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DISCUSSION

Results of a thermo-couple study in mass concrete in the Upper Tamar Dam

M. R. H. DUNSTAN & P. B. MITCHELL

Mr Mitchell

The Paper is concerned with large pours in mass concrete dams, ways and means of preventing cracking, speeding up construction and reducing costs, and possible future improvement in concrete dam construction.

93. Since 1945 our firm and its predecessors have been responsible for the design and construction of over 30 dams in the UK, of which about half were earth or rockfill and half concrete, and certain trends have been noticeable in recent years. The proportion of earth and rockfill embankments to concrete dams is increasing. One reason is that the sites now being developed are often less favourable to concrete dams, and another that the cost of earth and rockfill has not increased as rapidly as the cost of concrete, mainly because of the availability of larger and more efficient earthmoving and compacting plant.

94. Although some years ago we were able to get low-heat cement for the Lamaload buttress dam at Macclesfield, it is now difficult to obtain moderate heat cement in the UK and this fact, together with the traditional methods of construction has led to more cracking than in the past.

95. There seems to be a tendency to think that the British climate is so bad that there is no need to worry about cooling aggregates and curing concrete, but the results of this study indicate that more attention should be given to it.

96. The technology of mass concrete construction has not kept pace with that of earthmoving; it seems strange that there has not been any real change in the bucket-by-bucket method of moving mass concrete into place. Concrete dams are still constructed by the traditional methods of lifts and blocks, with numerous construction and contraction joints, which are expensive and slow down the rate of construction. In these days of inflation, with high labour costs and high interest rates, financial considerations are very important. If a dam can be built in three years instead of four one can probably save at least 15% in cost.

97. Others have suggested treating concrete in gravity dams as a fill material placed in continuous layers across the valley, using earthmoving and compaction plant. Gentile has described[22] the Alpe Gera Dam in Italy where concrete was placed in layers 0·8 m thick, being brought to the site in large dump trucks, spread by angledozers and vibrated by batteries of vibrators fixed on tractors. Each layer was cleaned by machines fitted with brushes and air and water jets, and the contraction joints were cut afterwards by special sawing machines. Such methods could be used on medium sized dams in the UK.

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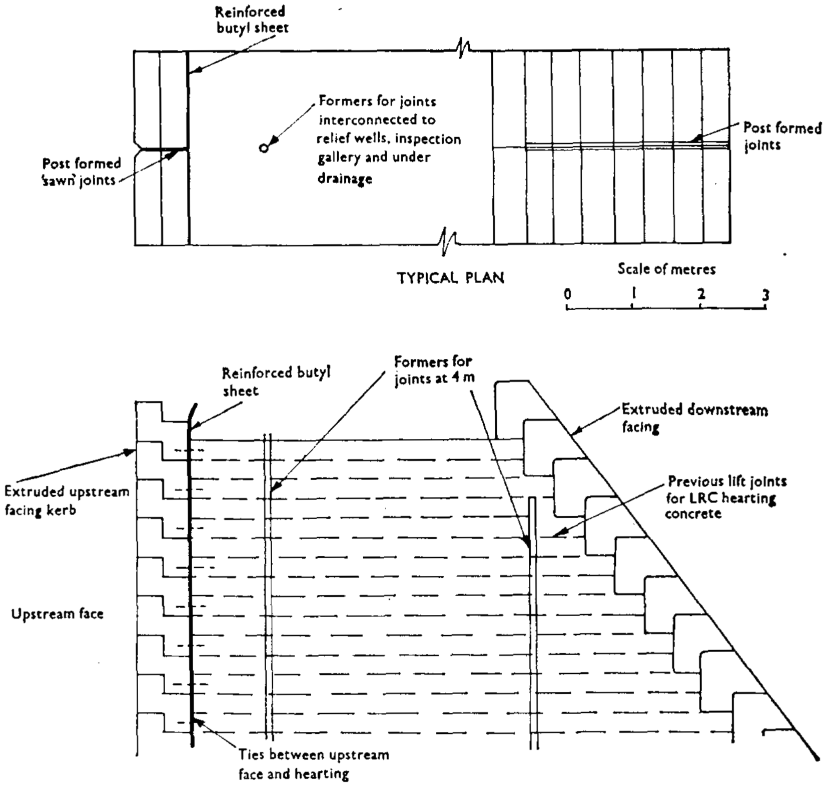

Fig. 19. Proposal for placing concrete in horizontal layers using extruded 'kerbs' as in situ shutters

Mr Dunstan

The modified specification detailed in the Paper will make a reasonable saving but I feel that a total change in the constructional procedure of dams could make an even greater saving. Various suggestions have been made in the past to reduce the cost of concrete dams. Some suggest the use of precast panels as in situ shutters and others the use of dry lean concrete.[23] Precast panels have the advantage of reducing the shuttering problems and providing excellent insulation for the hearting concrete. They also almost eliminate the finishing of the final surfacing of the dam. The major problem seems to be the sealing of the joints between the panels. Precast forms have, in fact, been used on a number of dams in Russia but the different materials/labour costs relationship seems to make them less economic in the west.

99. A real saving could be made if the joints between leading and following monoliths could be eliminated. Speaking purely on the thermal problem, these could be eliminated by reducing the placing temperature. The actual isotherms in a leading and following monolith with a fairly standard placing temperature of 17°C have been compared with the estimated isotherms in the same concrete with the same depth of pour if the lift was placed horizontally without joint shutters and the placing temperature

reduced to 10°C. It is likely that the thermal movement would be considerably less with the latter method. Consequently, it seems logical to place concrete horizontally, right across the valley with a low placing temperature. If the thickness of the pour was limited to 600 mm and the cement content reduced to say, 120 kg/m^3, the temperature increases would probably be reduced to not more than 4 degC. One of the additional advantages of placing concrete horizontally is the constant rate at which the concrete has to be produced throughout the contract. At the bottom of the valley the lifts are wide but short, and at the crest of the dam they are narrow but long. Taking the cross section of the valley at Meldon as fairly typical (it is in fact probably on the steep side for Britain) the rate of placing of the concrete would vary less than 30% above the average rate during the great majority of the contract, only falling off in the last 20% of the time. The concrete could be compacted by either tractor mounted vibrators or ideally by vibrating rollers.

100. A small trial bank of low slump concrete has in fact been compacted by vibrating roller under the spillway chute at Tims Ford Dam in the USA. This was a rockfill dam which had all the necessary equipment available for adequate compaction of this type of concrete. The results of the tests on the trial bank seem to be very promising, the strengths and densities being comparable with those obtained with normal mass concrete dams.[24]

101. If joints were considered necessary, they could be induced by formers. This in fact, happened by mistake on the Upper Tamar Dam. The pressure relief wells were extended up to the dam to within 2–3 m of the crest. At this level, the dam was about 5 m thick and the formers of the relief wells induced cracks through the blocks from the upstream to the downstream face.

102. The problems of the shutters could possibly be overcome by the use of extruded kerbs. The cross section of the dam could be as shown in Fig. 19. A waterproof membrane possibly consisting of reinforced butyl rubber, could be cast in just behind the upstream facing kerb. There would have to be some form of tie between the kerbs and the hearting concrete which could be placed when the concrete in the kerbs was green.

103. Two contractors have made estimates of the savings that could be made by the modified specification as detailed in the Paper and by the horizontal placement of concrete. These have been compared with the standard specification which has been used at the Upper Tamar, Meldon and a number of other dams. The saving for the modified specification is in the range of 5–10% and with the horizontal placement of concrete between 20 and 25%. These figures include an allowance for excavation and the periphery reinforced concrete works. The saving on the dam itself is rather more, up to 35%. A further financial benefit would be the considerable reduction in the construction period. A typical 55 m high dam could be constructed in 18 months as compared with the 2½ years normally taken. Hopefully, this could make concrete dams rather more of a front runner as opposed to the 'poor relation' they seem to be at present.

Mr M. F. Kennard, Rofe, Kennard & Lapworth

The work described was undertaken by Mr Dunstan as part of his normal duties as Resident Engineer, and was not a special research project, with a research budget and a research timetable. As a result of that approach it has been possible for the Institution to publish this work within two years of it being carried out, which is unusually early.

105. Both Authors have mentioned the change in cement over the years. This is very important; part of the problem has been that a practice has grown up in the UK based on a very large number of concrete dams, especially the North of Scotland Hydro-electric Board's dams in the 1950s, which has been applied in certain cases to recent dams, and cracking problems have occurred. This is because ordinary Portland cement these days is not the standard cement it used to be. BS12 for ordinary cement does not have an upper limit to the fineness, whereas rapid hardening cement has a higher fineness, and the current OPC is virtually a rapid hardening cement. This has

not been publicized, because the cement industry is not really interested in mass concrete dams despite the large amounts of cement that are used. Whereas in the past one had a cement which was satisfactory, this is not so today. This is shown by the temperature rises which have been quoted. Mr Dunstan mentioned the Mullardoch Dam in the 1950s, and based on readings which I took myself, the maximum rise was less than 25°C, yet nowadays there are figures of, at Cow Green, 26–30°C, at Meldon at one time 42°C, at Tamar 32°C, etc. A great deal of this is due to the cement, and this is why certain practices which have been used in the past are now causing some problems.

106. I am convinced that if BS12 was adhered to as was intended when it was drafted, a great number of these problems would not exist. It would be interesting to have the cement manufacturer's views.

107. I think that concrete has now priced itself out of the market for dams. The increases since 1973 have been so tremendous that any economic studies comparing concrete dams with, for instance, rockfill dams, will nowadays show a strong economic advantage in favour of the latter.

Mr J. D. Llewellin, W. & C. French (Construction) Ltd

The business of recommendation for the specification is very much my concern as a contractor's engineer. In Fig. 18 the maximum Portland cement content and maximum exposure times are related to the lift depth in a manner which would be entirely suitable for inclusion in a contract specification. Obviously a tendering contractor can weigh up local resources and decide upon his method with a greater degree of both freedom and certainty at the point of tender. These are the two ingredients of genuine economy.

109. But the same cannot be said of the Authors' remarks about non-standard test cubes (the 250 mm, 90 day test) or the level of PFA replacement found to be appropriate. These are matters which can be determined only by a programme of tests which it is quite unrealistic to expect a contractor to undertake during the tender period. Here the Engineer must investigate and decide firmly what is required, or provisional quantities must be allowed.

110. Turning to the size of aggregates, my firm can point to a very successful use of large aggregate on the Rochon Dam in the Seychelles, using a hand-placed 300 mm aggregate bound in a matrix of vibrated 40 mm concrete. About 30% of the total mass was of the large stone. This 'gap graded' concrete was, however, specially bespoke for a Third World labour-intensive scheme. Machines do not like large aggregates: mixers do not like them and conveyors do not like them, and, let us face it, neither does the industry which would have to supply them. The essence of the matter is insensitivity to the idea of stability of granular mixtures which is often encountered among people who do not actually have the responsibility of handling these materials and coping with the problems of segregation.

