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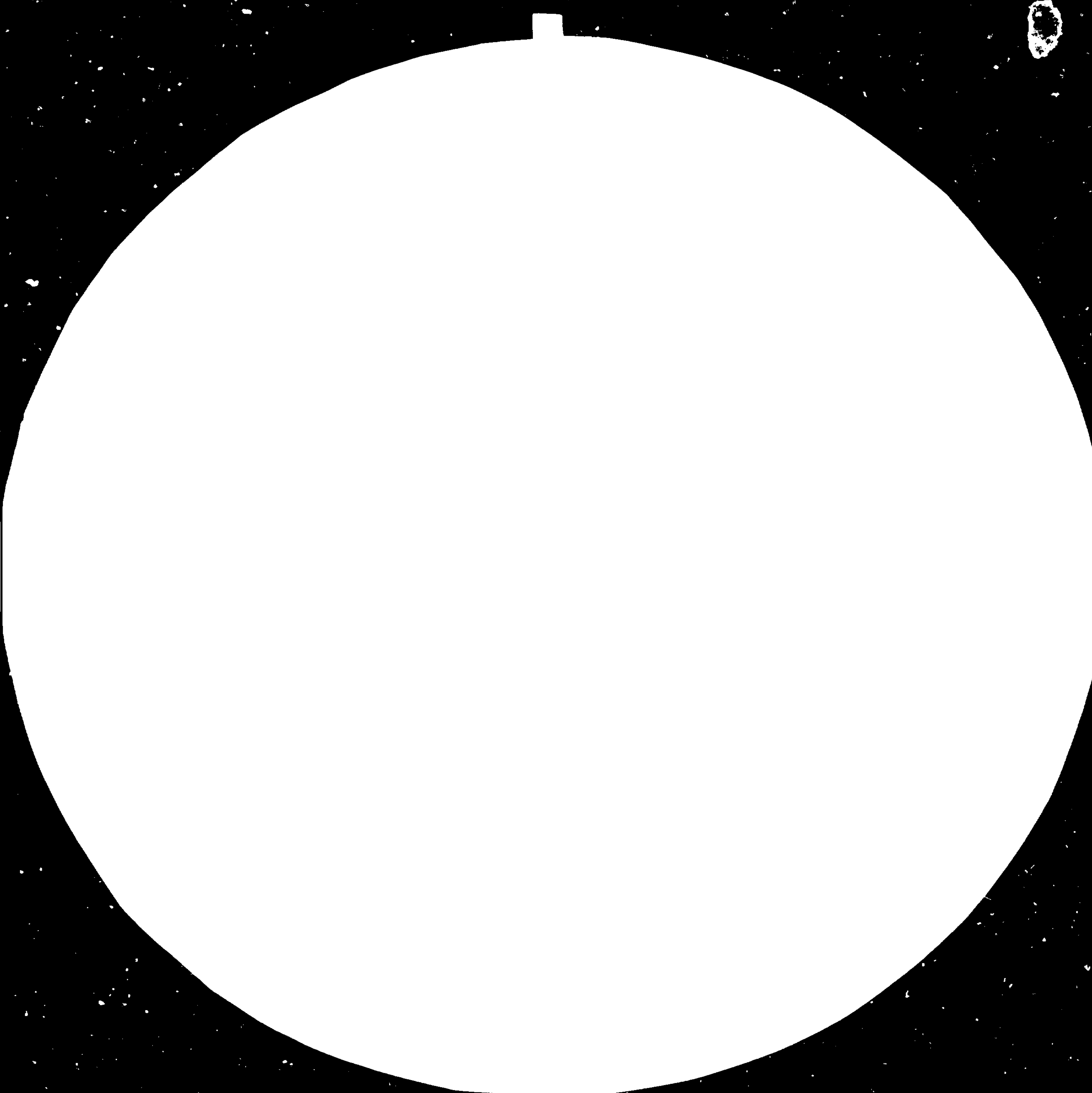

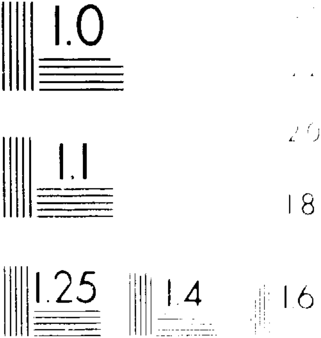
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ASSISTANCE TO THE LIBYAN CEMENT FACTORY, BENGHAZI

TF/LIB/82/002

LIBYAN ARAB JAMAHIRIYA

Libya

# Mission report: Evaluation of the raw-materials situation of the Al Khums I Cement Plant

Prepared for the authorities of the Libyan Arab Jamahiriya
by the United Nations Industrial Development Organization

Based on the work of A.R. Marei, project co-ordinator

V.83-63251

## Explanatory notes

The following technical abbreviations have been used in this report:

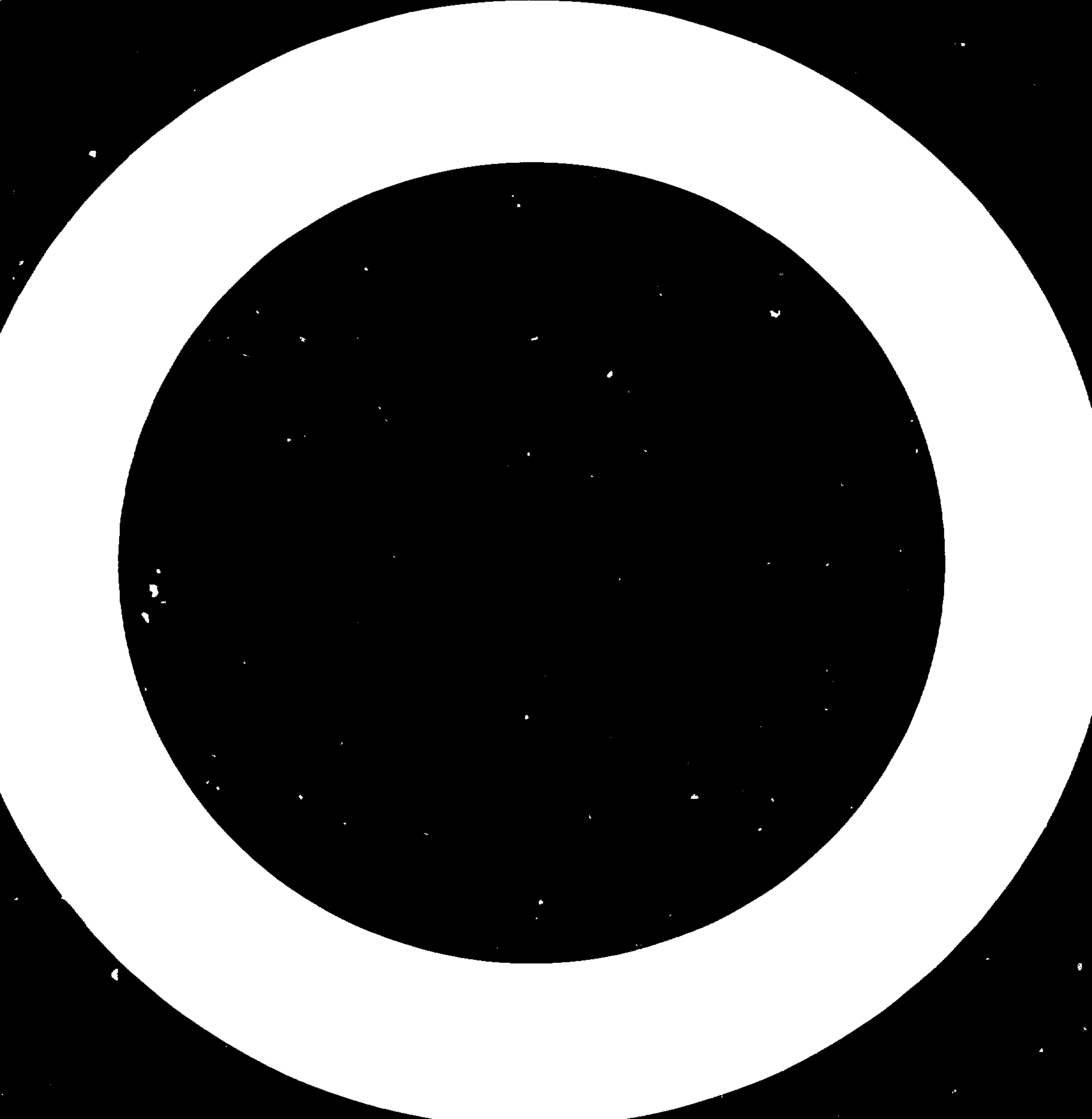
| | |
|---|---|
| CES | computerized evaluation system |
| RHC | rapid-hardening cement |
| LOI | loss on ignition |
| LSF | lime saturation factor |
| SRC | sulphate-resisting cement |

# ABSTRACT

This project, "Assistance to the Libyan Cement Factory, Benghazi" (TF/LIB/82/002), is being carried out for the authorities of the Libyan Arab Jamahiriya by the United Nations Industrial Development Organization (UNIDO) under a trust-fund agreement. The project, which has been in operation since 1975, represents a new form of technical assistance with direct support to industry. The expert took over as co-ordinator of project activities in May 1980.

Apart from his duties in connection with the Libyan Cement Company the expert is asked from time to time to advise on the problems of other cement plants in the Jamahiriya. In this case, he was asked to evaluate the raw-materials situation of the Al Khums I Cement Plant and the production options open to it.

The expert reviews and comments on the findings of investigations previously carried out by Polservice on the Mannubia and Kebir limestone deposits and describes other deposits investigated and their possible exploitation. The proposal to convert the Al Khums I plant to the production of rapid-hardening cement is discussed and the expert recommends an alternative proposal to introduce the production of sulphate-resisting cement.



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# INTRODUCTION

This project, "Assistance to the Libyan Cement Factory, Benghazi" (TF/LIB/82/002), is being carried out for the authorities of the Libyan Arab Jamahiriya by the United Nations Industrial Development Organization (UNIDO) under a trust-fund agreement. The project, which has been in operation since 1975, represents a new form of technical assistance with direct support to industry. The expert took over as co-ordinator of project activities in May 1980.

The co-ordinator is not only involved in the administration of the technical-assistance team and the day-to-day running of the Libyan Cement Company plants in Benghazi, but also advises on the problems of the cement industry in general and of other cement plants in the Libyan Arab Jamahiriya. In this case, he was asked to evaluate the raw-material situation of the Al Khums I cement plant of the National Cement and Building Materials Company.

The Al Khums I Cement Plant is situated 110 kilometres east of Tripoli and 10 kilometres west of the town of Al Khums on the northern side of the Tripoli-Al Khums highway, and lies approximately two kilometres from the sea. This cement plant was the first to be built in the country and started up production in January 1969 with an output capacity of 330 tonnes of clinker per day and 108,900 tonnes per year. During the period 1972-1974, the plant was extended by a second production line with an output of 1,000 tonnes of clinker per day and 330,000 tonnes per year.

Both production lines had some problems due to bottlenecks in the clinker and cement processing. Production line I managed to reach 95% of its rated capacity but production line II has not reached more than 72% of its rated capacity up to the time of writing this report, although the capacity of the kiln to produce 1,000 tonnes of clinker per day has been established.

The raw materials used in the Al Khums I Cement Plant (limestone and marl) were excavated from two main deposits, marl from the Margheb deposit and limestone from the Juma deposit. The Margheb deposit is situated about 400 metres north-east of the factory and the Juma deposit lies about 2.5 kilometres south-west of the cement plant. The upper limestone bench of the Juma deposit had limestone reserves sufficient for a short period only. Accordingly the General National Organization for Industrialization (GNOI) contracted with Polservice (Poland) in September 1973 to investigate the actual and potential reserves of limestone and marl in the area and determine their suitability for cement manufacture at Al Khums. Polservice carried out geological investigations on the Margheb, Mannubia and Kebir deposits. They submitted the report on their evaluation in 1974.

As mentioned above, neither of the two production lines had managed to reach their rated capacity. The Secretariat of Heavy Industries therefore considered two alternative plans, either to modify the Al Khums I plant so as to change its production from normal Portland cement to that of rapid-hardening, high-strength cement (Alternative A) or to completely overhaul the plant to enable it to reach its rated capacity of normal Portland cement production, introducing any necessary modifications (Alternative B). The modifications were to be carried out by the contractor on a turnkey, lump-sum basis and were to include the supply and erection of all the mechanical and electrical equipment, commissioning, civil works, documents, know-how, spare-parts, technical assistance and training of Secretariat personnel. The Secretariat assigned a committee to study and prepare the tender documents for the modification and overhauling of the plant. The committee finished preparing the tender documents at the end of 1980.

In the meanwhile, a second cement plant, Al Khums II, was under construction at Libda. Early in 1981, A. El Gheriani, the Under-Secretary of Heavy Industries asked the co-ordinator to visit the Al Khums I and Al Khums II cement plants to assess the production situation of the first plant and to participate in solving the problem of lump formation in the cement silos of the second plant (see report, UNIDO/IO/R.33, 28 October 1981).

