Concrete for Benmore Power Project

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Considerations in the production of 500,000 yd³ of diverse grades of concrete are described. The favourable concrete materials at Benmore permitted very low cement contents to be used in the concrete, with a reduction in the amount of post-cooling of the mass concrete. Experience with the full-scale use of a water-reducing set-retarding admixture is described.

1. INTRODUCTION

THE Benmore hydro-electric power project being constructed on the Waitaki River of New Zealand has as its main feature a rolled-fill earth dam containing some 15,000,000 yd³ of material and having a structural height of 360 ft. Structures associated with the earth dam are:

(a) A powerhouse with an installed generating capacity of 540,000 kW.

(b) An intake structure and six precast prestressed concrete penstocks of 17 ft 6 in diameter which deliver water to the powerhouse at a maximum static head of 305 ft.

(c) A spillway block, channel, and deflector with a designed flood capacity of 120,000 ft³/s.

(d) A cut-and-cover twin-barrel river diversion culvert.

Contained in these features are some 500,000 yd³ of concrete of all grades from low-cement content mass concrete to high-strength concrete for the penstocks.

2. MATERIALS

2.1. Aggregates

Extensive river gravel deposits adjoined the dam site and after provision had been made for suitable gravels for the shoulders of the earth dam, an area containing at least 2,000,000 yd³ was reserved and prospected for concrete aggregates. This deposit was 1¼ miles from the concrete-batching plant.

Prospecting of the area was by shafts and cable-tool drill holes, and this investigation confirmed the consistency, suitability, and general high quality of the deposit. The natural, rounded particles were an ideal shape for concrete, the aggregate being in the main formed from river-worn greywacke (an indurated sandstone), non-reactive and containing no lightweight material.

With little excess of the 6 in size, the pit-run material had an overall grading not very much different from that required for the average of the concrete. There was not the shortage of 3 to 6 in size fraction experienced at Roxburgh (and also reported for the Glen Canyon dam). An "ideal" exponential grading curve for the proportions of the coarse aggregate could be used (see Fig. 1).

As predicted from the investigation, the fine aggregate (-3/16 in size) was in short supply, and although the contract for production of concrete aggregates permitted the manufacture of aggregates up to the ratio of 1:2 of artificial to natural material, the contractor decided to produce the deficient size by handling excess material. Apart from the 3 to 1½ in size fraction, the amount of excess material produced was not great.

Aggregates were produced in six size fractions: nominal size 6 in (i.e. 3 to 6 in); 3 in (i.e. 1½ to 3 in); 1½ in (i.e. ¾ to 1½ in); ¾ in (i.e. ⅜ to ¾ in); ⅜ in (i.e. 3/16 to ⅜ in); and fine aggregate (sand) passing 3/16 in.

All coarse aggregates were first screened to storage stockpiles, thence reclaimed and finish-screened at delivery to batcher bins to correct minor variations in grading due to the original screening, stockpiling, and aggregate breakage.

The grading of the sand was specified on a simplified basis having regard to the known characteristics of the deposit materials. A smoothly graded aggregate was required, complying with the following limits:

B.S. sieve	*Percentage by weight*
5/16 to 3/16 in	0 + 3
3/16 in to No. 14	25 ± 5
No. 100 to pan	8 ± 3

No sand classifier was incorporated in the screening plant, and although the sand complied with the specification it was much too variable in grading to be used to produce consistent concrete. Worse still, the variability in grading was accompanied by a variability in moisture content of the sand.

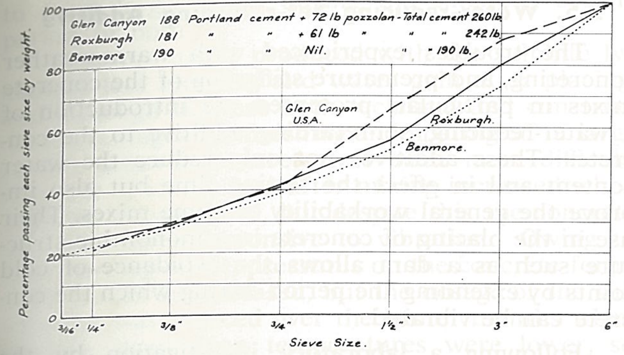

Fig. 1: Grading of coarse aggregate as used for interior mass concrete mixes. The grading of similar mixes used at Roxburgh and Glen Canyon is included for comparison.