111. Air entrainment should be used. The concrete in the Seychelles would scarcely have been possible without it, since the fine aggregate was of a coral sand of extreme harshness. The Tamar concrete would have been the better for it. A level of 5% ± 1·5% should be specified.

112. The specification of concrete density is a mistake, in this context, since it depends principally on specific gravity of the local mineral and can operate very restrictively, for instance by preventing the use of entrained air. All that need be said is that the aggregates must be sound and the concrete has to be fully compacted.

113. The specification of water:cement ratio is also a mistake, not only because it is difficult to define and measure, but also because unreal values are usually laid down. Grade F concrete at Tamar is not likely to have had a water:cement ratio of less than 0·80, but the Authors in § 79 suggest that it should 'certainly not be in excess of 0·60'. Why not? The business of permeability should be kept in perspective and scale. A concrete that never dries never shrinks. Perhaps there is a virtue in porosity. The leaks and marks illustrated are not caused by this porosity, but by cracks or failures in compaction.

114. Some consideration has been given in the Paper to curing. In the end, Polythene sheet is recommended and where insulation is required, sand. Experience with large cement rich basement pours, where these problems present in their most severe form, suggests the use of ponded water, the top surface being flooded for a few inches. At Tamar the sloping joint prevented this, and I wonder whether this is really necessary.

115. I have worked out a table (Table 3) showing the difference between the Tamar grade F concrete, used for the hearting of the dam, and a typical rolled lean mix concrete that might well be used instead.

Dr R. D. Browne, Taylor Woodrow Construction

It is not only in the case of dams, but in other applications in construction that this early heat gain problem emerges, for example swimming pool walls. Figure 18 is of particular interest, since it provides limits to lift height, cement content and rates of placing

Table 3. *Contrast between Tamar grade F concrete and a rolled lean mix concrete*

	Grade F	Rolled lean concrete	Notes
Cement quantity kg/m^3 m^3/m^3	138 0·0439	91 0·0289	Much lower cement content of lean mix. Greater replacement by PFA likely to be possible
PFA quantity kg/m^3 m^3/m^3	40 0·0193	26 0·0127	
Water quantity kg/m^3 m^3/m^3	142 0.1424	134 0.1336	Lower water content of lean mix, in spite of higher w/c ratio
Water:cement ratio	0·80	1·14	
Air assumed left in (i.e. non-compaction) m^3/m^3	0.0200	0.0300	
Air+water volume m^3/m^3	0·1624	0·1636	Very similar
Aggregate quantity kg/m^3 m^3/m^3	2052 0·7744	2109 0·7957	Lean mix better
Aggregate/cement ratio	11·5	18·0	
Concrete density kg/m^3	2372	2360	Very similar
28 day adiabatic rise (§23), deg C	25·5	16·9	Much lower for lean mix
Mean 6 in. cube strength at 28 days, MN/m^2	15	25	Lean mix stronger

Note: Assumptions generally as in Paper but with the following in addition

(a) aggregate mean specific gravity 2·65
(b) concrete specific heat 0·239 (see § 23)
(c) PFA contribution to heat quantity, 20% of cement (see § 69)
(d) Water: cement ratio grade F concrete, 0·80
(e) optimum moisture content, lean mix concrete, 6%
(f) same proporation of PFA replacement

In every case quantities are in kg or m^3 of absolute volume per m^3 of compacted concrete.

identified from the work. It could well provide a basis for design of concrete mixes and concreting procedures.

117. Although my company has not as yet been involved in dams, we have for the last ten years been instrumenting concrete pours to study early age heat of hydration effects on cracking, initially in the construction of thick walled, concrete pressure vessels for nuclear reactors, both in the UK and overseas and, more recently, for a range of applications, including one of the 80 000 m^3 anchor blocks for the Humber Bridge.

118. The major difference between our approach and that of the Authors is that we measure the strain development in the concrete from casting as well as temperature. To do this we use a specially developed vibrating wire strain gauge which is flexible enough to pick up early strain changes after the concrete has hardened, yet robust enough to withstand the rigours of concrete placing. From such measurements, the degree of restraint to free thermal movement of the concrete during the heating and slow cool-down is determined at different locations in a lift. When such restraint values are multiplied by (*a*) the predicted temperature change at specific locations, (*b*) the relevant value of the effective elastic modulus, including creep, and (*c*) the thermal expansion coefficient of the particular concrete, the stress build-up with time can be predicted. When this is then related to the tensile strength development of the concrete, the likelihood of cracking can be assessed.

119. Figure 20 shows the correlation obtained between predicted and actual measured values in situ. This provides a mean of calculating the way stress and strain build up, and possibly how cracking occurs, before casting the structure.

120. I do not think the Authors have as yet found the cause, other than in very general terms, for the long-term cracking. Obviously, it is related to the locked-in tensile and shear stress resulting from the long-term cooling of pours combined with seasonal thermal movements of the dam. But the specific mechanisms appear still to be not fully understood. Such an understanding could possibly provide a valuable clue to crack prevention in the future. I should therefore like to ask the Authors whether they considered installing strain gauges in the Tamar Dam. Such measurements in other dams could well provide quantitative values for the degree of restraint causing both the vertical and horizontal cracking with time. Also, the maximum temperature rise can be readily predicted for specific lift situations. My firm uses a finite element heat diffusion programme based on the measurement of the heat output for the specific concrete mix.

121. The heat output is measured by casting a 300 mm block of concrete, heavily insulated to produce an almost adiabatic temperature rise. Would not such preliminary heat flow calculations, using the temperature characteristics of pretested mixes, be of value in checking out potentially vulnerable casting situations?

122. Finally, I should like to ask a few detailed points. All the data on temperature increase in the Paper relate to PFA mixes. Were any non-PFA controls tested? No actual temperature–time curves are presented. Perhaps the time taken to reach maximum temperature may be related to the occurrence of cracking both in the short and the long term, in terms of the amount of creep relief which can occur during this period.

123. With reference to Fig. 6, the increase in temperature rise with placing temperature is not surprising. Our work has shown an increase from 42°C to 50°C for an increase in placing temperature from 5 to 25°C for a cement content of 400 kg/m^3. However, we have not observed the sudden increase at a placing temperature of about 18°C. Could this not be due to the PFA reaction being suddenly accelerated at the higher temperatures?

124. It is differential strain which results in early cracking and as such is proportional not only to temperature, but also to the coefficient of expansion of the concrete. Was this measured for the mixes described in the Paper?

Mr C. D. Crosthwaite, Freeman Fox & Partners

Since 1950 I have been concerned with about ten concrete dams and I have examined a

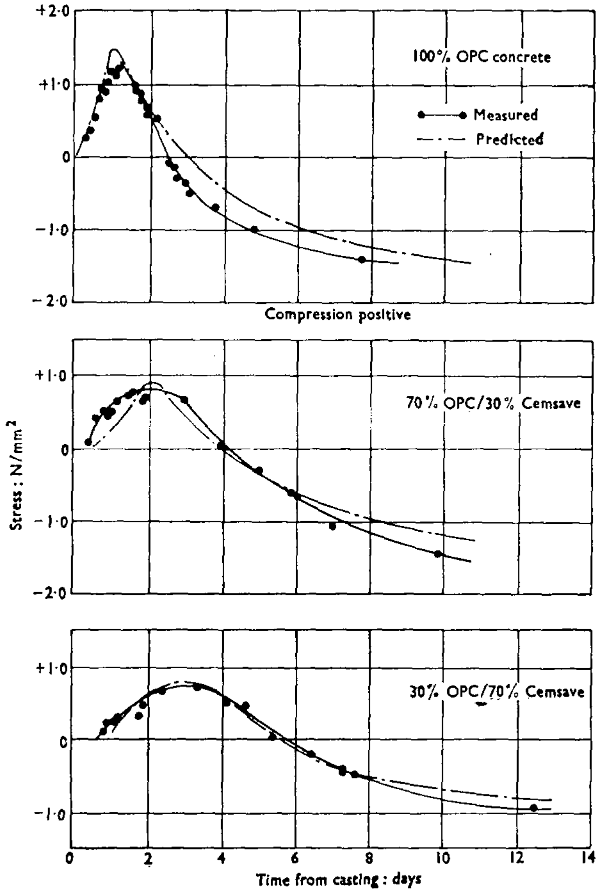

Fig. 20. Comparison between measured and predicted 'locked in' stresses in heavily restrained mass concrete [Hessle anchor block, Humber Bridge, Freeman Fox and Partners].

very large number at home and abroad. So far I have not seen a single one which does not exhibit signs of cracking, seepage, efflorescence, etc. with the exception of one or two in Hong Kong where, rather as in the Seychelles practice, a mass of boulders surrounded by concrete was used. This produces no definite constructional or contraction joints. What must be avoided are the horizontal efflorescent seepages which are almost universal. At one time it was thought that blast furnace cement would be the answer. In 1974 I visited the Bor les Orguos Dam in the Massif Central, built with blast furnace cement. This looks just like any other dam except that it is of a darker colour. The horizontal and vertical cracking and seepages are no fewer.

126. When building dams in Wales in the early 1960s, my firm tried very hard to get low heat cements by using coarse ground cements which did not quite come up to expectations. However, we did relate lift height to heat of hydration and accepted a 2·5 m

lift with a lower heat of hydration cement, whereas otherwise we would have insisted on 1·7 m. But there are always problems with workability of the mix, and whatever tests may be applied in the laboratory, it is very hard in practice if the contractor points out that he cannot get a really workable mix unless he increases the water:cement ratio or puts in more cement. I presume that the low cement mix which the Authors have been using on the Tamar Dam did come up to the Contractor's expectations and requirements in that respect because the implication is that a contractor should be allowed in effect to design his own mix. But there must be a strength requirement, and a certain weight/m^3 requirement.

127. The cement manufacturers are interested in selling cement, and their material is far and away stronger than it need be for concrete dams; but once the cement content is reduced it is difficult to get a sufficiently workable concrete.

128. The most important problem at present in the concrete dam world is how to produce a non-leaking concrete dam without efflorescence and unsightly cracking. It may be that the Authors' proposed method will work, but it has not yet been used to any significant extent.

Mr P. L. Owens, Pozzolanic Pty Ltd

The wider use and acceptance of fly ash as a pozzolana in the UK has been limited because there is no suitable materials standard such as ASTM C618 on fly ash and raw or calcined natural pozzolans for use in Portland cement concrete. Those wishing to use fly ash as a pozzolana have to use BS 3892 which is inadequate. However, before fly ash can be accepted as a pozzolana, certain criteria have to be established, and here the Authors' observations are of value.

130. Referring to § 62 dealing with strength, for equality of strength, for instance, based on 200 kg/m^3 OPC at 28 days, the proportions can range from 50 kg/m^3 fly ash and 175 kg/m^3 OPC (22%) to 200 kg/m^3 fly ash and 120 kg/m^3 OPC (37½%). Yet to take full advantage of the pozzolanic reaction with the same fly ash, say, at 180 days based on the same 200 kg/m^3 OPC, the proportions can range from 50 kg/m^3 fly ash and 135 kg/m^3 OPC (27%) to 200 kg/m^3 fly ash and 85 kg/m^3 OPC (70%).