Concerning the situation at Al Khums I, the co-ordinator gave it as his opinion that, before considering the details of overhauling the production lines, it would be necessary first to study the situation of the raw materials used in the plant's production. The co-ordinator expressed his willingness to carry out this evaluation. He also gave it as his opinion that the raw materials available locally might be more suitable to the production of sulphate-resisting cement than to the production of rapid-hardening cements and that serious consideration ought to be given to this since the proposed modifications to Al Khums I were expected to cost up to 80% of the cost of a new cement plant.

In February 1983, M. Fereg, Secretary of the National Cement and Building Materials Company, asked I. El Ghadamsi, Secretary of the People's Committee of the Libyan Cement Company, to release the co-ordinator from his duties in Benghazi to study the reports on the raw materials at Al Khums and to evaluate the situation. This was agreed and the co-ordinator studied the Polservice reports after visiting the quarries and investigating the various deposits on the spot. In this report, the co-ordinator gives the findings of the Polservice report and comments on them. He also gives additional material and expresses his own view on the situation.

He acknowledges the support and assistance given by the Al Khums Cement Plant, The Secretariat of Heavy Industries and the Libyan Cement Company.

## RECOMMENDATIONS

1. Further investigation has to be carried out of the raw materials in both the Mannubia and Kebir deposits by drilling more boreholes. The purpose of these is to determine the true bedding conditions and assess the suitability of each metre of depth in the deposit. Especially in the marly zones, it is necessary to select the most suitable areas in terms of quality and quantity in order to add these to the proven ore reserves. The boreholes have to be supplemented by digging more trenches surrounding the limestone outcrops.

2. In the areas of the Juma and Cretaceous limestone deposits, further investigation has also to be carried out by drilling more boreholes. Drilling in the Juma area ought to avoid penetrating the strata below 95.0 metres above sea level because of the magnesia contamination. This level can be varied according to the results of the abbreviated analyses for calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) content to be carried out on the spot at the time of investigation. It is hoped to confirm sufficient reserves of raw materials in both areas to supply the Al Khums Cement Plant for at least ten years more.

3. Evaluation of the geochemical data obtained from both the previous and the newly-recommended raw-material investigations can be substantially speeded up by a recently-developed computation system (Computerized Raw-Material Evaluation System).

4. The modifications to the Al Khums I Cement Plant, being planned by the Secretariat for Heavy Industries, must include the following:

(a) Erection of a suitable stockpile to provide finished products of a constant quality whilst adapting production to the inhomogeneous nature of the Mannubia and Kebir deposits. The main reason for erecting such an intermediate device is to avoid fluctuations in the chemical composition of the raw materials over periods of several days and to achieve a homogeneous raw mix so that the quality of the clinker produced is more nearly constant;

(b) Installation of a reliable sampling station to take representative samples of the raw materials coming in so as to have a precise knowledge of the mean chemical composition of the prehomogenization stockpile during its formation and to enable the necessary corrections to be made;

(c) The minimum equipment required is a programmable table-top computer in conjunction with x-ray flouresence analysis equipment and controls for the lime standard, silica modulus and alumina modulus. In this system, the computer would give print-outs indicating the readjustment required to the weighing machines.

If at least two of these modification methods are applied, constant and optimum quality of the raw materials can be achieved. The output of the basic raw materials from the deposits available to the plant will also be maximized by these methods of quality control.

5. Instead of the proposal to introduce the production of rapid-hardening cement, it is recommended to switch the production of the Al Khums I Cement Plant to sulphate-resisting cement. This would solve the problem of the

heterogeneity of the raw materials and would avoid the need to import bauxite. According to the author, all the raw materials needed for the production of sulphate-resisting cement are present.

6. If the plant authorities accept the idea of producing sulphate-resisting cement, it would be necessary to carry out some further laboratory investigations on the prevailing raw materials to be sure of the quality of the sulphate-resisting cement produced.

# I. GEOLOGICAL INVESTIGATIONS OF THE MANNUBIA AND KEBIR DEPOSITS

## A. Findings of the Polservice report of 1974

### Location of the investigated area

The main coastal road passes across the southern slopes of Ras el Kebir and Ras Mannubia. The area investigated was that of these two hills and covers about 22 square kilometres, lying some 2.5 kilometres from the Al Khums cement factory. These two hills are considered as the main sources of the basic raw materials, limestone and marl, and are relied on to contain proved reserves. Beside these two hills, Polservice examined another three areas; the Juma hill which contains limestone and marl, the Margheb hill (already being exploited) which contains clays and calcareous raw materials and an unnamed area of Cretaceous limestone occurrence.

### Investigations carried out

To fulfil the contract obligations, Polservice carried out drilling, trenching and pitting work in the different locations as shown in table 1. Forty-six boreholes with a total depth of 2,800 metres were drilled.

Table 1. Investigations carried out by Polservice

| | Type of investigation | | | | | |
|---|---|---|---|---|---|---|
| | Drilling | | Trenching | | Pitting | |
| Locality | Number of boreholes | Depth (m) | Number of trenches | Length (m) | Number of pits | Depth (m) |
| Margheb | 3 | 110.0 | 2 | 193.3 | 1 | 6.7 |
| Mannubia | 13 | 983.0 | 4 | 523.7 | | |
| Kebir | 17 | 997.0 | 2 | 255.5 | | |
| Cretaceous limestone | 7 | 406.5 | - | | | |
| Juma | 6 | 393.5 | - | | | |
| Total | 46 | 2 800.0 | 8 | 918.5 | 1 | 6.7 |

Table 2 shows the number of samples from these boreholes and trenches which were analysed by Polservice.

Table 2. Number of samples analysed

| | Chemical analyses | | | | |
|---|---|---|---|---|---|
| Locality | Abbreviated | Partial | Complete | Mineralogical analyses | Bulk-sample analyses |
| Mannubia and Kebir limestone | 1 523 | 217 | 304 | 33 | 66 |
| Juma and Cretaceous limestone | 524 | 11 | 87 | | |
| Iron ore | | | | | 15 |
| Total | 2 047 | 228 | 391 | 33 | 81 |

In addition, Polservice drew the following topographic contour maps:

(a) Of the entire investigated area (scale 1:5,000, 22.5 $k^2$);

(b) Of the area of Margheb, Mannubia, Kebir and Cretaceous limestone occurrences (scale 1:1,000, 5.0 $k^2$);

(c) Of the Mannubia-Kebir area for quarry and explosives-store design (scale 1:5,000, 1.4 $k^2$);

(d) Twenty one (21) cross-section maps of the Mannubia-Kebir deposit were made.

This chapter is concerned with the report on the Mannubia and Kebir deposits which supply the Al Khums I cement plant. The Juma and Cretaceous deposits, which were intended to supply the projected new factory, Al Khums II, are discussed separately in chapter III.

## Geological structure

The geological structure of the Mannubia deposit is very regular as the changes in base altitude and thickness of the individual members of the succession of strata are gradual. Table 3 describes the strata starting with the top of the deposit and indicates the range of thickness, type of material, altitude and the calcium oxide (CaO), calcium carbonate ($CaCO_3$) and magnesia (MgO) content of both the Mannubia and Kebir deposits as well as the silica and alumina moduli of the Mannubia deposit. Geologically, these are of Tertiary age.

The structure of the Kebir deposit is less regular than that of the Mannubia deposit. The individual members of the succession of strata show a wide range of variation both in base altitude and in thickness.

## Exploitable reserves at Mannubia and Kebir

Polservice indicated that the Mannubia and Kebir deposits can be divided into three main exploitable levels. The rocks of each level are of the same workability.

The three main levels of the Mannubia deposit are as follows.

Level I. Uppermost layer, composed of limestone, high-component raw material. The spot datum (top) of the level is 154.0 metres above sea level.

Level II. Middle layer, thickness around 12 metres, composed of marls, low-component raw material. The top of the level is 142 metres above sea level.

Level III. Lowest layer, 12 metres thick, composed of marls and limestones, it is a complete raw material. The bottom of this level is in line with the lowest boundary of the deposit. The spot level is 130 metres above sea level.

Table 3. Geological structure of Mannubia and Kebir deposits

| Locality | Superficial deposit | Upper marl | Upper limestone | Lower marl | Lower limestone | Lower series |
|---|---|---|---|---|---|---|
| Mannubia | | | | | | |
| Range of thickness (metres) | Variable, ranging from 0.2-2.6, increasing to 4 on the slopes | 0-6 depending upon morphology | 6.3-11.9, increasing from SE to NW | 17.5-24.8, increasing from SE to NW | 1.2-6.6, thickest in SE | 18.7-30.2, highest in the NW part of Mannubia |
| Material | Calcrete crust and limestone rubble | Nodular calcareous marl, mottled, brick red and white | Very hard limestone, grey-pinkish, porous (small areas) | Calcareous silty clay or friable chalky marl, yellow to grey | Yellowish grey or whitish yellow, hard, locally oolitic | Consists of alternating clays, marls, limestone. Clays occasionally silty |
| Altitude (metres above sea level) | | Ranges from 160-165.5 | Ranges from 151.7-156.5 | 131.2-137 | 128.0-133.1 | 101.0-111.4 |
| Quality: | | | | | | |
| CaO (%) | | 41.09-50.19 | 51.31-54.4 | 27.8-46.46 | 48.54-50.16 | 20.25-46.19 |
| $CaCO_3$ (%) | | 73.4-89.6 | 91.6-97.2 | 49.64-82.96 | 86.7-89.57 | 36.16-82.19 |
| MgO (%) | | 0.3-1.22 | 0.1-0.5 | 0.00-4.54 | 0.2-0.9 (4.25)[b] | 0.08-2.62 |
| Silica modulus | | 3.0-4.37 | 1.05-3.39 | 1.97-3.74 | 1.84-3.43 | 3.98-6.07 |
| Alumina modulus | | 1.85-3.65 | 1.34-6.19 | 2.19-3.26 | 1.18-4.2 | 1.85-3.34 |
| Kebir | | | | | | |
| Range of thickness (metres) | Does not differ from that of Mannubia | 4-5 discontinuous layer | 3.2-12.3 discontinuous layer | 5.9-20.0 | 1.0-5.4 | 8.3-18.7 |
| Material | Calcrete crust and limestone rubble | As in Mannubia | As in Mannubia | Upper part nodular marl and lower part tough limestone | As in Mannubia | The lithology is diversified as the CaO content varies widely |
| Altitude (metres above sea level) | | Ranges from 167.2-167.7 | Ranges from 155.2-165.2 | Ranges from 141.7-153.6, major part of the rock classified as marl but lower as limestone | Ranges from 129.0-140.6 | Ranges from 107.1-131.7 |
| Quality: | | | | | | |
| CaO (%) | | 52.8-54.64[a] | 49.64-55.44 | 17.95-48.04 | 35.11-53.85 | 7.28-47.57 |
| i.e. $CaCO_3$ (%) | | 94.3-97.8 | 88.64-99.0 | 32.05-85.8 | 62.7-96.16 | 13.00-84.5 |
| MgO (%) | | 0.19-0.57 | 0.2-2.28 | 0.5-2.04 | 0.2-0.95 | |

[a] This was considered as marl by Polservice but should be classified as pure limestone

[b] MgO content reaches 4.25% in a few limited areas

In the Kebir deposit, three levels are similarly distinguished. Level I is composed of limestone, level II of marl and level III of limestone again. The bottom of particular levels is irregular and the spot data are variable.

The exploitable reserves of the Mannubia-Kebir deposits are the total amount present minus losses in exploitation and material left as protecting pillars. It was assumed by Polservice that the exploitation losses would not exceed 5% of the total geological reserves owing to the simple structure of the body. It was calculated by Polservice from their laboratory investigations that the volume weight of the raw materials predominating in the two areas were as follows:

High-component raw material = 2.3 t/m$^3$
Low-component raw material = 2.1 t/m$^3$
Complete-component raw material = 2.2 t/m$^3$

The co-ordinator has collected data on the exploitation of the workable reserves and these are presented in table 4.

Besides the reserves in the three layers described, Polservice identified the existence of a fourth level (bench IV) in Mannubia between 130.0 metres and 110.0 metres above sea level, containing low-grade raw material. The exploitable reserves of bench IV were calculated as 13,703,000 tonnes. Adding this to the reserves in the other three levels (after deduction for exploitation losses), Polservice obtained a figure for total reserves of 42,525,800 tonnes, or 42,526,000 tonnes as corrected upwards by the co-ordinator in table 4.

## Exploitable reserves of corrective additives

Iron ore. Polservice assessed the exploitable reserves of the iron ore deposit in the Brak-Galmoya region as being 2,214,600 tonnes. The ore had an average $Fe_2O_3$ content of 70.9%. The ratio of overburden to deposit is favourable, being 0.23 cubic metres per cubic metre. The exploitable reserves within the area designated to supply cement production at Al Khums amount to 542,000 tonnes which is sufficient to meet the demand for iron ore at that plant. The overburden of this portion is 9,400 cubic metres and the ratio of overburden to deposit is 0.043 cubic metres per cubic metre (0.017 cubic metres per tonne as the average volume weight = 2.5 tonnes per cubic metre).