The difficulty was overcome by re-stockpiling the sand in a series of horizontal layers. After at least a month's storage, the sand had dried to a stable moisture content. Mixing was achieved and the variability in the grading reduced by excavating the stockpile in a full face.

Although the fineness modulus concept does not completely represent a grading, Table 1 illustrates the reduction in variability achieved. Each figure for fineness modulus (F.M.) is the average of one month's testing, and from these the standard deviations have been computed.

The grading of the accepted sand was a compromise to meet the requirements of the low-cement mass concrete on the one hand and of the high-strength concrete for the precast work on the other. Ideally, two sands were required: a sand with 10% passing the No. 100 sieve for the mass concrete, and a coarser sand with only 0 to 2% passing the No. 100 sieve for the high-strength concrete.

The grading curve of the sand used was of a good recommended shape, see Fig. 2, with perhaps a surplus of the No. 25 to 52 size and a deficiency in the No. 14 to 25 size. Nevertheless, the sand with its consistency in grading and moisture content permitted the production of uniform concrete.

2.2. Cements

Although the use of ordinary cement naturally predominated there was a significant usage of rapid-hardening cement for various purposes. No special properties were required in the rapid-hardening cement other than compliance with the appropriate requirements of B.S. 12:1958 (in place of the outdated N.Z.S.S. 43:1950).

Supply of the 80,000 tons total of cement used in the work was divided into two phases. In the first, the ordinary cement was specified to comply, additionally to B.S. 12:1958, with restrictions on alkali content to 0.60% equivalent Na_2O, on potential C_3A to 10.0%, and on the sum of C_3A and C_3S to 55.0%. The latter restriction was aimed at control of early hydration heat in the large volume of mass concrete work.

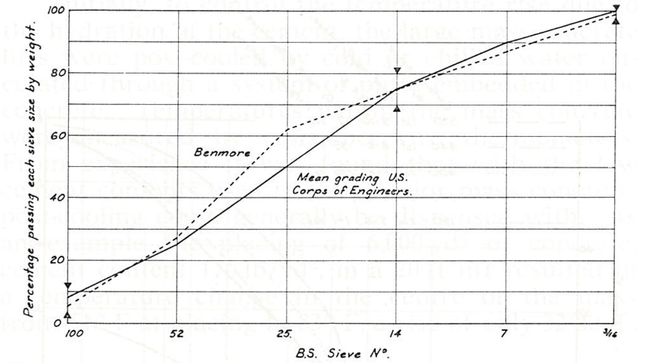

Fig. 2: Average grading of fine aggregate (specification limits shown by arrowheads).

At the height of the first two warm seasons there were incidents of rapid slump loss, characterised on the job as "rubber" or "chewing gum" set; however, false set as commonly experienced in the form described as "plaster" set was never identified as such. Additionally in the same periods (though not necessarily coincidentally with incidence of rapid stiffening) the strength gain between tests at 7 days and 28 days did not always reach normal expectation. On these occasions the 7 day results tended generally to be well above average and it was, therefore, all the more disconcerting when the 28 day tests failed to reach the specified level.

As an attempt at controlling the problem, the use of a set-retarding additive of the calcium lignosulphonate type was introduced on a regular basis at this stage, and was apparently effective (see section 2.5 below). The reactions are obscure, but this additive is known to interact with the aluminous phases in the cement composition. This apart, from past experience the difficulties described had tended to disappear, anyway, along with the passing of the warm season.

At the same time, the cement company of its own volition made progressive increases in the SO_3 content along with some further reduction of the C_3A. In the circumstances, the respective merits of the changes were difficult to unravel.