131. As to § 68 on water requirements, for equal consistency the water requirements are lower with fly ash than without. In fact, depending on the original water demand of the plain concrete, water reductions of between 15 and 35 litres/m^3 can be obtained. Leaner mixes, particularly with less than 200 kg/m^3 of cement (Portland cement and fly ash combined) give the greatest water reductions.

132. The effect of differences in colour of fly ash has traditionally been attributed to inefficient combustion of bituminous coal fuels and coarse particles. This is in part correct, but discoloration also originates from the practice of burning heavy fuel oils concurrently with the pulverized coal. Under certain furnace conditions, the oil produces minute carbon black particles, which cause severe ash discoloration not normally discernable by the accepted loss on ignition test. This undesirable form of carbon, which may only represent 0·25% of the loss on ignition, not only severely retards setting and early hardening, but discolours the finished surface as well.

133. On fineness of ash, specific surface area is misleading: it does not control or affect the maximum particle size, which is the overriding factor enabling interstitial void filling. Therefore, it is more expedient to exercise judgment of fineness by the quantity retained on the 45 μm sieve, which is the size that has been adopted by most international specifications for fly ash. Fineness is also related to pozzolanicity. Finer ashes (less than 10% retained at 45 μm) react exothermically, contributing much earlier to strength than do coarser ashes (between 20 and 30% retained at 45 μm). These coarser ashes contribute little to the early heat, but do not give such significant water reductions as the finer ashes. This goes a long way, we believe, towards explaining the effect shown in Fig. 6. As the temperature of the concrete rises at the time of placing, so does the ultimate temperature.

Mr E. M. Gosschalk, Sir William Halcrow & Partners

I should like to thank the Authors for publishing some very valuable data and proceed to disagree with their interpretation of much of it. However, most of my remarks relate to the construction of reinforced concrete buttress dams in the tropics, with thicknesses of section of about 1 m.

135. I have been investigating an Ambursen type buttress dam which was completed in the tropics in about 1930 and which displays a system of horizontal and vertical cracks. It is fairly clear that the initial cracking was largely attributable to a cement content of about 310 kg/m^3 resulting in a high temperature rise and cooling while the strength of the concrete was in an early stage of development. What is not clear is why the cracks have continued to develop in number and extent until the present time.

136. An idealized two-dimensional finite element analysis for the stresses resulting from water load, gravity and temperature on the downstream face showed that tensions are insignificant and compressive stresses are quite modest (Fig. 21). Stresses due to a temperature drop of about 20°C occasioned by the restraint on the upstream face due to an assumed cooling effect from the reservoir water are shown in Fig. 22. The anticipated tensile strength of the concrete at an early age would have been exceeded in the shaded areas and it can be calculated that the yield strength of the steel reinforcement would have been exceeded in an area in the bottom of the dam towards the downstream toe.

137. The analysis with restraint from the rock foundation seems to account fairly well for horizontal tensions which would, of course, give rise to vertical cracks. This is in contradiction to § 48 which postulates that restraint from old concrete or rock foundations causes horizontal cracks. I believe that the horizontal cracking may be accounted for by internal temperature differentials.

138. I do not think that high cement content produces inescapable thermal cracking. Other matters have to be considered. For example, in my experience, placing concrete in the tropics with cement content of about 325 kg/m^3, which is 80% higher than the limit suggested in § 37, has given rise to no problems, even though only modest precautions were taken to minimize the placing temperature of the concrete.

139. With regard to the placing temperature, I think it is a mistake to generalize on

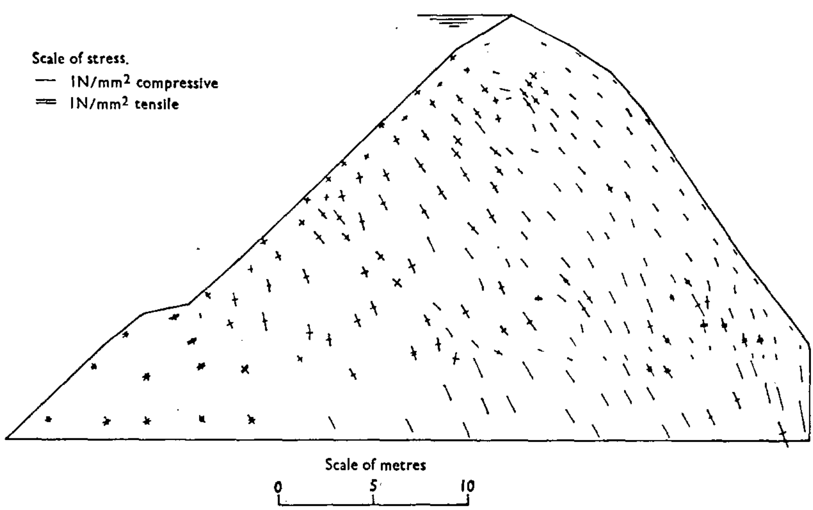

Fig. 21. Gravity and water load

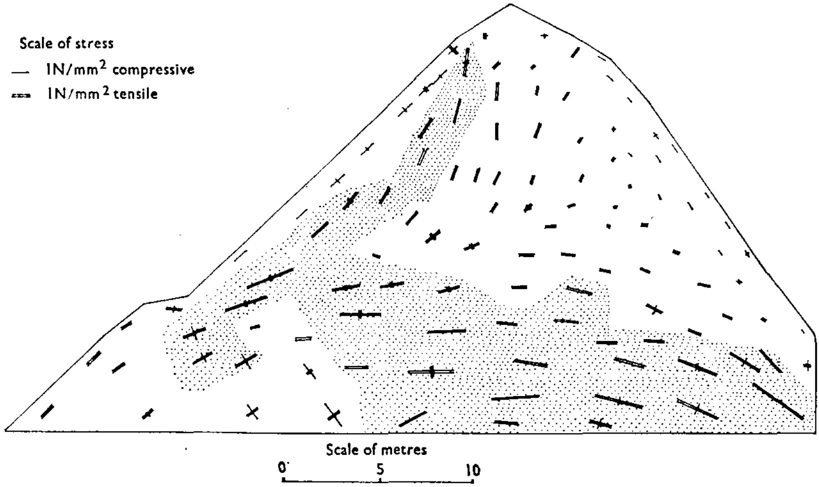

Fig. 22. Temperature decrease of 35°F

10°C as suggested in § 82. Again, no problems have been encountered in my experience in the tropics with placing temperatures of over 30°C, again with only modest precautions. The criterion should be to a much greater degree the range of ambient temperature that will be experienced and the control of concrete placing temperature should therefore be governed by the maximum range from the peak temperature reached within the concrete to the minimum temperature that will be reached under cold ambient conditions, related to the time dependent properties of the concrete while this temperature drop is taking place.

140. It seems that there is a contradiction in § 83 where it is pointed out that steel shutters are recommended to optimize cooling, and § 36 which recommends insulation. It would be interesting to know how the Authors reconcile these two suggestions.

141. It is relevant to point out that engineers are deluding themselves in talking about the compressive strength of concrete. The conventional so-called 'compression tests' do not measure compressive strength, but give some guide to shear strength and tensile strength depending on the size and shape of the specimen, and on the end restraints imposed by the testing machine. I believe that dams do not fail as a result of compression, and it is therefore fortunate that nothing is lost so far by failing to measure the compressive strength of concrete.

142. Fairly extensive inquiry has failed to find any record of failures of reinforced concrete buttress dams due to thermal cracking, although there have been several cases reported where cracks have appeared and strengthening measures have been carried out.

Mr B. Pattenden, Gleeson Civil Engineering Ltd

I have had the pleasure of working with Mr Mitchell on several mass concrete dams and have experienced his desire for co-operation between contractor and consultant in the interests of efficiency of construction which is so ably illustrated in this Paper. In order to improve the efficiency of the construction industry, this co-operation daily becomes more vital. One only has to visit a construction site and see the two ever-expanding vast office complexes with attendant car parks to wonder where the present contract system is leading us and whether nationalization will not deservedly overtake us both.

144. However, this does not mean that I agree entirely with the Authors as to the financial benefits to be derived from their recommendations. I do not feel qualified to comment on the effect on the suppression of cracking, but having built some eight mass concrete dams in the last 16 years I am in a better position to comment on the probable financial savings.

145. I have found that an aggregate supplier is not usually interested in large short-term projects such as a concrete dam, because the quantities involved are not sufficient to pay for the additional machinery required, and it interrupts the supply of his long-term customers in which he is most interested, since aggregate is often a limited wasting asset. Aggregates obtained and processed on site are similarly affected by the cost of the installation of machinery, and I consider if possible it would be more economical to design a mix to suit those types and sizes of local aggregate which are in plentiful supply.

146. This also applies to PFA, since usually in order to obtain adequate regular supplies one has to take what is available. As PFA is an industrial by-product it is difficult to enforce a strict specification.

147. I agree that the rate of construction is governed by the available plant, but the optimum type of plant is dictated by site conditions. Briefly, a narrow deep valley requires the use of a cableway: a cableway has a single hook carrying 10 t and this governs the rate of concreting. All the ancillary plant, planning, and progress has to start from this point, and whilst the greater permissible lift heights and the quicker turn-round of shuttering will make a contribution it will only be limited in degree.

148. Similarly, in a wider shallower valley derricks can be utilized, but again because of position and overlap usually only one derrick can be used at a time for concreting, with the same limitation on the rate of placing. Smaller low-height mass concrete dams can use mobile cranes for placing and the rate can then be speeded up, but the time scale and possible saving are relatively small. Of the eight mass concrete dams I have built, two used cableways, four used derricks, and two used mobile cranes.

149. In view of the difficulties likely to occur from time to time in the regular supply of materials and labour, it would be most unwise to plan on deep lifts and minimum exposure time, as I am afraid it would soon turn into half-lifts and double the shutter work, which would wreck the planned orderly progress that is so vital to economical construction. Moreover, it is no great financial advantage to a contractor to speed up the rate of construction beyond a certain limit if thereby he has expensive specialist machinery and technicians rendered idle awaiting another contract. For this reason it could be more economical to design mass concrete dams which utilise everyday normal construction machines, and this is why earth and rockfill dams now have a distinct financial advantage over mass concrete. Therefore the new method of construction proposed by the Authors could reverse this trend.

150. However, since my firm was one of those pricing the new method, I must utter a word of caution about the extent of the reduction in cost, since the geographical position, the topography and the general conditions of individual sites can, as I have previously stated, have a great effect on cost.

151. With regard to the new method, I am of the opinion that, owing to the short horizontal lengths of most dams in Britain, difficulties in orderly progress might be encountered on occasion by using such shallow lifts, and I would like to ask the Authors if it would be possible to use, say, 1 m lifts of lean mix concrete composed of on-site material, contained by in situ or precast concrete walls made watertight as necessary? Perhaps such a method would be a possible solution to the difficulties expressed by Mr Cuthbertson in his recent excellent paper on Megget Dam,[25] where I understand the local available stone is not suitable for normal concrete and also is not very good as rockfill.