Clay. Polservice discovered clay deposits under the bottom level of the original quarry at Margheb between spot datum 116.0 metres and 110.0 metres above sea level. The geological and exploitable reserves of clay in 1974 amounted to 1,215,600 tonnes and 972,500 tonnes respectively.

## Demand for raw material

The output of the quarry is determined by the overall output of the cement factory which is 440,000 tonnes of cement per year. This includes the addition of 3% gypsum to the clinker. The output of clinker is therefore 426,800 tonnes per year.

Assuming that the ratio of clinker to raw materials is 1:1.56, the quantity of raw materials required for the output of the cement plant would be 426,800 x 1.56 = 665,805 tonnes per year.

Table 4. Calculation of reserves from the Mannubia and Kebir deposits

| Deposit | level or bench number | Average thickness (m) | Average surface ($m^2$) | Geological reserves (tonnes) | (-) Reserves in protecting pillars (tonnes) | (=) Workable reserves (tonnes) | (-) Exploitation losses (tonnes) | (=) Exploitable reserves ($m^3$) | (tonnes) |
|---|---|---|---|---|---|---|---|---|---|
| Mannubia | I | 13.4 | 99 000 | 3 441 414 | 50 289 | 3 391 125 | 169 525 | 1 400 700 | 3 221 600 |
| | II | 12.0 | 223 000 | 5 690 136 | 410 936 | 5 279 200 | 264 200 | 2 388 200 | 5 015 000 |
| | III | 12.0 | 342 000 | 10 066 074 | 1 356 951 | 8 709 123 | 435 523 | 3 760 700 | 8 273 600 |
| Total | | | | 19 197 624 | 1 818 176 | 17 379 448 | 869 248 | 7 549 600 | 16 510 200[a] |
| Kebir | I | 4.9 | (not given) | 1 631 581 | 235 023 | 1 396 558 | 69 858 | 576 800 | 1 326 700 |
| | II | 10.4 | | 4 008 738 | 577 815 | 3 430 923 | 171 523 | 1 552 100 | 3 259 400 |
| | III | 13.0 | | 10 617 426 | 2 484 003 | 8 133 423 | 406 723 | 3 512 100 | 7 726 700 |
| Total | | | | 16 257 745 | 3 296 841 | 12 960 904 | 648 104 | 5 641 000 | 12 312 800 |
| Total of both areas | | | | 35 455 369 | 5 115 017 | 30 340 352 | 1 517 352 | 13 190 600 | 28 823 000[b] |

[a] The Polservice report estimates 16 510 000 tons

[b] The Polservice report estimates 28 822 800 tons

Given the nature of the particular raw materials from the Mannubia-Kebir deposit and the raw-mix requirements, the percentage of each component will be:

| | |
|---|---|
| Basic raw materials (limestone and marl) | 95.0% |
| Iron ore | 1.5% |
| Clay | 3.5% |

Therefore, the demand for the basic raw materials (limestone and marl) will be 95% of 665,805, which is 633,000 tonnes per year. Taking into account 17% loss during exploitation and processing, the output of the quarry will be 740,000 tonnes per year. The yearly feed to the crusher will be 696,300 tonnes or 383.0 tonnes per hour.

Duration of reserves

Assuming a quarry output of 740,000 tonnes per year, the lifetime of the reserves were estimated by Polservice by dividing the quantity of material in each exploitable area by the amount to be extracted annually. The results are given in table 5, which shows also the phases in which the exploitation of the quarry is planned and the reserves attached to them.

Table 5. The lifetime of the raw-materials reserves of the Mannubia and Kebir deposits

| Phase of exploitation | Designation of area | | Reserves attached to the phase (tonnes) | Duration of reserve (years) |
|---|---|---|---|---|
| | Deposit | Level | | |
| 1 | Mannubia | I + II | 5 696 600 | 7.7 |
| 2 | Mannubia | II + III | 4 358 900 | 5.9 |
| 3 | Mannubia<br>Kebir | II<br>I | 2 039 500 | 2.8 |
| 4 | Mannubia | II + III | 2 171 400 | 3.0 |
| 5 | Mannubia | III | 1 006 900 | 1.4 |
| 6 | Mannubia<br>Kebir | III<br>I | 2 328 800 | 3.1 |
| 7 | Kebir | I + II + III | 11 220 700 | 15.2 |
| Total | | | 28 822 800 | 39.0 |

The total reserves of these two deposits were estimated to last for about 39 years.

The Margheb deposit which was already being exploited at the time of the Polservice report in 1974 was estimated only to be sufficient for production up to the end of 1975.

## B. Results of the chemical analyses

On the samples taken from the various deposits (shown in table 1), Polservice carried out analyses of the chemical composition (see table 2). The results of the chemical analyses show that the Mannubia and Kebir deposits are formed of limestone, marly limestone, marl and clay. The limestone forms the capping as well as the base rocks. Marly limestone as well as marl and clay rocks form the medium layers.

However, a full description of the chemical composition of the deposits was not given by Polservice. The co-ordinator feels that it would be helpful to give this additional material here.

### The Mannubia deposit

Full details of the chemical composition of the samples from the Mannubia deposit are given in table 6.

Upper limestone zone. The limestone predominating in the capping as well as in the lower levels of the Mannubia ridge is of both high- and medium-quality calcium carbonate. The calcium oxide (CaO) of the capping rocks ranges from 54.4%, as represented in borehole M-6, to 43.17%, as shown in borehole M-10. Magnesia (MgO) ranges from 1.35%, as represented in borehole M-12, to 0.1%, as shown in the chemical analyses of borehole M-8. The alumina ($Al_2O_3$) ranges from 2.7%, as represented in borehole M-12, to 0.26%, as shwon in borehole M-6. The iron-oxide ($Fe_2O_3$) content ranges from 0.7%, as represented in boreholes M-7 and M-12, to 0.04%, as shown in borehole M-9. The silica ($SiO_2$) content ranges from 8.78% as represented in borehole M-6, to 1.02% as shown in borehole M-11. The sulphate ($SO_3$) percentage is a maximum of 0.17% in boreholes M-3 and M-6 and a minimum of 0.02% in borehole M-8. Alkalies and chlorides are relatively low.

From the lithological point of view, the upper limestone zone is contaminated by marl and clay/marl layers. These foreign layers have their own characteristic chemical composition and they influence the carbonate content of the limestone zone, i.e. the calcium and magnesium carbonates. These foreign layers are present in boreholes M-2, M-10, M-11, M-12 and M-13. The main effect of these foreign layers is to decrease the average percentage of the carbonate content of the whole upper limestone deposit and to increase correspondingly the silica, alumina, iron oxide and alkali contents.

The $SiO_2$, MgO, $Na_2O$, $K_2O$ and chlorine-ion content of the upper limestone samples indicate the following:

(a) The silica content is generally highest in the southern and the eastern boreholes (M-10, M-3, M-13, M-12, M-9, M-6). The silica gradually decreases to the north-eastern boreholes as shown in boreholes M-4 and M-1. The minimum silica content is shown in borehole M-2. The silica content tends always to decrease descending from the upper layers to the lower ones. From these analyses it can be stated that the limestone is somewhat silicified. The silicification can be attributed to ageing as well as to the additional silica content of the marly laminae contained in the limestone deposit;

Table 6. Chemical analyses of borehole samples from the Mannubia deposit[a]

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOT (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| **M-1** | | | | | | | | | | | | | |
| Spot level | 162.4[b] | | | | | | | | | | | | |
| Upper limestone | 0.0 | 6.3 | 41.26 | 53.10 | 0.08 | 3.47 | 1.03 | 0.39 | 0.11 | 0.05 | 0.20 | 95.00 | |
| Lower marl | 6.3 | 8.5 | 23.54 | 27.48 | 0.98 | 38.78 | 5.47 | 2.53 | 0.13 | 0.18 | 0.98 | 49.00 | |
| | 8.5 | 14.0 | 34.13 | 41.25 | 0.74 | 16.57 | 4.19 | 1.73 | 0.10 | 0.09 | 0.65 | 73.66 | |
| | 14.0 | 20.0 | 34.68 | 41.89 | 1.71 | 15.00 | 4.15 | 1.58 | 0.09 | 0.09 | 0.67 | 74.80 | |
| Lower limestone | 20.0 | 27.0 | 37.85 | 48.40 | 0.00 | 8.79 | 2.66 | 1.10 | 0.11 | 0.08 | 0.42 | 86.43 | |
| | 27.0 | 29.0 | 38.58 | 48.80 | 0.00 | 7.61 | 2.90 | 1.09 | 0.08 | 0.06 | 0.40 | 87.85 | |
| | 29.0 | 34.4 | 39.66 | 50.66 | 0.08 | 5.64 | 2.19 | 0.87 | 0.10 | 0.06 | 0.31 | 90.6 | |
| Rest of borehole | 34.4 | 65.0 | Marl and lowest bed (55.6-65.0 m) dolomitic rock. | | | | | | | | | | |
| **M-2** | | | | | | | | | | | | | |
| Spot level | 168.6 | | | | | | | | | | | | |
| Upper marl | 0.0 | 3.1 | 34.24 | 41.09 | 0.60 | 17.05 | 4.68 | 1.53 | 0.16 | 0.10 | 0.36 | 74.4 | |
| Upper limestone | 3.1 | 8.6 | 42.54 | 53.67 | 0.40 | 1.71 | 1.03 | 0.23 | 0.09 | 0.05 | 0.12 | 96.55 | |
| | 8.6 | 11.1 | 24.32 | 28.72 | 0.81 | 35.55 | 6.81 | 2.55 | 0.06 | 0.14 | 0.82 | 52.73 | Marly layer |
| | 11.1 | 15.0 | 42.68 | 53.79 | 0.43 | 1.54 | 0.92 | 0.31 | 0.12 | 0.09 | 0.12 | 96.82 | |
| Lower marl | 15.0 | 24.6 | 31.17 | 36.68 | 1.62 | 19.37 | 7.71 | 2.13 | 0.08 | 0.10 | 0.58 | 68.39 | |
| | 24.6 | 33.9 | 35.61 | 42.79 | 0.91 | 12.43 | 5.62 | 1.62 | 0.07 | 0.12 | 0.54 | 78.03 | |
| Lower limestone | 33.8 | 38.3 | 38.00 | 48.54 | 0.90 | 7.62 | 3.15 | 0.75 | 0.11 | 0.08 | 0.30 | 86.70 | |
| Rest of borehole | 38.8 | 71.0 | Marl and lowest bed (66.8-71.0 m) dolomitic rock. | | | | | | | | | | |

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[a] Based on the results of chemical analyses carried out by Polservice in 1974.

[b] Spot levels are given in metres above sea level.

continued

Table 6 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| M-3 | | | | | | | | | | | | | |
| Spot level | 161.1 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 4.0 | 40.35 | 48.85 | 0.80 | 6.25 | 2.00 | 0.64 | 0.10 | 0.29 | 0.23 | 88.7 | |
| | 4.0 | 10.7 | 40.14 | 49.49 | 0.40 | 6.37 | 2.00 | 0.67 | 0.17 | 0.45 | 0.30 | 89.1 | |
| Lower marl | 10.7 | 14.5 | 36.41 | 44.14 | 0.80 | 12,30 | 3.83 | 1.32 | 0.13 | 0.33 | 0.52 | 80,25 | |
| | 14.5 | 22.0 | 34.72 | 41.50 | 1.11 | 15.30 | 4.51 | 1.72 | 0.14 | 0.30 | 0.68 | 76.1 | |
| | 22.0 | 28.6 | 35.27 | 42.63 | 0.70 | 13.78 | 4.48 | 1.62 | 0.16 | 0.38 | 0.71 | 77.3 | |
| Lower limestone | 28.6 | 33.4 | 38.77 | 47.41 | 0.90 | 7.86 | 2.33 | 1.17 | 0.12 | 0.6 | 0.45 | 86.27 | |
| Rest of borehole | 33.4 | 67.0 | Marl | | | | | | | | | | |
| M-4 | | | | | | | | | | | | | |
| Spot level | 166.5 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 7.6 | 42.41 | 52.95 | 0.75 | 2.70 | 0.66 | 0.22 | 0.08 | 0.03 | 0.01 | 95.9 | |
| Lower marl | 7.6 | 16.0 | 27.79 | 33.06 | 1.17 | 28.85 | 6.10 | 1.55 | 0.07 | 0.10 | 0.93 | 61.13 | |
| | 16.0 | 22.8 | 34.86 | 42.03 | 1.45 | 15.29 | 4.04 | 1.20 | 0.03 | 0.04 | 0.55 | 75.08 | |
| Lower limestone | 22.8 | 29.5 | 38.54 | 47.62 | 0.97 | 8.34 | 2.74 | 0.94 | 0.03 | 0.04 | 0.39 | 86.8 | |
| | 29.5 | 35.1 | 32.67 | 42.30 | 0.81 | 6.34 | 2.31 | 0.79 | 0.04 | 0.04 | 0.31 | 89.6 | |
| Rest of borehole | 35.1 | 69.0 | Marl and the lowest bed (65-69m) dolomitic rock. | | | | | | | | | | |