When cement supply for the second phase came up for attention, opportunity was taken to modify the specification further. The C_3A was further restricted to 7.0% maximum and the sum of C_3S and twice the C_3A was limited to 65%. Performance of this modified cement can be described as very good. Heat rise in large mass work has been kept

TABLE 1

Values of Fineness Modulus: Average of One Month's Testing

Fineness modulus ex screening plant		*Fineness modulus with limited stockpiling*		*Fineness modulus with deliberate stockpiling*	
F.M.	*No. of tests*	*F.M.*	*No. of tests*	*F.M.*	*No. of tests*
2.40 ± 0.25	16	2.76 ± 0.10	44	2.46 ± 0.05	33
2.32 ± 0.19	17	2.70 ± 0.07	30	2.48 ± 0.045	41

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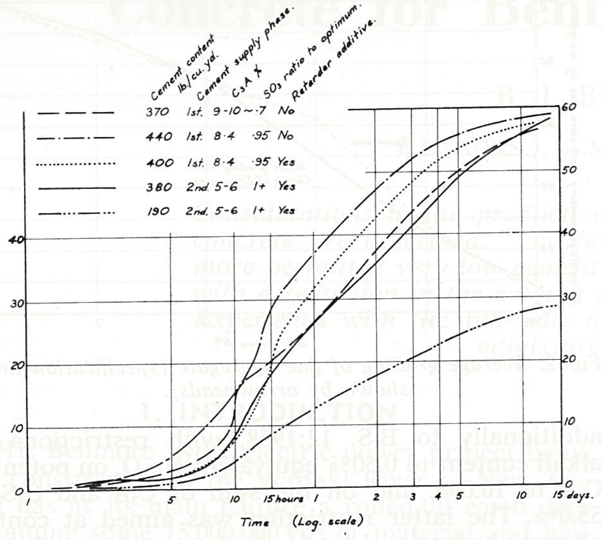

Fig. 3: Adiabatic calorimeter rise.

to a meanageable level. The ameliorating influences on early hydration heat of the change in cement composition and of the use of the retarder additive are graphically illustrated in Fig. 3. The dominant influence of a reduction in cement content may also be observed.

All cement was produced from one cement works, 130 miles from the damsite. Delivery of the bulk ordinary cement was by sealed rail wagons to the railhead at Kurow. Here the wagons were tipped and the cement stored in two 500 ton silos. It was transported by pneumatic-discharge road tankers the remaining 20 miles to the site. The rapid-hardening cement was railed to Kurow in pneumatic-discharge rail tankers and then transferred to the road tankers for the journey to the site.

2.3. Pozzolans

Before the work was started, consideration was given to the use of a natural pozzolanic cement. A deposit of diatomite at Middlemarch, 165 miles from the site, was prospected for this purpose, but high on-site cost prevented further consideration.

2.4. Air-entrainment Additive

A neutralised vinsol resin air-entraining additive was used in the concrete. The main advantage from the use of air-entrainment at Benmore was the satisfactory placement and consolidation of the otherwise dry and harsh mixes. The improved durability of the concrete and economy in production were secondary benefits.

No air-entrainment was deliberately provided in the high-strength concrete for the precast penstocks. With the high cement contents necessary, air-entrainment offered no advantages; the loss in strength and elastic modulus owing to air-entrainment was significant, and the durability of the concrete was already assured.

Air content of the concrete was kept within the range of 4.0 to 5.0% as measured on the -1½ in fraction of the concrete.

2.5. Water-reducing Set-retarding Additive

The troubles experienced with warm-weather concreting, and premature stiffening of the concrete mixes in particular, prompted the introduction of a water-reducing, set-retarding additive to the concrete. These additives not only reduce the water content and in effect the setting time but also improve the general workability of some mixes. Their use in the placing of concrete in a monolithic structure such as a dam allows the avoidance of cold joints by extending the period during which the concrete can be vibrated.

Following a laboratory investigation by the D.S.I.R. the additive selected was a calcium lignosulphonate, a yellow sulphite lye produced as a by-product of the paper industry and marketed under a number of trade names. The sulphite lye contains roughly equal proportions of calcium lignosulphonate, wood sugars, and also sodium sulphate and a host of other minor compounds. The degree of set retardation required and the concrete production temperatures determined the dosage rates of the additive, which were in general between 0.20 and 0.22% by weight of cement for the summer months, reduced to 0.16% for the winter. The sulphite lye, supplied in solid form, was dissolved in water to a standard solution for ease of dispensing and mixing in the concrete.