Mr D. J. Coats, Babtie Shaw & Morton

Reduction in cement content in recent years has been quite significant. For instance, in 1955 the cement content in the hearting concrete for Allt na Lairge Dam was 225 kg/m^3

with 65 mm aggregate and an air entraining agent. In the most recent concrete dam with which I have been associated, the Bradan Dam in Ayrshire, the cement content in the hearting concrete areas is 117 kg/m^3 plus 58 kg, or 33% substitution of PFA, also with 65 mm aggregate. Use of PFA inhibits the effect of an air entraining agent, and it is necessary to use one or the other. My preference is to use an air entraining agent for the facing concrete to increase frost resistance and PFA in the hearting concrete. I should be pleased to have the Authors' observations because it is not clear to me if PFA and an air entraining agent were used together at Upper Tamar.

153. I was most interested in the comments on lift height and exposure time. However, if contractors are to be allowed some latitude in lift height in consultation with the Engineer, I commend careful specification regarding lift height, and the associated minimum and maximum exposure times allowed which can be insisted upon if there is failure to agree. The dams with which I have been connected have been at a higher elevation and therefore probably cooler temperatures than the Upper Tamar, and this may have assisted in the prevention of cracking which has not been a serious factor. However, I have been the victim of the fineness of cement, and although it has sometimes been possible to arrange for batches of less fine cement to be delivered to dams, there are problems when the wrong stuff arrives.

154. One form of cracking which the Authors have not specifically mentioned is the tendency for the corners of a lift to curl upwards. It is probably only a tendency rather than a significant feature, but it was particularly noticeable in two dams where, for particular reasons, the lift sizes were fairly modest from upstream to downstream, and the cement content was possibly high due to the large proportion of facing concrete. These dams were the Allt na Lairge Dam in Argyll, which has a thin section because it is prestressed, and the Lochinvar Dam in Dumfries which is reinforced.

155. Finally, I was most interested to learn that the Upper Tamar Dam has been designed to allow the height to be increased at some later stage by post-tensioning. Did this have any particular influence on the concrete design or block length?

Mr P. G. K. Knight, Central Electricity Generating Board

Available information on the use of air entraining agents with PFA is that, in such cases, the quantity of the former almost invariably has to be increased, sometimes quite considerably. There is no information to suggest that this is deleterious to the resultant concrete in any way.

157. My main point however concerns the dark coloured (almost black) PFA which appeared on this contract. At that time there were no similar reports from other contracts and I should like to know whether any investigation was carried out to determine the cause. Mr Owens suggested oil, but this does not square with the results of tests carried out by the Board. The lowest loss-on-ignition figure found so far for PFA containing oil (an extremely small proportion of that produced) is 6%, while the maximum figure for material supplied to this contract was 5·4%. Was the possibility of contamination during transport looked into?

Mr G. R. Curtis, North of Scotland Hydro-Electric Board

Since my Board has been mentioned a few times, it might be useful to give a few details about its dams and their behaviour over the decades.

159. Heat reducing cement of one type or another has been used in eight of the Hydro Board dams. The basic reason was economy, but the secondary reason has been the reduction of temperature. This allowed 3 m lifts in the Giorra Dam. This was done successfully although there was, I believe, a temperature rise of 44°C above ambient, which may not be comparable with rises given in the Paper. Thermometers are used for the measurement of concrete temperatures in four or five dams. In the hearting the annual cyclic range is usually 10°C. It will be less in the case of a mild winter, and more for points near the surface.

160. Not much has been said about the length of pour, except that it can perhaps be infinite. It is our experience that if the length of a block exceeds 13–15 m, cracking is much more likely, usually at the half point.

161. Precast concrete panels were used in two dams because there was no timber for shuttering and they were successful. There was one dam where the consultant reckoned there might be seepages between blocks so drains were installed inside the downstream face. The drains took the water and the face remained perfectly dry. This is not applicable to horizontal lift joints.

162. How serious is efflorescence? It will be serious at the parts of the dam where tension occurs but at a vertical joint or on a compression face, to what extent does it matter? Cracks usually become more numerous over the first few years due to creep properties. Thereafter they tend to be sealed with the free lime, some of which is redeposited on the downstream face. The only cases where there has been no sealing action in this sense have been at Cluanie and Loyne dams where wet ground blast furnace slag was in use.

Mr B. G. Cox, Binnie & Partners

The rolled lean concrete proposal and ideas about incorporating earthfill methods for mass concrete placing raised interesting thoughts about future developments of methods that have already had some specialized use. The 'virtue of porosity' was mentioned by Mr Llewellin, no doubt visualizing the design problems of rolled lean concrete embankments.

164. The Authors have sounded a warning that any tendency to learn to live with cracks needs to be resisted. Engineers must endeavour to produce concrete free from cracks and the subsequent efflorescence that mars the appearance of many fine dams. This has been a problem for many years and while ample advice is available on methods of crack repair, more thought is needed about preventative measures.

165. Cracks can be controlled and it was particularly interesting to note § 59 quoting American practice. I have had experience of large concrete pours placed by American contractors in a sub-tropical area with British and American design collaboration. About 16 ha of spillway chutes and stilling basins with slabbing 1–2 m thick were designed with reinforcement to resist temperature and shrinkage stresses, and placed generally in 7·6 m square slabs with no significant crack problems. Two abutments containing about 250 000 m^3 of mass concrete with maximum height of 55 m were constructed on either side of the gate structure, in 14·6 m wide blocks and 1·5 m high lifts. Inspection several years after construction did not reveal any cracks in the blocks.

166. On the downstream battered face, which was south facing, horizontal construction joint partings were noticed at lower levels, a feature that appears to have an analogy with the curling of drying leaves or silt layers. Efflorescence was not evident at these joint partings and its absence in these arid conditions gives rise to the thought that some of the efflorescence illustrated on British concrete dams may be related to leaching action when acidic rain water collects in these crevices.

167. The specification required cooling of concrete below 21·2°C and the American contractor, who was experienced in cooling concrete to meet US Bureau of Reclamation and Corps of Engineers specifications, provided a cement cooling silo, dowsed coarse aggregates, and mixed concrete with refrigerated water. With ambient temperatures up to 40°C an artificial differential was obtained that appears to be of the same order as that proposed by the Authors when using simple cooling methods in a hot British summer.

168. Successful placing of blocks up to 600 m^3 appeared in a large part to be due to efficient cooling measures, but a batching plant with 250 m^3/h output was able to maintain a pouring rate of over 90 m^3/h and ensured that pours were completed with minimum disturbance to setting cement. Adequate vibration and use of water reducing set retarding additives also appeared to be significant factors in crack elimination.

Mr R. V. Ash, South West Water Authority

Applying a known theory of cracking together with one of the points made in the Paper, I would not be surprised to find a vertical crack opening up overnight in the unprotected outer faces roughly in the middle of a 14 m wide monolith. This is what may have happened, with the formation of thermal cracks in the outer faces of the stronger facing concrete progressing inwards until eventually the strength of the remaining facing concrete and the heart concrete was insufficient to resist the tension induced by the greater thermal differential at night. The use of a construction width of about 6 m is common practice in the other fields of concrete construction and this is usually by design to prevent cracking. I favour lifts greater than 1·5 m and would suggest this as a consideration, in conjunction with a monolith width of about 6 m, as an economic basis for quicker crack-free monolith dam construction.

170. In this context I also suggest two further alternative measures for consideration: (*a*) the provision of steel reinforcement at each outer face to resist cracking, similar to that provided at the crest of the spillway; (*b*) the provision of a groove or other means of initiating and directing a thermal crack and incorporating a facility for its eventual sealing; this would look tidier than any 'after the event' remedial work.

171. I am happy to see the results of PFA replacement of 40–50% and would agree with all the points made about reduced water:cement ratio and temperature, strength and workability. However I would be a little apprehensive, at this time, about the use of additives with PFA.

172. I, too, have been plagued with concreting in high ambient temperatures, but for me the critical problem was the change in the condition of the concrete during the period from the discharge of the batcher to the time of placement, speed being the essence here. I would advocate shading with insulated covers for concrete aggregate rather than the spraying of water to reduce the initial mix temperature, as the additional water would make the control of the water:cement ratio more uncertain, particularly with angular aggregate.

173. The Upper Tamar Dam and the Meldon Dam were constructed for the former North Devon Water Board and are now the responsibility of the South West Water Authority as is the Siblyback Dam. The investigations and construction changes of the Upper Tamar Dam were carried out with the approval of the former Board and the Authority. The trials and preliminary works for the Wimbleball Dam were also carried out with the approval of the Authority. It is evident from the Paper that the Authority's Wimbleball Dam will benefit from the work and conclusions described, and so too, it is hoped, will the other regional water authorities and other sponsors of any future mass concrete dam construction.

Mr R. A. Reader, Rofe, Kennard & Lapworth

I am at present Resident Engineer on the construction of Wimbleball Reservoir which is a buttress dam. Many of the suggested methods for reducing cracking in gravity dams mentioned in the Paper also apply to buttress dams, but of course, the method of placing concrete in horizontal layers like earth does not. Whether this will make buttress dams wholly uneconomic I would not like to say.

175. Many speakers have referred to the workability of lean concrete. I believe the water:cement ratios for dam concrete given in many past papers must be wrong. Even when allowance is made for different aggregates the concrete mixed to these published specifications is impossible to place. The water content may have been that given to the batching plant driver, but it certainly is not the water content of the concrete actually placed.

176. The remarks in the Paper about the availability of aggegates seem to me optimistic. Planning restrictions on quarries and the routing of lorries are likely to make the choice of aggregate very limited. This aggregate may not be of very good

quality or available to a constant grading without excessive waste. The concrete mix cannot be too critical therefore, but should be designed to accommodate these variations. Otherwise the Resident Engineer will be frequently called upon to make changes in the mix because it cannot be properly compacted.

177. I am interested to see that horizontal cracks have occurred in so many dams, probably because lifts of concrete have curled up at the corners. Vertical cracks can be seen more easily and can be sealed by normal methods, but horizontal cracks are often obscured by rough lift joints, give a much shorter leakage path around the contraction joint water bars and are much more difficult to seal. This leakage is usually taken away unnoticed by the internal drainage system of the dam. If unnoticed, perhaps it does not matter, but surely engineers should produce dams that are watertight. I do not agree with the Authors that horizontal cracking can be entirely overcome. A lift left exposed will curl up at the corners and no precautions taken with the subsequent lift will close the resulting crack. As grouting equipment is usually available on concrete dams it seems essential to design them so that the structure can be easily grouted after construction to seal horizontal cracks.