continued

Table 6 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| M-5 | | | | | | | | | | | | | |
| Spot level | 166.3 | | | | | | | | | | | | |
| Upper marl | 0.0 | 6.0 | 38.[illegible] | 45.9 | 1.07 | 11.18 | 1.79 | 0.87 | 0.08 | 0.19 | 0.32 | 83.9 | |
| Upper limestone | 6.0 | 12.4 | 42.34 | 52.85 | 0.49 | 2.78 | 0.47 | 0.35 | 0.04 | 0.12 | 0.26 | 95.25 | |
| | 12.4 | 14.6 | 41.08 | 51.55 | 0.24 | 4.27 | 1.58 | 0.54 | 0.03 | 0.10 | 0.22 | 92.48 | |
| Lower marl | 14.6 | 24.0 | 31.31 | 36.84 | 1.42 | 22.08 | 4.58 | 2.09 | 0.06 | 0.30 | 0.85 | 68.32 | |
| | 24.0 | 30.4 | 35.82 | 41.05 | 1.41 | 14.72 | 4.53 | 2.04 | 0.03 | 0.26 | 0.75 | 75.82 | |
| | 30.4 | 32.4 | 81.0 | 44.28 | 1.08 | 11.91 | 3.69 | 1.57 | 0.07 | 0.11 | 0.57 | 81.0 | |
| Lower limestone | 32.4 | 35.6 | 90.6 | 50.16 | 0.58 | 5.26 | 1.78 | 0.97 | 0.08 | 0.07 | 0.26 | 90.6 | |
| Rest of borehole | 35.6 | 69.0 | **Marl and the lowest bed (64.3-69.0.m.) dolomitic rock.** | | | | | | | | | | |
| M-6 | | | | | | | | | | | | | |
| Spot level | 166.6 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 4.0 | 39.6 | 47.66 | 1.21 | 8.78 | 1.46 | 0.55 | 0.17 | 0.14 | 0.25 | 87.26 | |
| | 4.0 | 13.0 | 43.27 | 54.40 | 0.50 | 1.10 | 0.26 | 0.12 | 0.15 | 0.04 | 0.06 | 98.04 | |
| Lower marl | 13.0 | 22.8 | 31.98 | 38.04 | 1.67 | 20.43 | 4.62 | 1.75 | 0.11 | 0.08 | 0.83 | 70.9 | |
| | 22.8 | 30.8 | 36.68 | 45.08 | 1.20 | 11.9 | 2.87 | 1.27 | 0.09 | 0.05 | 0.57 | 82.64 | |
| Lower limestone | 30.8 | 35.5 | 39.72 | 49.81 | 0.59 | 6.9 | 1.49 | 0.70 | 0.11 | 0.03 | 0.28 | 90.0 | |
| Rest of borehole | 35.5 | 68.0 | Marl and the lowest bed (59.5-68.0 m.) dolomitic rock | | | | | | | | | | |

continued

Table 6 (continued)

| Borehole no. | Thickness |  | Full analyses |  |  |  |  |  |  |  |  | Carbonate (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) |  |  |
| M-7<br>Spot level | 168.4 |  |  |  |  |  |  |  |  |  |  |  |  |
| Upper marl | 0.0 | 2.3 | 37.57 | 46.81 | 1.20 | 9.49 | 2.96 | 1.09 | 0.07 | 0.15 | 0.32 | 85.75 | Calcareous marl |
|  | 2.3 | 5.7 | 22.39 | 24.72 | 1.03 | 40.2 | 7.07 | 2.81 | 0.21 | 0.18 | 0.72 | 45.98 |  |
| Upper limestone | 5.7 | 15.9 | 39.95 | 49.59 | 0.68 | 6.28 | 1.80 | 0.74 | 0.06 | 0.10 | 0.38 | 89.77 |  |
| Lower marl | 15.9 | 27.0 | 2.04 | 38.21 | 1.12 | 20.81 | 4.50 | 1.92 | 0.10 | 0.21 | 0.53 | 70.23 |  |
| Lower limestone | 27.0 | 38.0 | 36.18 | 44.12 | 0.83 | 13.21 | 3.41 | 1.22 | 0.07 | 0.17 | 0.47 | 80.26 |  |
| Dolomitic limestone | 38.0 | 40.0 | 40.08 | 44.75 | 4.25 | 6.77 | 2.50 | 1.07 | 0.05 | 0.13 | 0.28 | 81.39 |  |
| Rest of borehole | 40.0 | 71.0 | Marl and lowest bed (53.5-71.0 m) dolomitic rock. |  |  |  |  |  |  |  |  |  |  |
| M-8<br>Spot level | 167.2 |  |  |  |  |  |  |  |  |  |  |  |  |
| Upper marl | 0.0 | 4.5 | 36.2 | 42.93 | 1.22 | 14.14 | 3.65 | 1.06 | 0.06 | 0.30 | 0.30 | 78.84 |  |
| Upper limestone | 4.5 | 11.2 | 41.30 | 52.08 | 0.10 | 4.02 | 1.65 | 0.42 | 0.02 | 0.15 | 0.12 | 93.17 |  |
|  | 11.2 | 16.2 | 25.33 | 29.06 | 1.23 | 31.46 | 8.88 | 2.70 | 0.06 | 0.2 | 1.07 | 54.1 |  |
| Lower marl | 16.2 | 25.0 | 34.05 | 41.76 | 1.02 | 16.22 | 3.89 | 1.57 | 0.02 | 0.20 | 0.60 | 76.4 |  |
|  | 25.0 | 36.0 | 37.58 | 46.46 | 0.50 | 10.07 | 3.21 | 1.24 | 0.05 | 0.15 | 0.42 | 83.86 |  |
| Lower limestone | 36.0 | 40.8 | 39.63 | 50.07 | 0.20 | 6.82 | 1.89 | 0.72 | 0.03 | 0.14 | 0.25 | 89.76 |  |
| Rest of borehole | 40.8 | 70.0 | Marl and lowest bed (60-70 m) dolomitic calareous marl |  |  |  |  |  |  |  |  |  |  |

continued

Table 6 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| M-9 | | | | | | | | | | | | | |
| Spot level | 169.2 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 5.0 | 40.57 | 49.40 | 0.73 | 7.13 | 0.91 | 0.10 | 0.15 | 0.25 | 0.73 | 89.52 | |
| | 5.0 | 10.8 | 42.35 | 52.90 | 0.32 | 2.83 | 0.43 | 0.10 | 0.15 | 0.25 | 0.65 | 95.03 | |
| | 10.8 | 12.8 | 21.75 | 24.70 | 1.23 | 43.56 | 4.43 | 0.03 | 0.25 | 1.00 | 2.91 | 46.3 | Marl |
| | 12.8 | 15.7 | 42.52 | 52.89 | 0.48 | 2.87 | 0.35 | 0.04 | 0.10 | 0.20 | 0.50 | 95.3 | |
| Lower marl | 15.7 | 24.5 | 33.38 | 38.06 | 2.45 | 19.14 | 3.52 | 0.03 | 0.15 | 0.70 | 2.42 | 72.33 | |
| | 24.5 | 34.7 | 36.21 | 42.44 | 1.38 | 14.24 | 2.78 | 0.05 | 0.10 | 0.65 | 1.97 | 78.25 | |
| Lower limestone | 34.7 | 38.6 | 38.08 | 47.05 | 0.56 | 10.56 | 1.56 | 0.07 | 0.22 | 0.40 | 1.22 | 85.02 | |
| Rest of borehole | 38.6 | 72.0 | Marl and lowest bed (64.0-72.0 m) dolomitic calcareous marl. | | | | | | | | | | |
| M-10 | | | | | | | | | | | | | |
| Spot level | 164.3 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 2.0 | 40.11 | 49.06 | 1.21 | 7.31 | 1.76 | 0.52 | 0.10 | 0.10 | 0.17 | 89.76 | |
| | 2.0 | 5.4 | 42.23 | 52.86 | 0.60 | 2.89 | 0.92 | 0.28 | 0.09 | 0.11 | 0.13 | 95.46 | |
| | 5.4 | 7.3 | 35.44 | 43.17 | 0.80 | 15.17 | 3.76 | 1.20 | 0.10 | 0.12 | 0.35 | 78.5 | Calcareous marl |
| | 7.3 | 9.1 | 42.12 | 52.95 | 0.4 | 2.72 | 1.06 | 0.40 | 0.08 | 0.10 | 0.15 | 95.26 | |
| Lower marl | 9.1 | 19.0 | 34.55 | 42.04 | 0.80 | 15.4 | 5.18 | 1.56 | 0.06 | 0.12 | 0.35 | 76.5 | |
| | 19.0 | 29.0 | 34.5 | 41.60 | 1.02 | 15.2 | 5.29 | 1.76 | 0.04 | 0.12 | 0.35 | 76.1 | |
| | 29.0 | 34.2 | 34.7 | 42.77 | 0.60 | 16.48 | 3.59 | 1.04 | 0.06 | 0.13 | 0.35 | 77.45 | |
| Lower limestone | 34.2 | 35.8 | 38.01 | 46.67 | 1.21 | 8.25 | 4.00 | 0.96 | 0.04 | 0.10 | 0.18 | 85.4 | |
| Rest of borehole | 35.8 | 56.0 | Marl and lowest bed (52.9-56.0 m) dolomitic calcareous marl. | | | | | | | | | | |

continued

Table 6 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| M-11 | | | | | | | | | | | | | |
| Spot level | 170.0 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 4.0 | 39.31 | 48.80 | 0.70 | 8.21 | 1.61 | 0.53 | 0.10 | 0.12 | 0.32 | 88.39 | |
| | 4.0 | 5.6 | 19.55 | 21.42 | 0.50 | 45.02 | 8.45 | 3.28 | 0.07 | 0.06 | 0.13 | 39.14 | Marl |
| | 5.6 | 10.3 | 41.37 | 51.31 | 0.50 | 4.63 | 1.23 | 0.43 | 0.07 | 0.06 | 0.13 | 92.52 | |
| | 10.3 | 12.8 | 20.73 | 23.57 | 0.93 | 43.70 | 6.72 | 2.60 | 0.14 | 0.25 | 0.63 | 43.75 | Marl |
| | 12.8 | 15.8 | 43.38 | 54.50 | 0.38 | 1.02 | 0.31 | 0.12 | 0.06 | 0.04 | 0.12 | 98.0 | |
| Lower marl | 15.8 | 19.0 | 27.08 | 27.80 | 4.54 | 31.0 | 6.15 | 2.17 | 0.09 | 0.18 | 0.60 | 57.75 | |
| | 19.0 | 27.0 | 36.35 | 44.91 | 0.85 | 12.50 | 3.20 | 1.15 | 0.09 | 0.08 | 0.36 | 81.71 | |
| | 27.0 | 36.3 | 35.48 | 43.56 | 0.84 | 14.18 | 3.85 | 1.32 | 0.10 | 0.17 | 0.30 | 79.28 | |
| Lower limestone | 36.3 | 39.0 | 39.05 | 48.36 | 0.86 | 8.60 | 1.91 | 0.01 | 0.09 | 0.16 | 0.38 | 87.80 | |
| | 39.0 | 45.9 | 37.57 | 46.19 | 0.80 | 11.42 | 2.29 | 0.00 | 0.10 | 0.08 | 0.32 | 83.81 | |
| Rest of borehole | 45.9 | 71.0 | Marl and lowest bed (65.1-71.0 m.) dolomitic calcareous marl. | | | | | | | | | | |
| M-12 | | | | | | | | | | | | | |
| Spot level | 169.9 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 4.8 | 39.87 | 50.19 | 0.30 | 6.05 | 2.7 | 0.74 | 0.04 | 0.10 | 0.24 | 90.16 | |
| | 4.8 | 7.8 | 25.69 | 29.95 | 1.35 | 31.89 | 6.99 | 2.37 | 0.09 | 0.25 | 0.86 | 55.89 | Marl |
| | 7.8 | 15.2 | 42.16 | 52.97 | o.30 | 2.07 | 1.67 | o.27 | 0.06 | 0.04 | 0.16 | 95.13 | |
| Lower marl | 15.2 | 23.7 | 33.58 | 41.07 | 1.02 | 16.44 | 4.98 | 1.75 | 0.05 | 0.14 | 0.65 | 75.16 | |
| | 23.7 | 35.5 | 35.63 | 42.91 | 0.72 | 14.10 | 4.17 | 1.28 | 0.04 | 0.07 | 0.61 | 77.91 | |
| Lower limestone | 35.0 | 37.9 | 39.79 | 50.14 | 0.30 | 6.45 | 1.76 | 0.58 | 0.02 | 0.09 | 0.26 | 90.07 | |
| Rest of borehole | 37.9 | 72.0 | Marl and lowest bed (68.1-72.0 m.) dolomitic calcareous marl. | | | | | | | | | | |

continued

Table 6 (continued)

| Borehole no. | Thickness |  | Full analyses |  |  |  |  |  |  |  |  |  | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) |  |
| M-13<br>Spot level | 168.8 |  |  |  |  |  |  |  |  |  |  |  |  |
| Upper limestone | 0.0 | 3.3 | 40.90 | 50.28 | 0.80 | 5.69 | 1.52 | 0.40 | 0.15 | 0.03 | 0,16 | 91.21 |  |
|  | 3.3 | 5.3 | 26.68 | 29.88 | 1.97 | 31.05 | 6.91 | 2.09 | 0.14 | 0.20 | 0.60 | 56.87 | Marl |
|  | 5.3 | 11.6 | 41.22 | 51.87 | 0.56 | 4.35 | 1.19 | 0.42 | 0.07 | 0.03 | 0.17 | 93.63 |  |
| Lower marl | 11.6 | 13.6 | 22.65 | 25.83 | 1.49 | 40.86 | 5.95 | 1.70 | 0.08 | 0.17 | 0.60 | 48.78 |  |
| Lower limestone | 13.6 | 16.2 | 42.37 | 53.35 | 0.40 | 2.40 | 0.70 | 0.30 | 0.08 | 0.03 | 0.17 | 95.98 |  |
| Calcareous marl | 16.2 | 25.5 | 34.46 | 42.27 | 1.44 | 15.79 | 3.85 | 1.19 | 0.09 | 0.07 | 0.45 | 78.05 |  |
|  | 25.5 | 38.6 | 35.97 | 44.50 | 0.98 | 12.38 | 3.69 | 1.29 | 0.08 | 0.07 | 0.54 | 81.21 |  |
| Rest of borehole | 38.6 | 72.0 | Marl |  |  |  |  |  |  |  |  |  |  |