On-the-job experience with the sulphite lye water-reducing, set-retarding additive confirmed the laboratory test results that at the same water/cement ratio and cement content the workability of the concrete and its compressive strength at both 7 and 28 days were improved. When the concrete mixes were related back to equivalent workability and compressive strength the cement contents were reduced by 7 to 10%. This reduction represents a substantial saving of approximately eight times the cost of the sulphite lye. A further benefit associated with the reduction of cement content was the reduction of the total heat rise in the mass concrete work. Although far from complete, laboratory adiabatic tests have shown that retarded concrete with a 9% cement reduction will give a 15% lower temperature increase at 1 day, reducing to 4% at 7 days as compared with plain concrete.

A normal problem associated with summer concreting and the higher placing temperatures is an increased water demand that requires a corresponding increase in cement content to maintain the compressive strength. With an increased sulphite lye dosage over these warm periods, there was no significant increase in water demand and the additional cement was not required.

The sulphite lye aids the normal air-entraining admixture in the amount of air entrained in the concrete and, by comparison with plain concrete, a reduction of at least 50% in the dosage of air-entraining admixture was necessary when sulphite lye was used. The air void system of the hardened retarded concrete was coarser and possibly inferior to that of normal concrete. This probably resulted from the different chemical agent causing the air-entrainment, or the aggregation of the air bubbles to form larger voids during the extended setting period, or both.

Concrete mixes produced with the sulphite lye showed less bleeding and water gain after placing, and although this has both technical and construction advantages the finishing and floating-off of large surface areas of concrete was made more difficult. The rate of slump loss after mixing increased when sulphite lye was used, but despite this the concrete was still more responsive to vibration. Owing to the retarding effect, pressures on the concrete formwork would be increased, but the dosage of the sulphite lye was reduced over the winter months when concrete production temperatures were lower, so that this increase in formwork pressures was of no great moment.

3. METHODS

3.1. Production

The bulk of the concrete was produced from a main centrally-situated concrete-mixing plant having four 2 yd^3 tilting mixers. The high-strength concrete for the prestressed penstocks was produced from a small mixing plant erected alongside the precasting yard and having two 1 yd^3 tilting mixers. All materials were batched by weight, automatically in the central mixing plant and manually in the small plant. Details of the mix proportions of typical mixes are given in Table 2.

Concrete was transported from the central plant to the placing area in 4 yd^3 or 2 yd^3 bottom-discharge buckets mounted on trucks. Placing of the concrete was by crane, cableway, pump, or, in the particular case of the precast penstocks, by conveyor. In certain areas where cranage could not be provided a small bulldozer was used to push and spread the concrete.

No pre-cooling of the concrete materials or concrete mixes was provided. As a trial, pre-cooled mixing water was used during one summer period. The reduction in concrete mixing temperature was of the order of 2 to 4 degF and was of only small advantage.

Initially, to control the temperature rise due to the hydration of the cement, the large mass-concrete lifts were post-cooled by cold or chilled water circulated through a system of pipes embedded in the concrete. Temperatures within the mass concrete were measured by resistance-wire thermometers. From experience it was found that with the low cement contents used in the interior mass concrete, post-cooling could generally be dispensed with. As an example the placing of 6,000 yd^3 of concrete, cement content 170 lb/yd^3, in a 20 ft lift resulted in a temperature change in the centre of the mass from 51° F at placing to 83° F, a rise of only 32 degF.

3.2. Quality

A sample was taken from each burn of cement as delivered, and the full set of physical and chemical test results was secured, with the assistance of the D.S.I.R. for the chemical analyses. The results of the tests were checked against the specification requirements and compared with the results of tests done by the manufacturer.

A technician at the central mixing plant set-up, checked, and made any necessary adjustments to the batch weights of the materials so that the consistency of the concrete was maintained. An upper limit of water/cement ratio for each grade of concrete was established. The sand grading was checked each shift and frequent sand moisture determinations were made.

Random samples of the concrete mixes were taken at the point of placing, and tested for slump, air content, temperature, and placing performance, and the results of these tests were referred back to the technician at the central mixing plant. Samples of the concrete, with aggregates larger than the 1½ in size removed by hand, were made into standard 12 in × 6 in compression test cylinders and retained for testing at 7 and 28 days or for long-term testing as required. For confirmatory tests, 6 in diameter cores were cut from the concrete in the structures.

