing and non load-bearing fill, since the dividing line was often very difficult to draw.

**Mr K. H. Brittain** (Chief Technical Adviser, Cement Marketing Co. Ltd) observed that much recent experience did not confirm that P.F. ash with the fineness of that described in §§ 3 and 4 (3,160 sq. cm/g) had appreciable pozzolanic action.

76. References 1, 2, and 3 (§ 13) did not give quantitative evidence of improved resistance to chemical attack such as would be required by engineers. Any qualities of this nature were certainly linked with the pozzolanic action known to be possessed only by fine P.F. ashes, and the physical characteristics of P.F. ash used in this type of investigation should be clearly documented. Long-term exposure tests were the normal means of proving resistance to chemical attack, and the procedure used in any such tests should be checked with national and industrial research organizations in the country concerned, so that the results would be comparable with those being obtained in similar tests.

77. Table 2 was interesting, first, because it was most unusual to obtain an equality in strength with a 20% replacement of the cement in such a short time as 7 days. The second unusual feature about the results referred to in Table 2 was that there was no apparent development of the pozzolanic activity at the later dates. The number of tests involved in the preparation of Table 2 was very small to enable considered conclusions to be drawn and the range of ash finenesses from 2,980 to 3,950 sq. cm/g was too great.

78. The results given in Fig. 1 were also a very useful contribution. As with the tests referred to in Table 2, the true water/cement ratio both with and without the P.F. ash addition must be considered. It was shown in § 21 that P.F. ash must have an interesting future which could be realized when the quality of ash could be controlled in practice as it had been in the experiments using Chocques Power Station P.F. ash, and provided such materials were not more expensive on the site than the cement they replaced. As shown by Fig. 1, it was true that at all ages the compressive strength increased with fineness of the P.F. ash but at 7 days, even with a specific surface of 9,000 sq. cm/g, or at 28 days with a specific surface of 5,000, the strength was far below that of the mix without P.F. ash. It seemed that until this degree of efficiency was attained the results reported by Allen[8] must be accepted as typical. Here, although the water/cement ratio had been reduced from 0·6 to 0·56 with P.F. ash, the drop in the strength at 7 days had been 27% in laboratory tests, and at 28 days 19% in laboratory tests and 24% in site tests.

79. The Central Electricity Generating Board should go to considerable efforts to improve the delivery arrangements, since P.F. ash was not convenient to handle. It was stated in § 39 that contractors would prefer to have P.F. ash already incorporated in cement. This was not the view of many users who would prefer first to be able to vary the quantity of P.F. ash in the mix to meet the particular circumstances, and, secondly, not to be involved in haulage costs of P.F. ash to a cement works or expensive haulage of P.F. ash in cement lorries from the works to the site. P.F. ash was only

likely to be used where concrete control was good, and when a contractor had paid for control he would want the same flexibility in mix design as did the supplier of ready-mixed concrete.

80. If a P.F. ash was to be used specifically as a pozzolana it must be tested for pozzolanic activity and shown to possess not less than a certain degree of pozzolanic activity. A test for this was on the way and there was already a test which had been agreed by the International Standards Organization.

**Mr A. W. Hill** (Deputy Director of Research and Technical Services, Cement and Concrete Association) said that because of the differences in specific gravity of P.F. ash and cement the specific surface expressed in terms of sq. cm/cu. cm might be a more appropriate basis for comparison in some conditions. However, the specific gravity of P.F. ash was more variable than that of cement, so that a specification limit for specific surface by weight would be variable for specific surface by absolute volume. It was noted that the specification values proposed in § 5 for sulphate and specific surface were not consistent with the corresponding values recommended in §§ 21 and 23.

82. It appeared that § 13 required considerable qualification in regard to the resistance to chemical attack. When concrete was attacked by sulphates there could be two disruptive effects; first, that due to the reaction between tri-calcium aluminate hydrate and sulphate ions forming calcium sulphoaluminate, and secondly, that due to the reaction between sulphate ions and calcium hydroxide to form calcium sulphate. The latter reaction would not take place if the sulphate was due to gypsum or calcium sulphate deposits. Sulphate-resisting Portland cement was designed to have a low tri-calcium aluminate content, so that the susceptibility to the first form of attack was reduced. Some of these cements also limited the tri-calcium silicate, so reducing the amount of calcium hydroxide released during the hydration and thus providing protection from both forms of attack. P.F. ash, by reacting with the calcium hydroxide released during hydration, could therefore reduce the second form of attack arising from sulphate other than calcium sulphate on a concrete made with cement other than sulphate-resisting. Generally, it would be more satisfactory to use a sulphate-resisting cement.