(b) The MgO content of the upper limestone deposit is usually low (not exceeding 1.0%) throughout the stratum except in boreholes M-6 and M-10. The increase of magnesia content in some beds of these boreholes can be attributed to the presence of marly contaminations from the overlying or the underlying marly laminae or to the presence of marly layers as shown in boreholes M-9, M-12 and M-13. The lowest percentage of magnesia is found in borehole M-8;

(c) The values of $Na_2O$, $K_2O$ (alkalies) and chlorine are usually low but increase in the marly beds.

The upper limestone area is covered in some parts by marly layers as shown in boreholes M-2, M-5, M-7 and M-8. These marly layers are concentrated in the most northern part where the thickness ranges from 4.5-6.0 metres as seen in boreholes M-5 and M-8. The thickness of the marly beds decreases to the south where it varies from 2.3-3.1 metres as shown in boreholes M-2, M-6 and M-7.

Upper and lower marly zones. The upper marly zone shows the same characteristics as the lower marly zone and therefore both zones will be dealt with as one unit. The upper marly zone which caps the upper limestone zone can be considered as a calcareous marly zone as its calcium carbonate content ranges from 45.98% in the lower layer in borehole M-7 to 85.75% as shown in the upper layer in the same borehole. It is worth noting that most of these calcareous marly layers have been exploited together with the underlying upper limestone layers.

The lower marly zone is also formed of calcareous marly beds or layers. The carbonate content ranges from 48.78% (marl), as represented in borehole M-13, to 83.86% (calcareous marl) in borehole M-8. The marly zone shows variations in the carbonate content according to the clayey materials intercalating it. There is usually an increase in the carbonate content when going from the upper to the lower layers except in boreholes M-3 and M-11. The magnesia represented in the upper marly zone ranges from 0.6% (M-2) to 1.22 (M-8). In the lower marly zone it ranges from 0.5% (M-8) to 4.54% (M-11). The latter type of marl is very unsuitable for cement production when used as the main component. The silica content in the upper marly zone ranges from 9.49% to 40.2%, both shown in borehole M-7 (the upper and the lower marly layers respectively). The silica content in the lower marly zone ranges from 10.07%, as in borehole M-8, to 40.86% as in borehole M-13. The alumina content of the upper marly layer ranges from 1.79% (M-5) to 7.07% as in borehole M-7. In the lower marly zone, the alumina content ranges from 2.78% (M-9) to 8.88% (M-8). The iron oxide present in the upper marly zone ranges from 0.87% (M-5) to 2.81% (M-7), while in the lower marly zone it ranges from 0.03% (M-9) to 2.7% (M-8). The sulphate content is represented in the upper marly layer by 0.06% as the minimum (M-8) and 0.21% as the maximum (M-7). Alkalies and chlorides are relatively low due to the fact that the clay minerals are relatively low. It is worth noting that, when any of the layers constituting this marly zone tends to be more calcareous, i.e. containing more carbonates, the other oxides such as silica, alumina, iron oxide and alkalies tend to decrease. It is therefore not worth explaining in detail the silica, alumina, iron oxide and alkali content of the marly zones.

Lower limestone zone. This limestone zone lies beneath the lower marly zone. It is usually built up of more than one layer, each with its own characteristics and chemical analysis. The CaO (carbonate) forming the main constituent of this zone ranges from 44.12% (or 80.26% $CaCO_3$) as shown in borehole M-7 to 53.35% (95.98% $CaCO_3$) as shown in borehole M-13. Magnesia ranges from 0.00% as represented in borehole M-1 to 1.21% as shown in borehole M-10.

Silica is present as a minimum of 2.4% and a maximum of 13.21% both shown in borehole M-7. Alumina ranges from 0.7% (M-13) to 4.00% (M-10). Iron oxide ranges from 0.00% (M-11) to 1.22% (M-7). $SO_3$ ranges from 0.02% (M-12) to 0.22% (M-9). Alkalies and chlorides are relatively low.

The $SiO_2$, MgO, $Na_2O$ and chlorine-ion content of the lower limestone samples show the following characteristics:

(a) A silica content of more than 10% is usually met with at the centre of the Mannubia deposit as shown in boreholes M-7, M-9 and M-11 (lower layers). The southern part of the deposit (south-east and south-west) shows a relatively-high silica content as represented in boreholes M-3, M-11 (upper layer) and M-10. The silica in these layers ranges from 7.86% to 8.6%. Boreholes M-1 and M-4, located in the north-western part of the Mannubia area, also show a relatively-high silica content which ranges from 8.79% to 8.34% in the upper layers of these boreholes. The silica content usually decreases in percentage going down the limestone layers, as shown in boreholes M-1 and M-4. However, in borehole M-11, the silica increases downwards. The lowest silica content, 2.4%, can be met with south of borehole M-9 in borehole M-13;

(b) The magnesia content is relatively low;

(c) The alkali and chlorine content can also be considered as relatively low.

It should be pointed out that Polservice drilled deeper than the lower limestone zone in the Mannubia deposit. All the analyses of the strata drilled showed that they were mainly marly layers as shown in boreholes M-3 and M-13. In most of the boreholes (M-1, M-2, M-4, M-5, M-6, M-8, M-9, M-10, M-11 and M-12), these marly layers contain dolomitic beds especially in their lowest layers, as shown in table 6.

## Kebir Deposit

The complete analysis of samples from the Kebir deposit is given in table 7.

Upper limestone zone. Here, as in the Mannubia deposit, the limestone capping can be considered as of high- and medium-quality calcium carbonate. The CaO content of the capping limestone zone in the Kebir deposit ranges from 53.8% as in borehole K-3 to 47.72% as in borehole K-16. Magnesia ranges from 1.58% as in borehole K-17 (upper layer) to 0.4% as in borehole K-12. The alumina content is within the range of 1.94% (maximum) to 0-33% (minimum). Iron oxide content oscillates between 0.59% in borehole K-4 (upper layer) and 0.19% as in K-3 and K-14. The silica content ranges from 8.83% as in borehole K-4 (upper layer) to 1.37% as in borehole K-3. The $SO_3$ percentage is shown as a maximum of 0.19% in borehole K-14 and as a minimum of 0.00% in boreholes K-5, K-7 and K-9. Alkalies and chlorides are present in relatively low percentages.

## Table 7. Chemical analyses of borehole samples from the Kebir deposit[a]

| Borehole no. | Thickness From (m) | Thickness To (m) | Full analyses LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K-1 Spot level | 168.0[b] | | | | | | | | | | | | |
| Upper limestone | 0.0 | 8.1 | 43.12 | 52.27 | 0.62 | 3.05 | 0.82 | 0.26 | 0.13 | 0.05 | 0.10 | 94.33 | |
| Lower marl | 8.1 | 11.8 | 37.19 | 45.64 | 0.88 | 12.49 | 3.08 | 0.62 | 0.00 | 0.08 | 0.25 | 82.64 | |
| | 11.8 | 19.4 | 29.5 | 34.10 | 2.03 | 26.14 | 6.32 | 1.64 | 0.00 | 0.06 | 0.38 | 64.44 | |
| | 19.4 | 24.2 | 35.86 | 43.78 | 1.24 | 13.41 | 3.46 | 1.48 | 0.00 | 0.06 | 0.37 | 80.29 | |
| | 24.2 | 30.5 | 36.80 | 45.08 | 1.46 | 11.82 | 2.58 | 1.66 | 0.00 | 0.05 | 0.30 | 83.00 | |
| | 30.5 | 34.0 | 33.90 | 41.27 | 1.12 | 16.68 | 5.22 | 1.44 | 0.00 | 0.08 | 0.48 | 75.60 | |
| Rest of borehole | 34.0 | 56.5 | Marl | | | | | | | | | | |
| K-2 Spot level | 166.6 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 5.4 | 42.24 | 51.26 | 0.69 | 3.81 | 1.37 | 0.28 | 0.15 | 0.16 | 0.09 | 92.65 | |
| Lower marl | 5.4 | 13.0 | 31.21 | 36.98 | 1.72 | 19.95 | 7.11 | 2.31 | 0.17 | 0.16 | 0.45 | 69.00 | |
| Lower limestone | 13.0 | 17.7 | 38.80 | 47.58 | 0.89 | 7.55 | 3.85 | 1.08 | 0.19 | 0.10 | 0.25 | 86.44 | |
| | 17.7 | 24.2 | 39.59 | 47.75 | 0.88 | 7.98 | 2.55 | 0.96 | 0.10 | 0.09 | 0.22 | 86.73 | |
| | 24.2 | 28.3 | 41.23 | 50.93 | 0.46 | 4.67 | 1.93 | 0.48 | 0.08 | 0.09 | 0.13 | 91.65 | |
| Rest of borehole | 28.3 | 50.0 | Marl with high magnesia content. | | | | | | | | | | |

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a/ Based on the results of chemical analysis carried out by Polservice in 1974.

b/ Spot levels are given in metres above sea level.

continued

Table 7 (continued)

| Borehole no. | Thickness From (m) | Thickness To (m) | Full analyses LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K-3 | | | | | | | | | | | | | |
| Spot level | 167.8 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 4.0 | 43.01 | 53.80 | 0.78 | 1.37 | 0.33 | 0.19 | 0.09 | 0.05 | 0.07 | 97.34 | |
| Lower marl | 4.0 | 12.0 | 29.5 | 34.97 | 1.55 | 24.71 | 5.42 | 2.40 | 0.01 | 0.09 | 0.90 | 65.13 | |
| Lower limestone | 12.0 | 20.0 | 37.95 | 46.55 | 1.11 | 9.90 | 2.4 | 1.13 | 0.02 | 0.06 | 0.43 | 85.00 | |
| | 20.0 | 27.9 | 39.25 | 48.57 | 0.87 | 7.33 | 2.1 | 1.03 | 0.03 | 0.05 | 0.34 | 88.18 | |
| Rest of borehole | 27.9 | 71.0 | Marl with high magnesia content. | | | | | | | | | | |
| K-4 | | | | | | | | | | | | | |
| Spot level | 171.2 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 7.5 | 39.03 | 48.63 | 0.75 | 8.83 | 1.77 | 0.59 | 0.10 | 0.07 | 0.18 | 88.07 | |
| | 7.5 | 13.0 | 40.2 | 50.43 | 0.50 | 6.87 | 1.30 | 0.36 | 0.09 | 0.06 | 0.13 | 80.83 | |
| Lower marl | 13.0 | 23.5 | 20.75 | 22.30 | 2.57 | 39.40 | 10.30 | 3.40 | 0.08 | 0.15 | 0.93 | 44.36 | |
| Lower limestone | 23.5 | 41.9 | 38.8 | 48.19 | 0.79 | 8.55 | 2.18 | 0.92 | 0.10 | 0.08 | 0.28 | 87.36 | |
| Rest of borehole | 41.9 | 73.0 | Marl with high magnesia content. | | | | | | | | | | |
| K-5 | | | | | | | | | | | | | |
| Spot level | 165.6 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 9.2 | 40.61 | 50.89 | 0.60 | 5.38 | 1.52 | 0.48 | 0.00 | 0.12 | 0.13 | 91.83 | |
| Lower marl | 9.2 | 21.0 | 31.70 | 38.07 | 1.64 | 18.76 | 6.86 | 1.95 | 0.00 | 0.14 | 0.63 | 70.82 | |
| | 21.0 | 33.2 | 36.8 | 45.64 | 0.91 | 11.58 | 3.26 | 0.90 | 0.00 | 0.12 | 0.37 | 83.02 | |
| Rest of borehole | 33.2 | 68.0 | Marl with high magnesia content. | | | | | | | | | | |