TABLE 2

One Cubic Yard Mix Proportions for Typical Concrete Mixes

Mix Type	*Specified strength* (lb/in^2)	*Max. W/C**	*Aver. W/C**	*Air content* (%)	*Sulphite lye* (% of cement by wt.)	*Cement* (lb)	*Water* (lb)	*Sand* (lb)	*Sand* (% of aggs.)	*Aggregate proportions (nominal sizes)* ⅜ *in* (lb)	¾ *in* (lb)	1½ *in* (lb)	3 *in* (lb)	6 *in* (lb)	*Weight C/A†*
Mass, interior	2,000 at 28 days	0.75	0.72	4.5	0.16 to 0.22	170 to 190	137	765	20.1	300	400	555	740	1,040	1:22 to 1:20
Mass, exterior	3,500 at 28 days	0.55	0.53	4.5	0.16 to 0.22	280	149	745	20.0	275	380	530	780	1,010	1:13
Exposed surfaces subject to water abrasion	4,000 at 28 days	0.50	0.50	4.0	0.16 to 0.22	400 to 420	210	970	27.6	505	800	1,240			1:8.8 to 1:8.4
High-strength grade for prestressed precast concrete penstocks	5,000 at 7 days		0.43	—	0.16 to 0.22	580 to 600	250	1,000	30.0	430	700	1,210			1:5.8 to 1:5.4

*W/C = water/cement ratio by weight. †C/A = cement/aggregate ratio by weight.

TABLE 3

Statistical Analysis of Typical Concrete Compressive Test Results

(All concrete compressive strengths are expressed in lb/in²)

Mix type	*Spec. comp. strgth f′c* (lb/in²)	*Spec. prob. of exceeding f′c* (%)	*No. of tests*	*No. of 3-monthly prod. periods incl. in analysis*	*Mean value* (lb/in²)	*Std. deviation* *Population*	*Std. deviation* *Within test*	*Coefficient of variation* *Population*	*Coefficient of variation* *Within test*	*Exceeding f′c* (%)	*Strength exceeded by* *90%*	*Strength exceeded by* *95%*	*Strength exceeded by* *97.5%*
Mass, interior	2,000 at 28 days	90	199	13	3,222	515	177	16.0	5.5	99	2,549		
Mass, exterior, and reinforced structural concrete	3,500 at 28 days	95	866	15	4,963	591	208	12.0	4.2	99		3,975	
Exposed surfaces subject to water abrasion	4,000 at 28 days	95	424	14	5,611	729	221	13.0	4.0	99		4,391	
High-strength grade for prestressed precast concrete penstocks	5,000 at 7 days	97.5	310	8	6,049	454	253	7.5	4.2	99			5,160

TABLE 4

Production Costs for Typical Concrete Mixes

Costs include all plant erection and dismantling costs and all normal project overhead charges. All cost figures are in £/yd³ of concrete produced.

Mix type	*Specified strength* (lb/in²)	*Maximum aggregate size* (in)	*Materials, cost at batching plant* *Cement* (£/yd³)	*Aggregate* (£/yd³)	*Additives* (£/yd³)	*Batching plant (establishment, removal, & operation)* (£/yd³)	*Testing (investigations, trial mixes, and routine tests)* (£/yd³)	*Total cost* (£/yd³C)
Mass, interior	2,000 at 28 days	6	1.10	0.71	0.033	0.96	0.126	2.93
Mass, exterior	3,500 at 28 days	6	1.63	0.71	0.046	0.96	0.126	3.47
Exposed surfaces subject to water abrasion	4,000 at 28 days	1½	2.45	0.74	0.059	0.96	0.126	4.34

A statistical analysis of the concrete compressive test results, given in Table 3, shows a good standard of control for the main central concrete plant and a high standard of control for the small concrete plant supplying high-strength concrete for the prestressed precast concrete penstocks. The difference in the standard of control in the two cases is because the small plant was essentially a "personal" plant as compared with the central plant which was essentially a "production" plant. The small plant was required to produce only two batch types, it had ample capacity to cope with the demand, and the technician could personally check all phases of batching and mixing. Further, because of the importance of quality in the concrete penstocks, the technician had instructions to reject any concrete batch if for any reason the quality was in doubt.

3.3. Concrete Production Costs

The production costs for typical concrete mixes are given in Table 4. The figures given are the cost of the concrete mix in the concreting bucket, but do not include the cost of transportation and placing. In the separate items allowance has been made for plant installation and removal, and all normal project overhead charges are included.