Mr J. E. Gray, Institute of Technology, MARA, Selangor

The Authors give valuable recommendations about vertical lift depth and exposure time, which conflicts with many older specifications. Such large pours are rare, and it is to be hoped that similar information will be made available by those responsible for other schemes. What would be the Authors' reaction to the idea of a steady pour, using climbing formwork? This would give the ideal against their criterion of minimizing vertical temperature discontinuities. To ensure continuity of concreting would require a rate of pouring only slightly greater than that indicated by the upper end of Fig. 18 ($2\frac{1}{2}$ m in 5 days). Such a rate should be feasible at least in the narrower upper section of a 'gravity' dam.

179. If pouring were to be interrupted, how could it be recommenced? An answer is given in § 81 where the 'normal lift height' is definable. To recommence a continuous pour one might suggest a series of small lifts at three-day intervals.

180. Although it is mentioned that Tamar Dam was cast in blocks 11 m to 13·75 m wide (§ 1), horizontal dimensions are left out of the discussion and recommendations. Vertical joints would presumably be designed as complete discontinuities in the concrete apart from compression at shear keys, with waterstops near the upstream face. If large and rapid vertical lifts are adopted, causing large horizontal temperature movements as well, would short gaps between blocks be desirable, only to be filled after most temperature movement has stopped? This would of course almost double the cost of vertical joints, but the main blocks could be longer. Otherwise, what would the Authors recommend as a maximum horizontal dimension?

Mr J. E. Smith, Engineering and Resources Consultants

The Authors have presented a very interesting paper which gives an enormous amount of data on one dam in particular and collates data on other British dams and overseas practice. The Authors and all concerned are to be congratulated on undertaking such a comprehensive study and presenting such thought-provoking conclusions. The comments and suggestions which follow are made mainly to complement the Authors' suggestions and present a little information gleaned by the writer on overseas practice, particularly in Australia.

182. The Paper identifies two types of thermal cracking: (*a*) short-term, steep temperature gradients in the concrete mass; (*b*) long-term cooling of the mass to ambient temperature. In the first case, the Authors found, as have many other workers and as can be shown theoretically, that there is a very steep temperature gradient at the free faces of a block just cast. It is at these faces that shrinkage cracking has been maximized by design needs as the concrete used is generally richer in cement, and often uses a

smaller maximum aggregate size. It is almost impossible to keep continuously moist and cured properly. This appears to make a strong case for some form of insulation layer to reduce evaporation and temperature differentials and would seem to conflict with the use of steel forms. The use of curing compounds is widespread in Australia in this regard, but they are rather unsightly. An opaque (usually white) compound appears to be quite effective in reducing evaporation losses, and, by its reflective colouring, reducing rapid variations in surface temperature and thermal transmission. Their benefit is, however, limited and the use of some form of precast panel, as successfully used in the USA, would seem to be the direction in which design should be moving.

183. The long-term effect of temperature variation on cracking can be minimized by placing concrete at such a temperature that it will rise to the final mean temperature of the finished dam, which usually appears to be about the mean ambient. It may not be practical or economic to achieve this totally, but it is now normal practice in Australia to use flaked ice for the mixing water. It is also common to insulate or use a reflective paint on the cement silos and to shade and irrigate coarse aggregates. These simple measures generally enable concrete to be placed at around 10°C, which, as suggested, is generally the desirable target. Some problems of cracking have been partially attributable to the high temperature of the cement itself, and this has also been noted on the Upper Tamar. This has often been due to the use of freshly made cement, still warm from the kilns, and can be controlled by suitable production lead time.

184. In the Paper, use is continually made of the term water:cement ratio. This, of course, is generally a very valuable concept, but for mass concrete it is possibly misleading as it is rather the water to total concrete ratio or unit water content that is of concern. At the low cement contents aimed at for mass concrete dams, the properties of the concrete, particularly shrinkage, are controlled by the total water present almost independent of cement content. Work in America has shown that the required unit water content does not increase as cement content is increased, and that the increased cement content does not materially affect shrinkage. The use of this concept of unit water content thus avoids the expression of high, and therefore apparently deleterious, water:cement ratios, and relates the water demand to the total concrete mix, which is the more important. Other properties, such as strength and permeability are affected by the water:cement ratio but, as easily placed concrete carefully compacted will provide adequate strength and impermeability in the structure, this is of limited concern in a mass concrete dam and preferable to a poorly placed material.

185. As found at Upper Tamar, fly ashes which are dark can cause difficulties, usually associated with excessive carbon content. This is a common problem in Australian ashes, apparently due to the extensive use of brown coals. However, Snowy Mountains practice is to set up a close control on ash supply and accept only ashes with low specified loss on ignition. This has assisted greatly in reducing problems such as bleeding and loss of workability. In Tasmania, the Hydro Electric Commission has found that ash replacements of 35–40% are generally the optimum for strength and other properties such as freeze/thaw resistance, confirming the trend noted at Upper Tamar. Generally, air-entraining agents and water-reducing agents, which are usually also retarders, are used extensively as a matter of course, with the entrained air content specified to be within limits proposed by the US Bureau of Reclamation, that is up to about 5%. Their use can cause some difficulties, especially if sands are used which have a high silt content. They are successful in conjunction with fly ashes in reducing the cement and total water required, so together reducing two crack causing elements.

186. It would seem that the majority of the cracking problems encountered at the Upper Tamar and at most other dams can be attributed in large measure to the cement used. Being effectively a rapid hardening cement, on this project its heat of hydration is very high. As the adiabatic temperature rise is directly proportional to the heat of hydration, any reduction in this latter figure will have direct benefit on the total temperature rise. By way of comparison, readily available Victorian cements (Type A) have heat of hydration figures around 70–85 cal/g at 7 days.

187. It is believed that it is comparatively simple to vary the properties of cement during manufacture and achieve much lower heats of hydration. During discussions with cement manufacturers for a proposed dam in Victoria, offers were made to produce for the job cements with heats of hydration around 50–60 cal/g at 7 days. As the quantity of cement used in a dam is fairly large, it seems worthwhile exploring the possibilities of this approach, producing and storing a special cement tailored to the job in hand. As no new materials are involved, but only minor changes to a standard manufacturing procedure, there should be only a minor cost penalty, probably for storage.

Mr W. J. Haley, Lawrence-Allison Associates

This Paper, a state of the art report, is the type engineers are eager to see. State of the art papers are invaluable to busy engineers, and more should be published. Much duplication of effort would be avoided.

189. Could the Authors say exactly where the minimum of the short-term temperature differentials was measured. How close did the minimum keep to ambient temperatures?

190. It was a pity that the Authors gave few references to European practice. The importance of concrete temperature control, both in placing and during curing, has been well recognized in the renowned dam building countries of Spain, Portugal, Switzerland, Italy and France.

191. It might be of interest to recall that concrete may also expand in dams.[26] Volume changes other than thermal are often expansions. However, autogeneous expansion of concrete seems to occur only where the average concrete curing temperature is above 18°C. Thus the Author's recommendation to keep curing temperatures down would also beneficially reduce autogeneous expansion. Dams have been observed to grow in height, albeit a few millimetres, after impounding. This growth has been ascribed to swelling of the saturated upstream face. The swelling also induces compression in the upstream face, benefiting watertightness.

192. Could the Authors say what is the rough percentage increase in the unit cost of in place concrete by providing refrigerated mixing water? Surely this must now be considered an essential measure for producing crack-free concrete dams. Designers should bear in mind that the real cost of specifying refrigerated mixing water is reduced because contraction joint spacing can be increased, thereby eliminating one or more costly joints.

Mr J. D. Evans, *South West Water Authority*

I welcome the conclusions of the Authors which have at last pinned down 'scientific' reasons for the cracking and efflorescence which disfigure the majority of concrete dams. No longer can one blame poor curing or dirty lift joints or grout spread on the lift interface, although these factors remain of great importance. I also welcome the ideas that engineers should, in future, attempt to bring the construction techniques for concrete dams up to date and look forward to seeing these put into practice. I would like to mention two concrete dams for which I was Resident Engineer and which have cracked to some extent.

194. The most recent was Crowdy, a gravity dam in Cornwall, which has, in the three years since its completion, shown very little tendency to crack. This is perhaps surprising because no particular precautions were taken with regard to exposure times and placing temperatures.

195. Crowdy was constructed in 1·2 m high lifts and blocks 9·1 m long. Because neither low heat cement nor PFA were available, sulphate resisting cement was used, not of necessity, but because of its considerable low heat properties. The cement content of the concrete was 278 kg/m^3 with a high aggregate: cement ratio of 7:1, which was necessary, together with a plasticizer, to obtain workability of a very harsh mix. The harshness was due to the use, as the coarse aggregate, of local crushed slate waste, which had been passed through a jaw crusher to produce an 'all in' aggregate

graded from 76 mm to dust. By normal standards the aggregate was very flakey (70%) and elongated (65%) and with the dust content looked extremely 'dirty'. However, the broken stone had a rough surface which ensured a good bond and the dust was an important factor in producing a concrete with a density of 2516 kg/m^3. A slight deficiency in the grading of the slate aggregate was made up by the addition of 'as dug' waste sand from a local china clay pit. Cubes from the concrete gave an average 28 day strength of 26·6 N/mm^2.

196. During construction some crude but effective measurements of the temperature rise were made. The apparatus was a dip thermometer which was lowered down a 19 mm dia. test tube cast into the concrete and filled with water. Although there were some problems with displacement of water while lowering the probe down the tube, it was possible to detect the temperature gradient through the concrete lifts. The results indicated that the maximum temperature reached by the concrete after placing was 34°C with an average air temperature of 11°C.

197. No cracking occurred during construction and immediately thereafter and a recent survey has indicated that there still are no vertical cracks in the blocks. This is presumably due to most of the dam above ground level being constructed during the winter and spring periods, and in any case the observation of any vertical cracks is likely to be difficult due to the exposed aggregate finish used on the downstream face. However, there is evidence of cracking at the horizontal joints where eleven of the 49 lifts visible above ground level have slight cracks. The exposure times were as given in Table 4.

198. These results appear to fit in well with the theories set out in the Paper apart from the lift with the 45 day exposure time which must be 'the exception which proves the rule'. It is perhaps fortunate that at Crowdy, although the cement content was high, the small lift height and pouring during the winter kept cracking to a minimum.

199. The other dam was Stithians, also in Cornwall, which is a concrete arch set between gravity wings. Here quite extensive cracking has occurred although some may be due to the flexure of the arch.

200. Stithians was constructed in lifts 1·37 m high and blocks 16·5 m long in the arch and 13·7 m long in the gravity section. OPC was used with up to a 20% PFA replacement in the arch and 25% replacement in the gravity sections. The aggregates were a crushed hard blue elvin and a mixture of china clay and sea sands used with an aggregate: cement ratio of 10:1. The gravity section mix contained 204 kg/m^3 of cement and 68 kg/m^3 of PFA. The average density was 2404 kg/m^3 with an average 28 day cube strength of 31 N/mm^2.