continued

Table 7 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| K-6 | | | | | | | | | | | | | |
| Spot **level** | 166.2 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 10.5 | 40.72 | 50.85 | 0.68 | 5.75 | 1.00 | 0.48 | 0.03 | 0.06 | 0.18 | 91.9 | |
| Lower marl | 10.5 | 15.8 | 33.6 | 40.36 | 1.50 | 18.20 | 3.30 | 1.70 | 0.12 | 0.67 | 0.67 | 74.65 | |
| Lower limestone | 15.8 | 30.6 | 38.6 | 47.82 | 0.95 | 8.88 | 1.80 | 1.00 | 0.01 | 0.06 | 0.41 | 86.98 | |
| Rest of borehole | 30.6 | 54.5 | Marl with high magnesia content at lowest bed (51.8-54.5 m.) | | | | | | | | | | |
| K-7 | | | | | | | | | | | | | |
| Spot level | 172.7 | | | | | | | | | | | | |
| Upper marl | 0.0 | 3.5 | 37.8 | 45.54 | 1.49 | 11.47 | 2.58 | 0.72 | 0.00 | 0.12 | 0.25 | 83.88 | |
| | 3.5 | 5.0 | 18.6 | 18.07 | 3.06 | 45.88 | 10.60 | 2.52 | 0.00 | 0.30 | 1.16 | 37.69 | |
| Upper limestone | 5.0 | 14.7 | 40.67 | 50.50 | 0.69 | 5.58 | 1.84 | 0.28 | 0.00 | 0.10 | 0.15 | 91.29 | |
| Lower marl | 14.7 | 20.6 | 31.17 | 36.94 | 1.58 | 21.10 | 6.73 | 1.97 | 0.00 | 0.13 | 0.73 | 68.70 | |
| Lower limestone | 20.6 | 30.0 | 38.12 | 46.99 | 1.00 | 9.67 | 2.89 | 0.83 | 0.00 | 0.12 | 0.35 | 85.6 | |
| | 30.0 | 33.0 | 40.96 | 51.42 | 0.50 | 4.58 | 1.83 | 0.43 | 0.00 | 0.12 | 0.22 | 92.6 | |
| | 33.0 | 36.2 | 39.91 | 49.69 | 6.21 | 6.21 | 2.42 | 0.56 | 0.02 | 0.12 | 0.52 | 99.7 | Dolomitic limestone |
| Rest of borehole | 36.2 | 75.0 | Marl with high magnesia content (50.4-75.0 m.) | | | | | | | | | | |
| K-8 | | | | | | | | | | | | | |
| Spot level | 166.6 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 5.3 | 41.5 | 51.97 | 0.62 | 4.26 | 0.79 | 0.41 | 0.04 | 0.06 | 0.16 | 93.79 | |
| Lower marl | 5.3 | 10.5 | 27.3 | 31.2 | 1.75 | 29.61 | 5.87 | 2.50 | 0.00 | 0.1 | 1.07 | 58.86 | |
| | 10.5 | 21.8 | 37.2 | 45.5 | 1.25 | 11.35 | 2.77 | 1.33 | 0.02 | 0.07 | 0.05 | 83.47 | |
| Lower limestone | 21.8 | 27.0 | 39.7 | 49.2 | 1.04 | 6.78 | 1.74 | 0.76 | 0.03 | 0.07 | 0.34 | 89.71 | |
| | 27.0 | 29.0 | 41.6 | 52.3 | 0.42 | 3.81 | 0.96 | 0.46 | 0.02 | 0.0 | 0.16 | 94.10 | |
| Rest of borehole | 29.0 | 53.0 | Marl with high magnesia content (44.3-53.0 m.) | | | | | | | | | | |

continued

Table 7 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | | Carbon-ate (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | | |
| K-9 | | | | | | | | | | | | | |
| Spot level | 171.0 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 6.7 | 41.46 | 51.62 | 0.70 | 3.48 | 1.94 | 0.36 | 0.00 | 0.12 | 0.12 | 93.31 | |
| Lower marl | 6.7 | 15.0 | 30.31 | 36.90 | 1.00 | 21.79 | 6.97 | 2.00 | 0.00 | 0.13 | 0.57 | 67.60 | |
| Lower limestone | 15.0 | 34.7 | 37.69 | 46.75 | 0.90 | 9.05 | 3.93 | 1.00 | 0.00 | 0.07 | 0.30 | 84.98 | |
| Rest of borehole | 34.7 | 65.0 | Marl with high magnesia content (43.2-65.0 m.) | | | | | | | | | | |
| K-10 | | | | | | | | | | | | | |
| Spot level | 166.7 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 3.2 | 41.4 | 51.56 | 0.81 | 3.92 | 1.29 | 0.39 | 0.02 | 0.09 | 0.17 | 93.40 | |
| Lower marl | 3.2 | 11.3 | 31.01 | 36.85 | 1.56 | 21.83 | 5.81 | 1.56 | 0.11 | 0.12 | 0.81 | 68.50 | |
| | 11.3 | 21.3 | 37.4 | 45.5 | 1.23 | 10.93 | 2.94 | 1.06 | 0.06 | 0.10 | 0.42 | 83.34 | |
| Lower limestone | 21.3 | 28.1 | 39.5 | 48.57 | 1.22 | 6.87 | 2.09 | 0.96 | 0.10 | 0.12 | 0.31 | 88.80 | |
| Rest of borehole | 28.1 | 45.0 | Marl with high magnesia content (37.5-45.0 m.) | | | | | | | | | | |
| K-11 | | | | | | | | | | | | | |
| Spot level | 167.6 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 6.7 | 39.43 | 48.77 | 0.88 | 8.26 | 1.61 | 0.40 | 0.14 | 0.21 | 0.25 | 88.55 | |
| Lower marl | 6.7 | 11.0 | 24.97 | 28.79 | 1.37 | 32.07 | 8.69 | 2.2 | 0.05 | 0.35 | 1.4 | 53.80 | |
| | 11.0 | 18.3 | 32.52 | 38.90 | 0.78 | 19.68 | 5.44 | 1.14 | 0.06 | 0.25 | 0.95 | 70.77 | |
| Lower limestone | 18.3 | 23.1 | 38.95 | 48.1 | 0.59 | 8.64 | 2.39 | 0.58 | 0.11 | 0.25 | 0.47 | 86.86 | |
| | 23.1 | 27.0 | 38.54 | 48.42 | 0.71 | 8.53 | 2.60 | 0.70 | 0.11 | 0.15 | 0.35 | 87.62 | |
| Rest of borehole | 27.0 | 48.5 | Marl with high magnesia content | | | | | | | | | | |

continued

Table 7 (continued)

| Borehole No. | Thickness | | Full analyses | | | | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | Carbonate (%) | |
| K-12 | | | | | | | | | | | | | |
| Spot level | 167.5 | | | | | | | | | | | | |
| Upper lime-stone | 0.0 | 5.1 | 41.40 | 51.60 | 0.40 | 4.36 | 1.47 | 0.40 | 0.03 | 0.07 | 0.12 | 92.74 | |
| Lower marl | 5.1 | 10.3 | 27.52 | 32.85 | 1.03 | 28.55 | 6.71 | 2.15 | 0.00 | 0.13 | 0.76 | 60.42 | |
| | 10.3 | 14.8 | 22.30 | 25.11 | 1.21 | 37.55 | 9.42 | 3.07 | 0.00 | 0.13 | 1.00 | 46.94 | |
| | 14.8 | 18.0 | 35.7 | 44.50 | 0.60 | 11.98 | 4.98 | 1.31 | 0.00 | 0.11 | 0.38 | 80.43 | |
| Lower limestone | 18.0 | 25.8 | 39.85 | 49.78 | 0.60 | 6.19 | 2.27 | 0.72 | 0.00 | 0.06 | 0.20 | 89.85 | |
| | 25.8 | 29.1 | 39.29 | 48.95 | 0.70 | 7.29 | 2.56 | 0.70 | 0.00 | 0.12 | 0.25 | 88.55 | |
| Rest of borehole | 29.1 | 50.0 | Marl with high magnesia content (38.8-50. 0. m.) | | | | | | | | | | |
| K-13 | | | | | | | | | | | | | |
| Spot level | 165.6 | | | | | | | | | | | | |
| Upper lime-stone | 0.0 | 7.0 | 41.85 | 51.76 | 1.09 | 3.35 | 1.15 | 0.30 | 0.05 | 0.05 | 0.14 | 94.26 | |
| Lower marl | 7.0 | 15.5 | 22.46 | 25.30 | 1.81 | 37.81 | 8.27 | 2.46 | 0.03 | 0.19 | 1.49 | 48.35 | |
| | 15.5 | 21.1 | 36.17 | 44.61 | 0.97 | 12.32 | 3.65 | 1.17 | 0.04 | 0.13 | 0.64 | 81.30 | |
| Lower Limestone | 21.1 | 30.7 | 39.33 | 48.77 | 0.89 | 7.37 | 2.21 | 0.73 | 0.06 | 0.08 | 0.26 | 88.57 | |
| Rest of borehole | 30.7 | 52.0 | Marl with high magnesia content (43.3-52.0 m). | | | | | | | | | | |
| K-14 | | | | | | | | | | | | | |
| Spot level | 166.4 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 8.5 | 42.08 | 52.27 | 0.46 | 3.40 | 1.03 | 0.19 | 0.13 | 0.20 | 0.15 | 94.04 | |
| Lower marl | 8.5 | 16,9 | 21.7 | 23.52 | 1.86 | 38.97 | 9.75 | 2.19 | 0.80 | 0.30 | 1.28 | 45.26 | |
| | 16.9 | 23.6 | 36.30 | 44.6 | 0.88 | 12.05 | 4.23 | 0.88 | 0.12 | 0.2 | 0.52 | 81.11 | |
| Lower limestone | 23.6 | 27.0 | 39.50 | 49.12 | 0.61 | 7.14 | 2.02 | 0.80 | 0.09 | 0.25 | 0.35 | 88.69 | |
| | 27.0 | 32.7 | 39.8 | 49.79 | 0.47 | 7.05 | 1.86 | 0.52 | 0.07 | 0.20 | 0.25 | 89.64 | |
| Rest of borehole | 22.7 | 52.0 | Marl with high magnesia content (48.3-52.0 m.) | | | | | | | | | | |

continued

Table 7 (continued)

| Borehole No. | Thickness | | Full analyses | | | | | | | | | Carbon-ate (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) | | |
| K-15 | | | | | | | | | | | | | |
| Spot level | 168.1 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 10.0 | 41.7 | 51.02 | 1.40 | 3.60 | 1.36 | 0.40 | 0.09 | 0.07 | 0.18 | 93.5 | |
| Lower marl | 10.0 | 18.0 | 29.81 | 33.87 | 1.79 | 24.53 | 7.26 | 1.70 | 0.07 | 0.10 | 0.58 | 63.59 | |
| | 18.0 | 29.0 | 38.02 | 45.24 | 1.50 | 9.60 | 3.35 | 1.30 | 0.09 | 0.08 | 0.33 | 83.36 | |
| Lower limestone | 29.0 | 32.4 | 38.80 | 46.09 | 1.60 | 9.10 | 3.00 | 0.85 | 0.10 | 0.08 | 0.28 | 85.05 | |
| Rest of borehole | 32.4 | 72.0 | Marl with high magnesia content (45.5-72.0 m.) | | | | | | | | | | |
| K-16 | | | | | | | | | | | | | |
| Spot level | 168.2 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 3.0 | 39.50 | 47.72 | 1.46 | 8.82 | 1.41 | 0.64 | 0.02 | 0.04 | 0.21 | 87.71 | |
| Lower marl | 3.0 | 14.2 | 24.70 | 27.21 | 1.73 | 35.39 | 6.93 | 2.72 | 0.2 | 0.13 | 0.93 | 51.61 | |
| | 14.2 | 24.4 | 35.90 | 44.04 | 1.15 | 13.51 | 3.02 | 1.40 | 0.03 | 0.05 | 0.74 | 80.6 | |
| Lower limestone | 24.4 | 28.7 | 39.70 | 49.51 | 0.72 | 7.02 | 1.80 | 0.64 | 0.02 | 0.04 | 0.04 | 89.58 | |
| | 28.7 | 33.8 | 34.40 | 42.27 | 0.99 | 16.58 | 3.57 | 1.38 | 0.01 | 0.05 | 0.52 | 77.15 | |
| Rest of borehole | 33.8 | 50.5 | Clayey marl with high magnesia (41.0-50.5 m.) | | | | | | | | | | |
| K-17 | | | | | | | | | | | | | |
| Spot level | 167.5 | | | | | | | | | | | | |
| Upper limestone | 0.0 | 3.0 | 40.15 | 49.16 | 1.58 | 6.41 | 1.25 | 0.54 | 0.19 | 0.22 | 0.38 | 90.5 | |
| | 3.0 | 11.2 | 41.70 | 52.41 | 0.78 | 3.12 | 0.90 | 0.39 | 0.19 | 0.24 | 0.28 | 94.86 | |
| Lower marl | 11.2 | 13.7 | 35.00 | 43.19 | 1.36 | 15.56 | 3.05 | 1.24 | 0.16 | 0.18 | 0.63 | 79.45 | |
| | 13.7 | 20.1 | 23.50 | 25.39 | 2.58 | 35.28 | 8.28 | 3.07 | 0.13 | 0.36 | 1.62 | 49.88 | |
| Lower limestone | 20.1 | 27.7 | 40.20 | 50.28 | 1.56 | 5.25 | 1.09 | 0.93 | 0.16 | 0.2 | 0.5 | 92.45 | |
| | 27.7 | 31.5 | 41.00 | 51.04 | 1.56 | 3.25 | 1.63 | 0.62 | 0.16 | 0.2 | 0.39 | 93.81 | |
| Rest of borehole | 31.5 | 61.00 | Marl with high magnesia content (48.8-61.0 m.) | | | | | | | | | | |

Lithologically, the upper limestone zone of the Kebir deposit is mostly devoid of marly and clayey laminae and therefore the carbonate content of the layers forming the limestone zone is usually high.