4. CONCLUSIONS

With the type of cement, the excellence of the aggregates, the use of additives, and a standard of concrete mix control, good quality and consistent concrete was produced at an economic price. By reducing the cement content to a low level the temperature rise due to hydration of the cement was minimised and the normal problems associated with the post-cooling of mass concrete were avoided.

5. ACKNOWLEDGMENTS

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Earthmoving for Benmore Earth Dam

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1. INTRODUCTION

THE Benmore earth dam was constructed at the downstream end of the upper gorge of the Waitaki River, 60 miles from the mouth of the river. Crest height was reached in May, 1964, three years and nine months after the main construction of the earth dam began.

The crest of the rolled earth dam is 2,700 ft long, and the maximum height is 360 ft. The upstream and downstream shoulders are built from sandy gravels, the core from clayey gravels. The total measured volume is 15,300,000 yd³.

The Ministry of Works designed and built the structure; about a third of the plant used was hired from New Zealand contractors.

2. GENERAL

2.1. Climate

The climate is good for earthmoving. Rain averages 15 in distributed evenly throughout the year. Three months of drought are common. However, in 1961 and 1962 rainfall reached 21 in and in 1963, 17 in; 1964 was a drier year.

Winter frosts can cause losses of up to half the available working time.

Summer brings very strong winds at times. Mid-afternoon temperatures in December and January often exceed 85° F. Apart from these minor difficulties, conditions throughout spring, summer and autumn are very good.

However, despite the favourable climate, time lost because of weather and its effects amounted to 25% on placing the core and 10% on placing the shoulders.

Major earthmoving machines were offered, on an average, 2,000 hours of work a year.

2.2. Construction Planning

2.2.1. *General*

The first stage of planning was completed in 1957 when the *Benmore Construction Report* (1) was issued. This said: "Fill materials of the earth dam approach 18 million cubic yards. In comparison, no other earth dam done by Ministry of Works has exceeded half a million cubic yards. Construction programme has been based on construction in 400 to 450 days or three seasons' work. This will require placing rates in excess of 700,000 cubic yards a working month and working two shifts in suitable weather. Nothing like this has previously been attempted in New Zealand though it has sound precedent in the U.S.A. . . . Only the development of high speed rubber tyred tractor has made this possible."

It was obvious that large numbers of rubber tyred earthmoving machines would be needed, and the report compared various types of machines: scrapers, end-dump wagons, bottom-dump wagons, their associated pusher dozers, and face shovels. In particular numbers, capital investment (mostly overseas funds), and likely working methods were compared.

2.2.2. *Method of Construction*

One of the most important decisions made in 1957 and later confirmed was: "That the dam should be constructed by the use of direct labour, augmented by contractors' manpower and equipment as required. It was considered that this system gave flexibility and would make the best use of the existing resources within the country." (2) Flexibility and good use of resources were certainly achieved. At times the resources of the Ministry of Works and of the contractors were stretched to the limit.

2.2.3. *Machinery*

Four 4 yd³ excavators—with face-shovel, dragline, and crane rigs—arrived from the U.S. in the latter part of 1958. These were closely followed by 14 yd³ end-dump wagons and rotary-percussion air-track rock drills. Two excavators were used as cranes on the diversion culverts. The other two were used as face shovels for loading rock from the foundation excavations into the end-dump wagons.

Investigations of materials and machines, and estimation of production continued until the end of 1959. Orders for motor scrapers, end-dump wagons, and crawler tractors were placed early in 1960, and deliveries were completed early in 1961.

2.3. Site

The site is shown on the front cover. The dam spans the downstream end of the upper gorge of the Waitaki River. Areas F and E are the large basins, respectively 6,000 ft upstream and downstream from the site, which provided the gravels for the shoulders. The clayey gravels for the core came from a borrow area further downstream, about 18,500 ft away.

The open site greatly facilitated the moving of all materials round the job. The haulroads and access ramps on the dam were laid out and graded to suit the machines first and the site secondly.

2.4. Roads

2.4.1. *General*

The readily-available gravel deposits were most suitable for building roads. The roads were formed, rolled, and finished with a rock running course. Unweathered blue argillite rock from foundation ex-

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