Table 4. Crowdy Dam cracking

No. of lifts	Exposure time	Details of cracks
44	4–12 days	Two fully cracked, 7 partially cracked
3	13–20 days	One partially cracked
1	40 days	Partially cracked
1	45 days	No crack

Table 5. Stithians Dam cracking

No. of lifts	Exposure time	Details of cracks
102	3–12 days	15 fully cracked, 3 partially cracked
45	13–26 days	7 fully cracked, 3 partially cracked
5	65–79 days	No cracks

201. During construction some cracking occurred. This took the form of horizontal cracking at the corners of the lift joints and vertical cracks at the mid or third points of the blocks. Where the cracks were considered to be of especial significance i.e. in the thin section at the top of the arch, the lift height was reduced by half and extra curing was introduced; after this no further cracks were noticed.

202. Although no detailed records are available, I have the impression that there are now more cracks visible than when the dam was completed 11 years ago. My recent survey has shown that there are both horizontal cracks at the lift joints and vertical cracks in the blocks visible above ground level. The details of the horizontal cracks compared with exposure time are given in Table 5.

Messrs Dunstan and Mitchell

We must thank **Mr Kennard** for providing the data from Mullardoch Dam. As well as showing the smaller temperature rises which were prevalent at that time, it also gives an indication of a relationship between maximum temperature/regenerated temperature and exposure time, on a completely different dam from the Upper Tamar. A typical result had an expected maximum temperature of 35°C–36°C; with an exposure time of 5–7 days, the regenerated temperature was approximately 34°C–35°C. It is interesting to note that these results fall almost precisely on the lines of Fig. 14 for the Upper Tamar Dam.

204. Mr Kennard also mentions the increasing fineness of the cement, as do **Mr Crosthwaite** and **Mr Coates.** The fineness of the cement has a considerable effect on the rate at which heat is generated. An example of this is shown in tests on a particular cement[27] in which the rate of heat evolution with a specific surface of 250 m^2/kg was 2·09 W/kg, an increase to 350 m^2/kg increased this by 45% to 2·92 W/kg and a further increase to 450 m^2/kg raised it 80% to 3·67 W/kg.

205. It is unfortunate that the cement companies do not seem to be as co-operative as those in Australia which **Mr Smith** describes in § 187. During the three-day week, in 1974, a circular was sent by the cement companies apologizing for a decrease in specific surface which had been necessary to reduce power output. Thus the cement being requested by dam constructors would in fact probably be cheaper.

206. We agree with Mr Kennard that concrete dams are unlikely to be economic using the existing method of construction, but hope that dams constructed with lean rolled concrete (LRC) would be cheaper than other methods in certain applications.

207. We are glad that **Mr Llewellin** feels that Fig. 18 would provide a basis for economy by giving more freedom to the contractor. **Dr Browne** also mentions that it could be useful in designing concreting procedure. It is interesting that something similar has already been used by Freeman Fox and Partners as described by Mr Crosthwaite. It is unfortunate that these feelings are not shared by **Mr Pattenden.** However, by giving freedom to choose the rate at which concreting can progress, some contractors may like to increase the speed of construction, while Mr Pattenden would seem to be happy with the present rate of pouring.

208. We believe that a misunderstanding has arisen regarding Mr Llewellin's comments on trial mixes. It was the intention that the Engineer should carry out the trial mixes up to a year before the contract is let. During these trials, the proportion of PFA could be fixed and a reasonable concrete density (on which the shape of the dam could depend and which should be specified) defined.

209. The benefits of as large an aggregate as possible are shown in Fig. 23 (from Fig. 5 of Scott and Reeve[28]). The cement efficiency increases up to a maximum at 150 mm maximum size of aggregate (m.s.a.) and the water content and cement content reduces as the size of the aggregate increases; the percentage of fines also decreases.

210. An analysis has been made of 43 dams[15] constructed in America, Portugal Italy, Switzerland, France, Australia, Mexico and Russia. Of these, ten had m.s.a. greater than 150 mm, 20 at 150 mm, eight between 100 and 150 mm and only five below 100 mm.

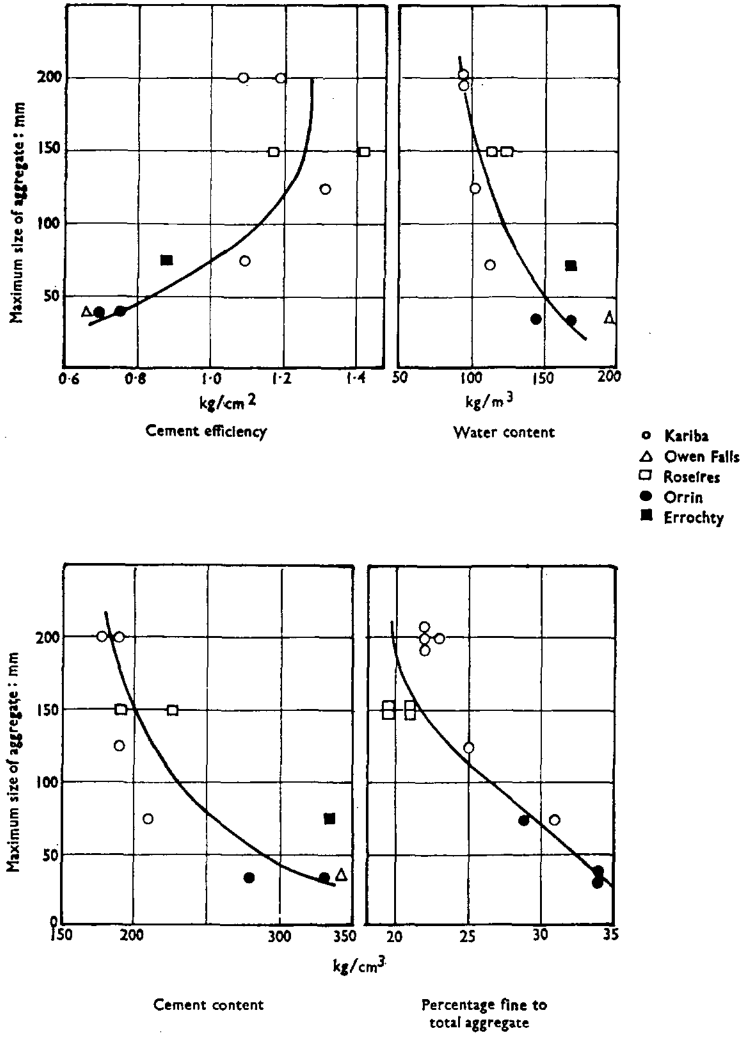

Fig. 23. Effect of aggregate size

211. It is unlikely that the use of air entrainment will have a detrimental effect on the density. It is estimated that with a mix containing a cement content of 180 kg/m^3 and an initial water content of 145 kg/m^3, 5% air entrainment would increase the density by up to 2%.

212. It has been found that hearting concrete containing 125–140 kg/m^3 of cement and entrained air can be compacted with less work than is required to compact non-air-entrained concrete made with 180–200 kg/m^3. It also bleeds less and is more resistant to segregation.[12]

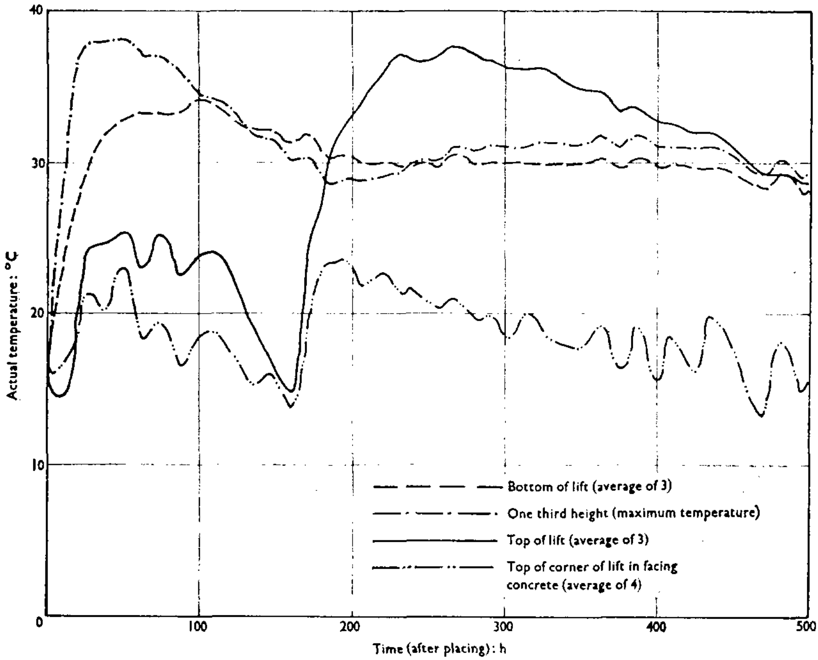

Fig. 24. Actual temperature/time relationship for typical leading monolith (NB. Temperature taken from lift 2E/9 (leading, 1·5 m deep) placed on 16 July 1974. Previous lift had been placed on 6 July 1974 and subsequent lift was placed on 23 July 1974. Air temperature at time of placing approximately 15°C)

213. Mr Llewellin mentions that he feels the specification of a water:cement ratio is unwise. **Mr Reader** also doubts the validity of some ratios mentioned. **Mr Smith** in the written discussion has made the point that for low cement content mixes, it is the water content which is most important. We agree with his views, and it was this point that was being made in § 79.

214. The term 'water:cement ratio' was used because it is the generally accepted method of measuring water content. A figure of 0·60 was mentioned with regard to a m.s.a. of 150 mm; this is equivalent to 0·72 for a 75 mm m.s.a. and to 0·86 for a 38 mm m.s.a.[15] The latter figure was approximately that obtained at the Upper Tamar.

215. In the analysis of dams mentioned above, only eight of the 43 have a published water:cement ratio in excess of 0·6 and only four above 0·63 (the majority of the latter had a cementitious content below 140 kg/m^3).

216. With regard to the problems of curing, the reason for the sloping of the horizontal joints is to help with the cleaning of the joint and does not, we believe, have any structural significance (although the foundation is usually sloped in this fashion). It is unfortunate but the only efflorescence of any note on the Upper Tamar Dam is on a horizontal joint. This was not on a slope because it was directly above the access gallery which led from the downstream face of the dam to the valve shaft, and which had a level soffit. The joint was not cleaned adequately due to the horizontal surface and seepage has occurred.

217. Dr Browne asks if strain gauges were considered. They were, but the only satisfactory ones that could be found, after considerable searching, were German and

were rather expensive (£75 each). As Mr Kennard mentioned, there was no research budget for this investigation and it was decided not to use them. Similarly the coefficient of expansion was not measured, although it is hoped to define this in the long term with on-going readings.

218. The long-term cracking seems to be caused because the concrete changes from a liquid/plastic state to a final plastic/solid state near its maximum temperature. Eventually when it reaches the average yearly temperature of the surroundings, there will be a strain induced by the thermal contraction from its initial expanded form. This is shown in Fig. 20, but the delay to the change to tensile strain can be two, three or more years. It is hoped that an opportunity will arise to define this relationship more precisely with the use of strain gauges.