The $SiO_2$, $MgO$, $Na_2O + K_2O$ and chlorine-ion content of the upper limestone layers of the Kebir deposit indicate the following:

(a) The silica content is concentrated in the most southerly part of the upper limestone zone as in boreholes K-4, K-16 and K-11. The silica usually decreases in percentage descending to the lower limestone layers as in boreholes K-4 and K-17 situated in the south and the south-east respectively. The lowest silica content was met in borehole K-3 situated in an area north-west of the boreholes rich in silica, i.e. K-11, K-16 and K-4. In the other boreholes, the silica content does not exceed 5.58% as in borehole K-7 and accordingly the limestone can be considered to be predominantly of low silica content. This can be attributed primarily to aging and also to the presence in some parts of the deposit of clay and marly laminae;

(b) The MgO content of the upper limestone deposit is generally low (lower than 1.0%) in most of the drilled boreholes. The maximum magnesia content is met within the southern and the south-eastern areas as shown in boreholes K-16, K-17 and K-15. The magnesia content shows a gradual decrease towards the lower limestone layers.

(c) The $Na_2O$, $K_2O$ (alkalies) and chlorine contents are usually low and it is not of great value to describe them in detail.

Upper and lower marly zones. The upper marly zone is found only in one area where borehole K-7 was drilled. This marly zone, capping the upper limestone zone, is a calcareous marly zone as its calcium carbonate content ranges from 37.69% to 83.88% (lower and upper layers respectively). The magnesia content reaches a minimum of 1.49% in the upper layer and a maximum of 3.06% in the lower layer. The silica ranges from 11.47% to 45.88%. The alumina content is rather low in the upper layer (2.58%) and somewhat high in the lower layer where it reaches 10.6%. The marly layers are completely devoid of $SO_3$ and the alkali values are low. The iron oxide ranges from 0.72% (upper layer) to 2.52% in the lower layer.

The lower marly zone underlying the upper limestone can also be considered as calcareous marly layers as the carbonate content ranges from 44.36% as seen in borehole K-4 to 83.47% as in borehole K-8 (lower layer). In most of the boreholes, the carbonate content of the lower marly zone increases towards the lower layers. The magnesia of this lower marly zone ranges from 0.6% as shown in the lowest layer of the marly zone (K-12) to 2.57% (K-4). The silica content varies from 9.60% as in borehole K-15 to 39.4% as shown in borehole K-4. The alumina content is within the range of 2.27% to 10.30% as seen in boreholes K-8 and K-4 respectively. The iron-oxide content oscillates between 0.62% and 3.4% as shown in boreholes K-1 (uppermost layer) and K-4 respectively. The $SO_3$ content ranges from 0.00% as shown in boreholes K-1, K-5, K-7, K-8 (upper layer), K-9 and K-12 to 0.8% as in borehole K-14.

Alkalies and chlorides are relatively low. This can be attributed to the presence of small amounts of clay minerals in the lower marly zone.

Lower limestone zone. In the Kebir deposit, the lower limestone zone (containing more than 85% $CaCO_3$) is absent in some parts of the area as in boreholes K-1 and K-5, for example. In all the other boreholes, this limestone zone is present with one, two or three layers with different carbonate contents. The CaO and carbonates forming the main constituents of the layers of this zone range from 46.09% as in borehole K-15 to 52.33% as in borehole K-8 (lower layer). Therefore the carbonate content ($CaCO_3$ + $MgCO_3$) ranges from 85.05% to 94.10%. Magnesia varies from 0.42% in borehole K-8 (lower layer) to 1.6% in borehole K-15. The minimum silica value is 3.25% in borehole K-17 (lower layer) and the maximum value is 9.90% in borehole K-3 (upper layer). Alumina ranges from 0.96% to 3.93% as in boreholes K-6 (lower layer) and K-9 respectively. Iron oxide ranges from 0.43% to 1.13% as shown in boreholes K-7 (lower layer) and K-3 (upper layer) respectively. The $SO_3$ content ranges from 0.00% as in boreholes K-7, K-9 and K-12 to 0.16% as shown in borehole K-17. Alkalies and chlorides are relatively low.

The $SiO_2$, MgO, $Na_2O$ + $K_2O$ and chlorine-ion content of the lower limestone layers of the Kebir deposit reflect the following facts:

(a) A silica content of more than 9.0% is found in boreholes K-3 (upper layer), K-7 (upper layer), K-9 and K-15. This high silica content is not localized as these boreholes are distributed all over the Kebir area. A silica content from 6.0-9.0% is found in the boreholes K-2 (upper two layers), K-3 (lower layer), K-4, K-5, K-6, K-7 (lower layer), K-8 (upper layer), K-10, K-11 (both layers), K-12 (both layers), K-13 and K-14. A silica content of 6.0-9.0% is therefore typical of most of the limestone in this area. A silica content below 6.0% is found in boreholes K-2 (lowest layer), K-7 (lower layer), K-8 (lower layer) and K-17 (both layers). The silica content of the limestone layers shows a percentage decrease when going down to the lower layers as shown in boreholes K-2, K-3, K-7, K-8, K-11 and K-14. Borehole K-11, where it increases downwards, is an exception;

(b) The magnesia content can be considered as relatively low in all the lower limestone layers shown in the boreholes;

(c) The alkali and chlorine contents of the lower limestone layers are usually low.

As can be seen in table 7, Polservice drilled deeper than the lower limestone layers but unfortunately all the drilled layers were marly (as shown in boreholes K-1) or marl with its lowest layers rich in magnesia as seen in the rest of the boreholes. In some cases, this lowest marly layer is covered by dolomitic limestone as indicated in borehole K-7.

## II. EVALUATION OF THE GEOLOGICAL INVESTIGATIONS

In attempting to assess the supply of raw materials needed for cement production at the Al-Khums I Cement Plant, the co-ordinator evaluates and comments upon the findings of the Polservice report of 1974, the method of investigation, proposed exploitation of the raw materials, quality control and raw-mix designs. Information not dealt with in the Polservice report is included since, although Polservice carried out extensive investigation work, the co-ordinator believes that the supplementary information and advice will be of assistance to the Al Khums authorities in determining the best way of exploiting the raw-material quarries and the correct use of these materials in producing the proper type of cement.

The study of economic feasibility presented by Polservice is not commented upon here as it is outside the co-ordinator's brief and the figures presented will anyway have become out of date.

### A. The chemical composition of the deposits

It is obvious from the results of the chemical analyses given in tables 6 and 7, that the Mannubia and Kebir deposits in general are of an inhomogeneous character and that the chemical composition of one zone can vary vertically as well as laterally, even in the same bed, from high-quality limestone to marly or clayey material. To demonstrate the inhomogeneity of the different layers forming the Mannubia deposit, figure I shows the chemical composition of the deposit in graphic form. In borehole M-1 for instance, within 10 metres depth (150-160 m), there are more than five layers with different chemical compositions. The difference in CaO content varies from 25% up to more than 50%. This means that this zone contains high-quality limestone which drops within a few metres to a clayey material. The abrupt change in the CaO content, without preblending, would affect the raw-mix design and therefore also the behaviour of kiln burning.

There is no exact boundary between the limestone zones, either upper or lower, and the marly zones. The difference will be felt in the quarry at the time of exploitation because of the difference in the physical properties of both types of rock. As a matter of fact, this factor will influence the methods of exploiting both types, as explosives are required for extracting limestone and ripping will be used for the marly and clayey layers. The amount of marly layers present in the limestone zone will therefore influence the consumption of explosives.

The chemical analyses of the upper and of the lower limestone zones showed that it is suitable for cement production as the CaO content is sufficient to supply the raw mix with the lime component. On the other hand, the marl, either upper or lower, is unable to supply the raw mix with the alumina or the iron component. Therefore, the deficiency in $Al_2O_3$ and $Fe_2O_3$ has to be supplied by incorporating an alumina-rich raw material like bauxite or Margheb clay and an iron-rich ore such as Galmoya iron ore.

The magnesia as well as the alkali content as shown in tables 6 and 7 are of low values and therefore will create no problems either in the kiln operation or to the cement produced.

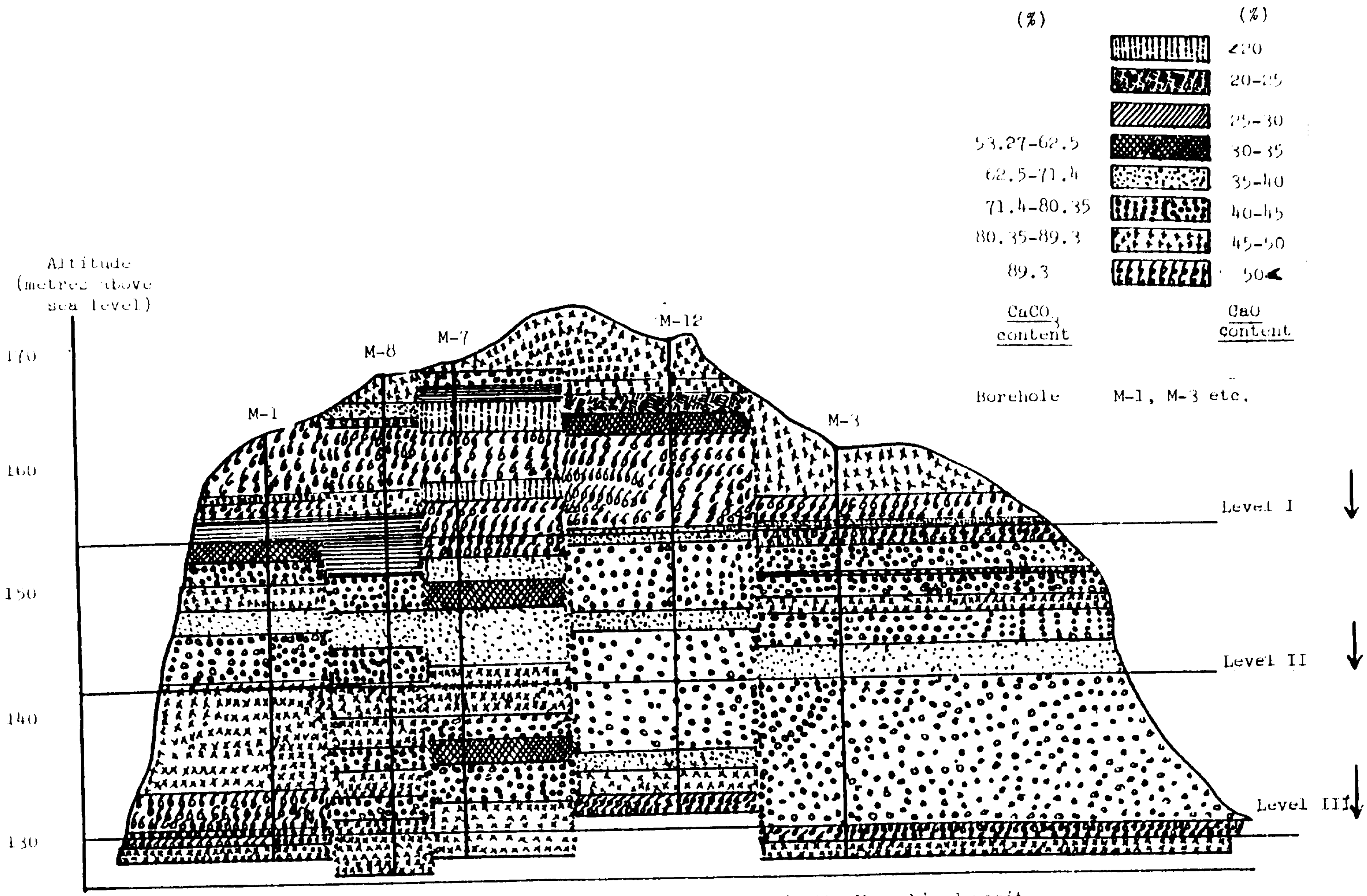

Figure 1. The inhomogeneity of the layers in the Mannubia deposit

If the proper quarrying, exploitation and preblending methods are adopted, it does not seem necessary to equip the kilns with a by-pass.