83. The rate and quantity of lime taken up also depended upon the temperature and the quality of fly ash, and considerable variation had been found in tests. The Paper did not make it clear that chemical composition was no guarantee of pozzolanic activity. The recent Paper by Simons and Jeffery[24] showed that the overall chemical composition varied from particle to particle and that pozzolanic activity was more related to the glass content, which was, in turn, related to firing temperature.

84. The information given in Table 2 on the early gain of strength of concrete containing P.F. ash needed further verification, since eight results provided the average for the P.F. ash, while the control was based on only one test. Plotting the results on a log-time scale gave a very unconvincing comparison. It was difficult to assess the adequacy of the experimentation in references 4 and 5, since so little work was reported, but an explanation of the apparent rapid gain of early strength reported in § 17 might lie in the degree of experimentation employed.

85. In § 43 the Author claimed that the addition of 10% of P.F. ash enabled the cement content of stabilized "aggregate" to be reduced from 10 to 5%, thus saving *1s. 5d.* per sq. yd. No mention was made of the strength which was required. An as-raised gravel or crusher-run material would not require more than 5 or 6% of cement to meet the Ministry of Transport requirement for cubes compacted to, or corrected to, the dry density obtained in the base to reach a 7-day strength of between 500 and 1,200 lb/sq. in. The addition of P.F. ash in such a case could be unnecessary.

86. P.F. ash had not been used to any great extent in roads because of the importance of obtaining the required strength at 7 days or less, so that the work could be opened to traffic. It could, of course, be used as a filler to improve the grading of a material.

**The Author,** in reply, said that he proposed to divide his reply into two parts.

*P.F. ash as fill material*

88. Mr Raymond's statement on publication of the results obtained at the Royal Technical College, Salford, was very welcome because such information was urgently needed.

89. The remarks on hydraulic placing, referred to by Mr Edwards, had been prompted by investigations into a case very similar to that quoted. It had been found in that instance that while the top 3 or 4 ft of P.F. ash had consolidated satisfactorily the underlying layers had remained in a semi-liquid condition. This would have been a serious matter in the case of a load-bearing fill.

90. There was no doubt that there was still a good deal to be learnt about filling techniques when using P.F. ash, particularly when hydraulic placing was under consideration. In order to expedite progress in this field the Central Electricity Generating Board had joined with the South of Scotland Electricity Board in sponsoring a programme of research at Glasgow University.

*P.F. ash in concrete*

91. The Author's purpose in drawing attention to the results given in Table 2 and others obtained elsewhere was to show that the incorporation of P.F. ash did not necessarily involve a lower 28-day compressive strength. It was not intended to imply that the simple partial replacement of cement was the only or the best answer. Examples of what could be done with appropriate mix design techniques had been given by Lovewell and Washa[25] in the U.S., and Jackson and Goodridge in Britain. The whole question of mix design was being investigated for the Central Electricity Generating Board by Glasgow University and it was hoped to publish the results when available.

92. The Author agreed with Mr Brittain that P.F. ash in bags was not a very convenient material to handle. For this reason bulk handling, which with modern equipment was perfectly satisfactory, was being increasingly used. The statement in § 39 that contractors would prefer the ash already incorporated in cement was based on remarks made by members of their staffs. Mr Brittain's observations showed that there was a wide range of views on this topic.

93. Referring to Mr Hill's comments it must be realized that the limits given in § 5 were intended to apply to all uses of P.F. ash as a raw material. Those in § 21 and § 23 were somewhat narrower and restricted to its use in concrete. Mr Hill's remarks on resistance to chemical attack were of great interest and again more experimental work would be useful. The Author understood, however, that there were differences of opinion as to what constituted a satisfactory test of this property.

94. With regard to the stabilized road base at Rugeley Power Station, it must be realized that this was the first job of this type and that the proportions of cement and P.F. ash had been kept on the conservative side.

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