219. We feel that the maximum temperature can be readily predicted. However, the temperature gradient near a joint, which is particularly important for definition of horizontal cracking, is rather more difficult to define precisely. This is due to the number of variables involved, such as length of exposure time, ambient conditions just prior to and during the pour, etc.

220. A number of non-PFA concretes were tested under laboratory conditions, but none in the field (as the probability of cracking would have been greatly increased). Thus no thermocouple readings are available from non-PFA mixes.

221. Figure 24 shows an actual temperature/time curve. It was found that with decreasing cement content the time to maximum temperature increased. A similar increase was found with increasing depth of pour. The average time for a 1·5 m pour with grade F concrete (138 kg/m^3 cement + 40 kg/m^3 PFA) was 50 h, while with a similar concrete and a depth of pour of 0·75 m the time was 22 h. For grade E concrete (190 kg/m^3 cement + 46 kg/m^3 PFA) with similar depths of pour, the times were 40 h and 15 h.

222. It is probable that the sudden increase in temperature rise which occurs at a placing temperature of about 18°C, is due, as Dr Browne and **Mr Owens** suggest, to the PFA reaction. This will be aggravated to a certain extent by the higher ambient temperatures and thus the slower loss of heat to the environment.

223. We agree with Mr Crosthwaite that cracking seems to be an almost universal problem, particularly in Britain. However, we feel sure that it is possible to produce a non-leaking dam. We believe that the Americans and Japanese in particular are succeeding in doing so.

224. This seems to be confirmed by **Mr Cox**'s comments (§ 166). The suggestions put forward are generally in line with the methods he describes.

225. The low cement mix used at Tamar did not generally seem to cause any problems as far as workability was concerned. This may have been due in part to the use of electrical rather than air-driven vibrators. These were easier to handle and were thus used more effectively (during power failure the standby air vibrators were far less effective).

226. Mr Owen's comments on the properties of cement and PFA are most interesting and confirm our recommendations. The temperature increase with a mix proportion of 200 kg/m^3 fly ash and 85 kg/m^3 OPC is likely to be 70–80% of that of an equal strength (at 180 days) OPC mix. Considerable work on the use of pozzolans has been carried out in America.[29]

227. The reduction in water requirement mentioned by Mr Owens is also similar to that found elsewhere, for example, during trial mixes which were carried out at the Tamar site for Wimbleball Dam. Three cement contents were tried: 174 kg/m^3, 218 kg/m^3 and 263 kg/m^3. Taking the middle cement content as an example, at 28 days the strengths for 100% OPC, 25% replacement by PFA, 40% replacement and 60% replacement, were 25·0, 21·7, 19·0 and 16·4 N/mm^2 respectively. At 90 days all the strengths were between 25 and 27 N/mm^2. The water:cement ratio decreased from 0·75 with 100% OPC to 0·68 with 60% replacement, a net loss of 15 l/m^3 in water content.

228. Because the long-term strength of cement and PFA together is in excess of

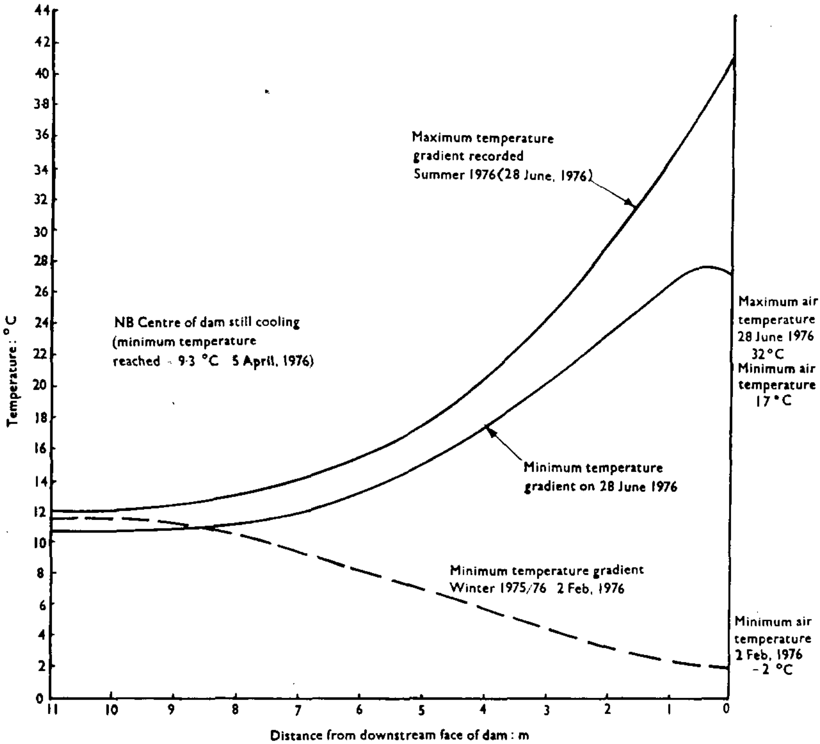

Fig. 25. Variation in temperature in Upper Tamar Dam due to ambient temperature variation

cement alone, it has even been suggested that the total cementitious content could be reduced if PFA were added.[30]

229. The black PFA which caused problems at the Upper Tamar Dam, did cause considerable discoloration of the surface of the concrete. On the surface of the water, bleeding from the mixture, was an oily substance. It seems likely that the carbon black particles, suggested by Mr Owens, could have caused this problem. **Mr Knight** has reservations, however.

230. We would agree with Mr Owens that a different form of specification is necessary for the PFA so that full use can be made of this material.

231. We feel that the conditions applicable to the reinforced concrete dam mentioned by **Mr Gosschalk** are rather different from massive non-reinforced sections. The time taken for a 1 m thick section to cool is less than a week, while a dam even as small as the Upper Tamar will take 2–3 years (it is suggested that the Hoover Dam will take in excess of 200 years to cool).[15] The reinforcement must also prevent some cracking (see § 36).

232. A possible cause of long-term cracking has been described in § 218 but this is not likely to apply to buttress dams as they will have cooled fairly quickly. However, the suggestion that the ambient conditions could have caused this is most interesting, as long-term tests are being carried out at the Tamar Dam to investigate just this possibility. A preliminary idea of the temperature range found on the dam is given in Fig. 25. As can be seen, the range on the downstream face is almost 40°C. The range

No. of pours	3	4	3	12	10	10	16	18	16	10	3	1
No. of cracks	3	4	4	27	16	17	22	25	9	3	0	1
Aver. no. cracks/pours	1·00	1·00	1·33	2·25	1·60	1·70	1·37	1·39	0·56	0·33	0·00	1·00

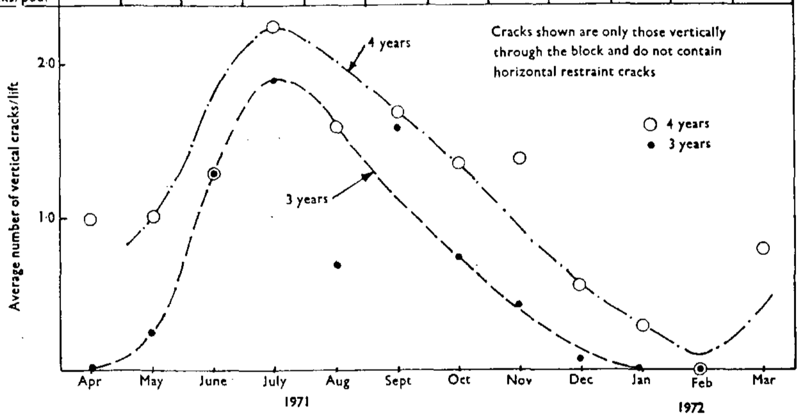

Fig. 26. Comparison of the thermal cracking relative to month of placing and age of concrete

Table 6.

Exposure time	No. of lifts	No. and % fully cracked	No. and % partially cracked	No. and % not cracked
Meldon Dam, March 1976				
< 11 days	51	6 (11·8)	14 (29·4)	31 (60·8)
12–19 days	36	12 (33·3)	9 (25·0)	15 (41·7)
> 20 days	22	13 (59·1)	5 (22·7)	4 (18·2)
Total	109	31 (28·4)	28 (25·7)	50 (45·8)
Siblyback, April 1976				
< 15 days	10	4 (40·0)	3 (30·0)	3 (30·0)
12–23 days	61	21 (34·4)	20 (32·8)	20 (32·8)
24–30 days	17	6 (35·3)	9 (52·92)	2 (11·7)
> 31 days	19	10 (52·7)	9 (47·8)	0 (0·0)
Total	107	41 (38·3)	41 (38·3)	25 (23·4)

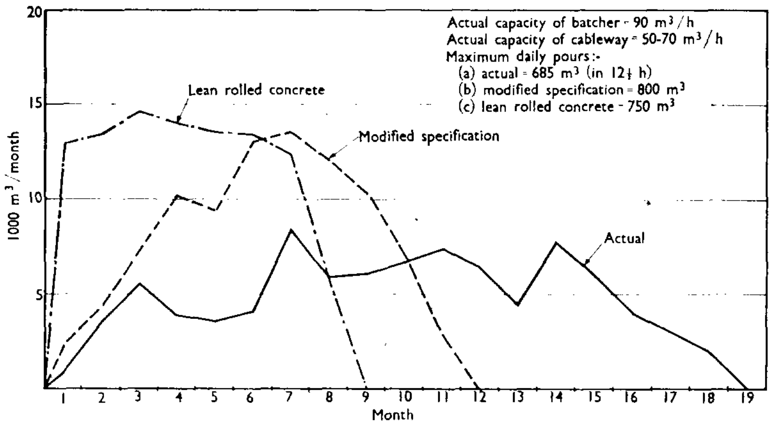

Fig. 27. Comparison of rates of placing concrete at Meldon Dam

in the centre of the dam has not yet been proved because it has not yet cooled completely. This figure seems to be similar to that found on the Stewartville Dam in Canada.[31]

233. An example of this propagation of cracks long after a dam has been completed can be seen from the study of Meldon and Sibleyback dams. In the spring of 1975 the results of the analysis of the cracks were as shown in Fig. 17 and Table 2. A further analysis was done in April 1976, and the results of this are shown in Fig. 26 and Table 6.[5] It can be seen that the number of cracks has increased in a very consistent pattern, almost parallel to the 1975 results. It was clear from the study that some of these cracks (particularly the vertical ones) are propagated from existing cracks in the lift below (see § 46) but some have occurred in completely new lifts. Some are probably due either to cooling of the dam (see § 218) or to temperature differentials on the surface, there being some quite cold nights during the 1975–6 winter.

234. Mr Gosschalk suggests that the horizontal cracks could be caused by internal temperature differentials. However, we feel that they are caused by the temperature differential across the joints: these can be seen in Figs 10 and 11. It should be noted that these gradients are in the centre of the block and the differentials are more acute at the corners. It may be that when the new lift is placed on the old concrete the latter expands initially due to warming, particularly in the corners, and this does not affect the new concrete due to creep. When the concrete cools, both concretes contract and the old concrete withdraws from the joint, thus causing the cracks to appear.

235. The way to prevent any horizontal cracks is to minimize the temperature differential across the construction joint, preferably by minimizing the temperature rise of the new concrete. The alternative is to place the concrete while there is still heat remaining in the old concrete, either by reducing the exposure time or by insulation of the surface. These were generally the conclusions reached on Spelga Dam.[8] By use of hessian screening and other preventative methods, the initial cracking on this dam was all but eliminated by the end of the contract.

236. If the cement content of 325 kg/m³, mentioned by Mr Gosschalk, was in a reinforced concrete buttress, it is unlikely to have caused cracking due to reasons mentioned above (§ 213). Due to the higher temperature in the tropics, rather different criteria exist.

237. The placing temperature of 10°C was suggested as it is the long-term average ambient temperature in the southern part of the UK. The suggested maximum

temperature rise of 20°C (§ 36) and the maximum difference between maximum temperature and long-term ambient conditions of 20°C (§ 52) are thus both fulfilled.

238. Mr Gosschalk and Mr Smith have raised the question of steel shuttering and insulation. The former is recommended for low cement content concrete to optimize cooling and to avoid thermal shock. It was found that when a wooden shutter was removed, at an age of 36–72 h, a sudden drop in temperature was recorded. This could cause cracking. Insulation is recommended for higher cement contents where it is necessary to keep the minimum temperature raised artificially until the maximum temperature has dropped, thus avoiding a short-term temperature differential.

239. We agree with Mr Pattenden that co-operation is vital to maintain or to recover the efficiency of the construction industry. Fig. 18 is hopefully an example of this co-operation. It does not mean necessarily that deeper lifts have to be used; however, maximum exposure times are necessary if cracking is to be avoided. Contractors elsewhere have come to terms with this criterion, apparently successfully.

240. We believe that generally the rate of construction of concrete dams is not governed by the rate of concreting but, usually by the rate of the erection of the shuttering. Fig. 27 shows the actual rate of placement of concrete at Meldon Dam (by Mr Pattenden's firm); the rate which would have been necessary if 2 m lifts and a maximum exposure time of 5 days had been specified; and also the rate of placement of concrete necessary for an LRC dam. It can be seen that the batcher and cableway capacity would not be extended by conforming with the specification. With an LRC dam, a cableway would not be necessary and the transportation could be by lorry.

241. We agree with Mr Pattenden regarding aggregate supply, which was also commented upon by **Mr Reader.** However, it is possible to make considerable savings in cement content by very little modification in aggregate shape and size (see Fig. 23). Not only will this cement reduction save money due to the decrease in cement, it could also make deeper lifts possible (if it is advisable) thus saving on joint preparation and shutter turn-around. A further reason for the early trial mixes (see § 208) is to provide as economic a concrete mix as possible at an early stage.

242. Mr Pattenden's comments on the PFA have possibly been answered by Mr Owens.

243. The depth of lift which could be compactable by vibrating roller seems to be 400–500 mm.[32] Fig. 27 has been based on a depth of 300 mm and this would complete a dam of say 55 m in height in 9–10 months, as opposed to the usual concreting period of 18–20 months. Thus, 1 m depth would seem to be rather too deep.

244. We believe that Megget Dam is to be a rockfill dam. Apparently, Professor Rowe did suggest that the slopes could possibly be steepened by strengthening those areas with a small cement content. However, the final decision has not yet been taken.[33]

245. Mr Coats' comments on the use of PFA and air entrainment are interesting. In fact, no air entrainment was used at the Upper Tamar Dam. As Mr Llewellin has pointed out, it would have been most beneficial. **Mr Ash** has also expressed reservations about the use of additions with PFA. However, Mr Knight feels that PFA can be used successfully with air entrainment. Mr Smith suggests that they have been used together successfully in Australia (§ 185) and they have also been used without difficulty in America.[15, 29] The only dam on which trouble seems to have occurred was Kariba.[28]

246. The tendency for lifts to turn up at the corners, mentioned by both Mr Coats and Mr Reader is due, I believe, to the reasons stated in § 234. This tendency will of course, be more noticeable if the cement content (and thus the maximum temperature) is greater.

247. The possible future raising of the dam, did, in fact, have very little influence on the concrete design or block length. The strength requirements for the former were slightly increased, but not beyond what could be obtained with a concrete with as small a cement content as possible (for workability).

248. In answer to Mr Knight's comments on the black PFA, an investigation was carried out, both into the carbon content and transportation. No satisfactory answer

was obtained, which leads one to believe that the reasoning of Mr Owens' (§ 132) could be correct.

249. It would be useful to compare the results of the work by the North of Scotland Hydro-Electric Board mentioned by **Mr Curtis**, with those in Fig. 25. The range of 10°C in the hearting concrete seems to be quite high.

250. Mr Curtis' experience that a crack is likely to occur in the centre if a lift exceeds 13–15 m in length, is most interesting. **Mr Gray** also asks why longer lifts are not possible. The length of the block would seem to be determined by two criteria. First the amount of concrete that can be sensibly placed during construction in one day and secondly, by the strain induced at the centre of the block due to thermal movement, both during and after construction. The first problem will depend upon the particular dam and lift heights. If there is control over the thermal movement in construction, the range of air temperatures in the locality of the dam might be the critical factor.

251. At Dworshak Dam, it was possible to use 20 m wide monoliths[34] which were over 150 m long by extensive precooling of the concrete. The maximum placing temperature was specified at 7·5°C. No cracking seems to have occurred. The reduction of even 50% of vertical construction joints would have a considerable cost benefit.

252. Mr Curtis asks how serious is efflorescence in itself. It is not important, but if by careful control it is possible both to reduce (or eliminate) cracks and efflorescence and have a saving in cost, it must be more satisfactory. Mr Cox seems to agree (§ 164).

253. Mr Cox's experience with American practice indicates that it is possible to obtain a watertight structure without great difficulty, although he also observed the tendency for horizontal cracks in the corners of lifts.

254. It is unlikely that the efflorescence is caused by leaching action of the rain, as we have seen water passing through horizontal joints on a perfectly dry day and flowing down the face of a dam.

255. Mr Cox again suggests that the judicious use of additives can only have a beneficial effect on mass concrete.

256. Mr Ash suggests a 6 m monolith could be advantageous. We feel that this is unlikely because the same maximum temperature occurs in any section greater than 5 m wide. It would also increase the cost of the dam. The same can be said for the steel reinforcement. The latter would, unfortunately, slow down the construction and thus increase the number of shutters necessary, thus increasing the cost in excess of the cost of the steel alone.

257. Deeper lifts can be used satisfactorily, as both Mr Ash and Mr Gray have suggested. In Canada,[31] a number of dams were constructed with pours the full height of the dam (up to 20 m deep). This was possible due to the climatic conditions (concreting continuing throughout the winter), and was economic because of the availability of considerable quantities of timber locally. The latter provided excellent insulation for the pours. With low cement content, this might be feasible in the UK. However, we feel that horizontal placement has greater benefits.

258. The problems that Mr Ash had with the time from batching to placement are not usually significant with concrete dams, as the concrete is batched in most cases on site. On the Upper Tamar Dam, the concrete was mixed during transportation by 5 m mixer trucks. The usual rate of placement was 25–35 m^3/h and thus one truckload was discharged in about 10 mins. Shading with insulated covers was not possible because of the use of a boom scaper. Spraying was found to be quite satisfactory and did not cause any significant problems with control of water content. Ideally, storage facilities with 'bottom take-offs' would be best; the aggregate would thus be at a fairly constant temperature.

259. Mr Reader has raised a number of interesting points, some of which have already been covered. We believe that, by careful control of the temperature rise and by reduction in exposure times (or insulation of the top surface if it is not possible), the elimination of horizontal cracks should be possible. We hope this will be proved by Mr Reader during the construction of Wimbleball Dam.

260. Mr Reader has been kind enough to let us study some of the temperature readings taken at Wimbleball. A typical reading has been a maximum temperature of 42°C; this together with an exposure time of 7 days has produced a regenerated temperature of 37°C. This result, in a similar fashion to the results given by Mr Kennard at Mullardoch, falls on the lines of Fig. 14. Thus, the results from two totally different dams, one built in 1950 and the other in 1975, seem to produce very similar results to those found on the Upper Tamar Dam.

261. Mr Gray suggests that climbing formwork would be practical. This was the subject of a study in America[35] for the proposed Trumbell Lake Dam. A saving can be made by this method and it has been tried on a small scale at Miners Lake Dam.

262. Mr Smith has made a very interesting contribution regarding the practice in Australia, which has indeed answered a number of questions by other contributors.

263. The suggestion that precast panels would be advantageous is agreed. In fact, they have been used in Russia for many years.[36] They seem to be less economic in this country due to the different labour/materials relationship. Two dams in Scotland have been built using panels. The main reason at the time was the shortage of timber. However, later dams proved to be more economic with standard shutters. The extruded 'kerb' in situ cast facing would have most of the advantages of precast panels, and would also reduce the number of disadvantages, such as the necessity for craneage, ties, etc.

264. The control over materials that is possible in Australia seems to be somewhat better than in the UK and we hope we can learn from Mr Smith's experiences.

265. In answer to **Mr Haley**'s query regarding the measurement of temperatures, after the initial experiments with thermocouples (§ 22), the temperature was measured at at least four points in a lift: the interface between the old concrete and new; the maximum temperature in the new (approximately at one-third height); the surface of the new concrete (in fact 50 mm into the concrete); and the top corner of the lift. Typical temperatures are shown in Fig. 24. Without insulation, the minimum temperature approached ambient temperature after about three days, i.e. at about the same time as the maximum temperature was generated.

266. The autogenous expansion (or contraction) was studied in detail at Dworshak Dam.[37] There it was found that expansion only occurred on a few samples, whereas the majority indicated a contraction. The few that did expand were at low curing temperatures and with a cement replacement by PFA of 30%. As Mr Haley comments, this would have a beneficial effect.

267. The percentage increase in unit cost of refrigeration is difficult to define, as it will vary according to circumstance; but it has been estimated at 3%.[38] If the saving due to pours which are larger, both in depth and length, is greater than this, as Mr Haley suggests, refrigeration should be used.

268. The results of cracking at Crowdy Dam, described by Mr Evans, are interesting, because again the results conform with those at the Upper Tamar. The temperature increase to 34°C with an air temperature of 11°C can be calculated from the results and this is just within the limit for avoidance of vertical cracks (see § 36).

269. By keeping the lift heights shallow (1·2 m deep) and by placing the great majority of concrete during the winter, cracks have been avoided.

270. The table of horizontal cracks at Crowdy conforms with that which would be expected. During other studies, the cracks in the spillway section have been excluded as they are usually difficult to see due to discoloration. The exposure time of 45 days was, in fact, in the spillway.

271. It is interesting that at Stithians, when the lift height was halved, no further cracks were found. This was probably due again to a reduction in maximum temperature and conforms with the reason suggested in § 81.

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