The type of chemical analysis carried out by Polservice was sufficient to give a good overall knowledge of these deposits.

## B. Methods of investigation used

As described above, Polservice drilled 13 boreholes in Mannubia (total depth 983 metres) plus four trenches (total length 523.7 metres). In the Kebir area, 17 boreholes were drilled (total depth 997.0 metres) plus two trenches (total length 255.5 metres). This drilling and trenching was carried out to give detailed information on the raw-material in the deposits, their type and quantity.

It is clear that most of the boreholes were haphazardly distributed all over the upper parts of the two ridges. All the boreholes drilled were concentrated above the 160 metre contour line in both the Mannubia and Kebir areas. It is also clear that some boreholes cover very narrow areas as in boreholes M-1, M-3, M-4, M-5, M-10, K-2, K-3, K-4, K-10, K-11, K-12 and K-13, while elsewhere, wide areas were covered and investigated only by one borehole, i.e. K-7 or K-4.

Even if it is accepted that there was no other way in which Polservice could have distributed these boreholes more evenly, the adequacy of the investigation can only be accepted if the results from these boreholes were supplemented along the deposit peripheries by digging trenches every 200 metres to show the boundaries of the different layers and their chemical composition.

The four trenches in the Mannubia area and the two trenches in the Kebir area were only dug along two sides, on the northern and eastern edges. These trenches were not only too few but leave us without any information about the stratification of raw materials on the other two sides. Because of this, the boundaries of the deposit drawn by Polservice cannot be relied on. Similarly, the calculation of the amount of ore reserves of the different types of raw materials must be considered uncertain.

It should be pointed out that the total depth of drilling carried out could have been used to cover more of the area with more boreholes if Polservice had made use of the results of the abbreviated analyses carried out at the time of drilling. It is well known that abbreviated (or quick) analyses have to be carried out at the time to determine some facts about the CaO and especially the MgO content in the deposit. The magnesia ought not to exceed a certain limit in the raw materials to be used in the cement industry as it is poisonous above this limit. It is clear from all the abbreviated chemical analyses carried out by Polservice that in most of the boreholes the magnesia started to exceed the maximum limits at depths below 50.0 metres in Mannubia and below 30.0 metres in Kebir. In spite of the quick-analyses results given at the time of drilling, no action was taken by Polservice to stop drilling at that point and in most of the boreholes drilling was continued to depths of about 70.0 metres.

Apart from the magnesia content, the excessive depth of the drilling penetrated into marly layers of no great use as the upper and lower marly layers represent reserves of material in excess of that required for cement production in the Al Khums I Factory.

## C. The exploitation of the available raw materials

Based on the chemical analyses of the Mannubia and Kebir deposits, Polservice proposed to divide the Mannubia deposit into four benches or exploitation levels. Bench I, with a base altitude of 154 metres above sea level, consists of limestone and calcareous marls with a $CaCO_3$ content in the range of 85-90%. Bench II, with a base altitude of 142 metres above sea level, is composed principally of marly rocks with a $CaCO_3$ content in the range of 67-75%. The underlying bench III, with a base altitde of 130 metres above sea level is composed of marly limestone with a $CaCO_3$ content of 75-78% which is in the range of a natural cement mix or slightly above it, as stated by Polservice. The lowest bench, bench IV, (base altitude 110 metres above sea level) consists of clayey marls with an average $CaCO_3$ content in the range of 53-66%.

In order to assess the above-mentioned proposal, the co-ordinator tried to draw maps showing a cross-section of the deposit at the base altitude of each of the top three proposed benches in the Mannubia deposit. The percentage of CaO content at that altitude was also shown on the maps as indicated by the analyses of the drilled boreholes. These three cross-sections are given as figures II, III and IV.

From the cross-section at the level of bench I, it can be seen that the limestone with a CaO content of more than 50% is mostly found on the eastern side of this bench. In a very small area surrounding borehole M-10, the CaO content ranges from 40-45%, i.e. the $CaCO_3$ content ranges from 71.3-80.26%. The remaining areas consist of marly deposits with a CaO content of 25-30%. The area surrounding borehole M-1 has a CaO content of 35-40%. These statements appear to contradict the Polservice results mentioned previously. The co-ordinator believes that while, according to Polservice calculations, the average $CaCO_3$ content of the deposits predominating above this base altitude is within the range of 85-90%, this assumption can be accepted only if quarrying were carried out according to the Polservice procedure, which turned out in practice to be very difficult to follow.

In fact, selective mining was followed by the Al Khums I Plant as it is the easiest way to ensure compliance with the specification requirements of their raw-mix design. Limestone is selectively quarried and excavated as limestone regardless of whether it contains 85% or more than 95% $CaCO_3$ or whether the thickness of the limestone strata is one metre or more than 15 metres. The same process will be followed when dealing with the marly strata. In practice, therefore, Polservice's bench proposal has not been carried out in the Al Khums quarry over the last years.

To clarify the situation, the co-ordinator plotted various vertical cross-sections of the Mannubia area. These sections show all the possibilities that could be chosen for exploiting the raw-material deposits in this area. These vertical cross-sections cutting the deposit in different directions are shown in figures V, VI, VII, VIII, IX and X.

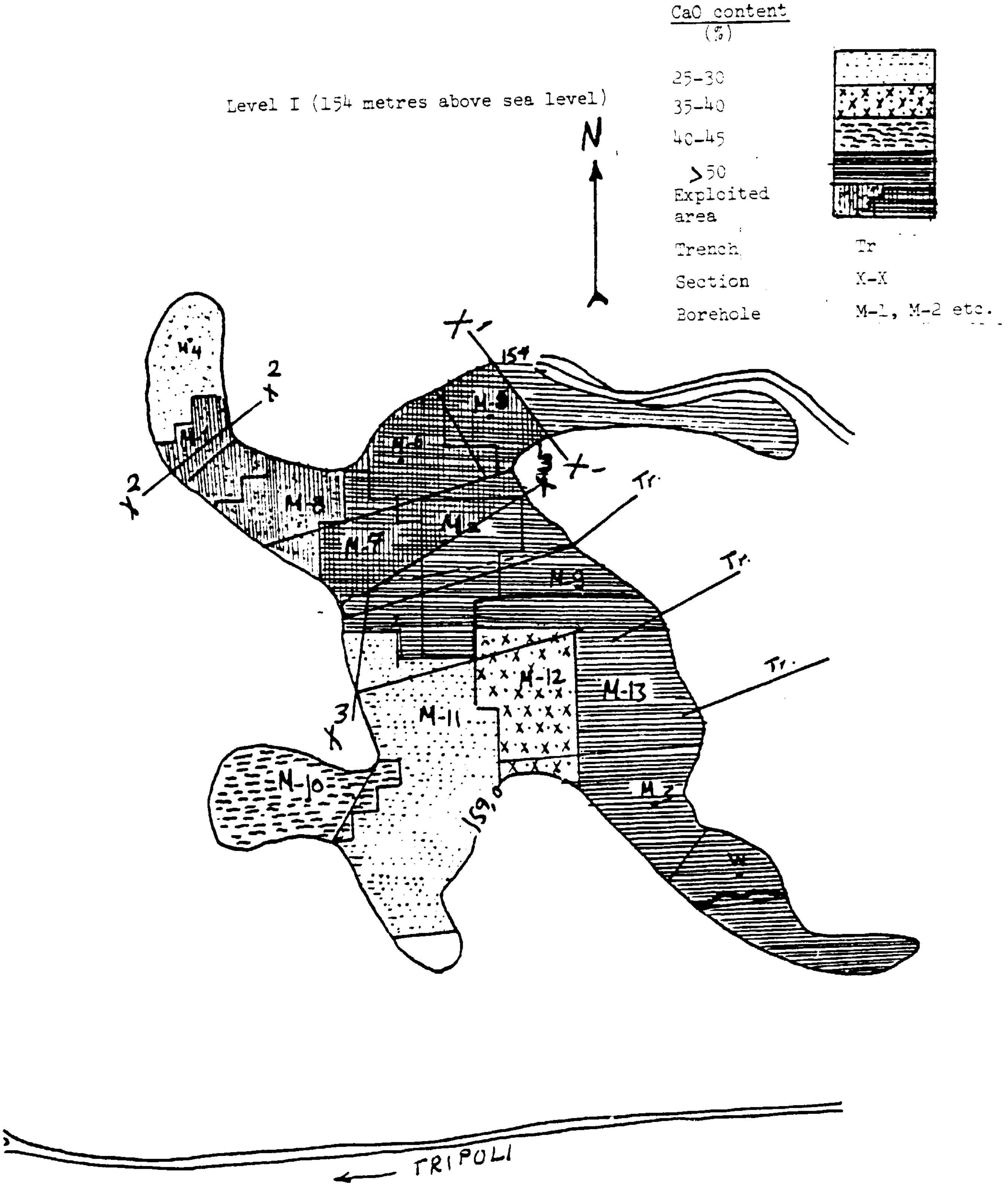

Figure II. Cross-section of the Mannubia deposit at the level of bench I

Level II (142 metres above sea level)

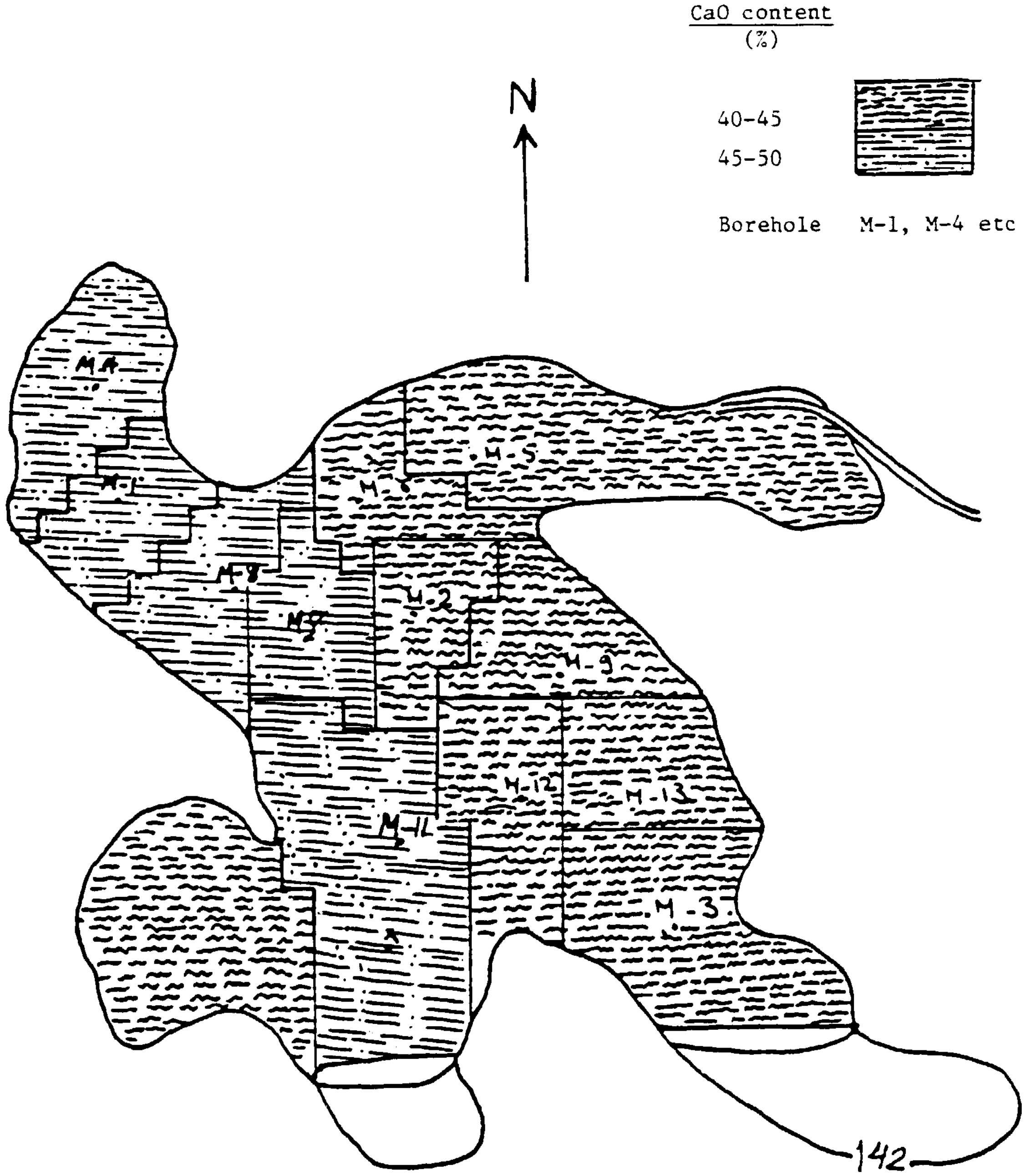

Figure III. Cross-section of the Mannubia deposit at the level of bench II.

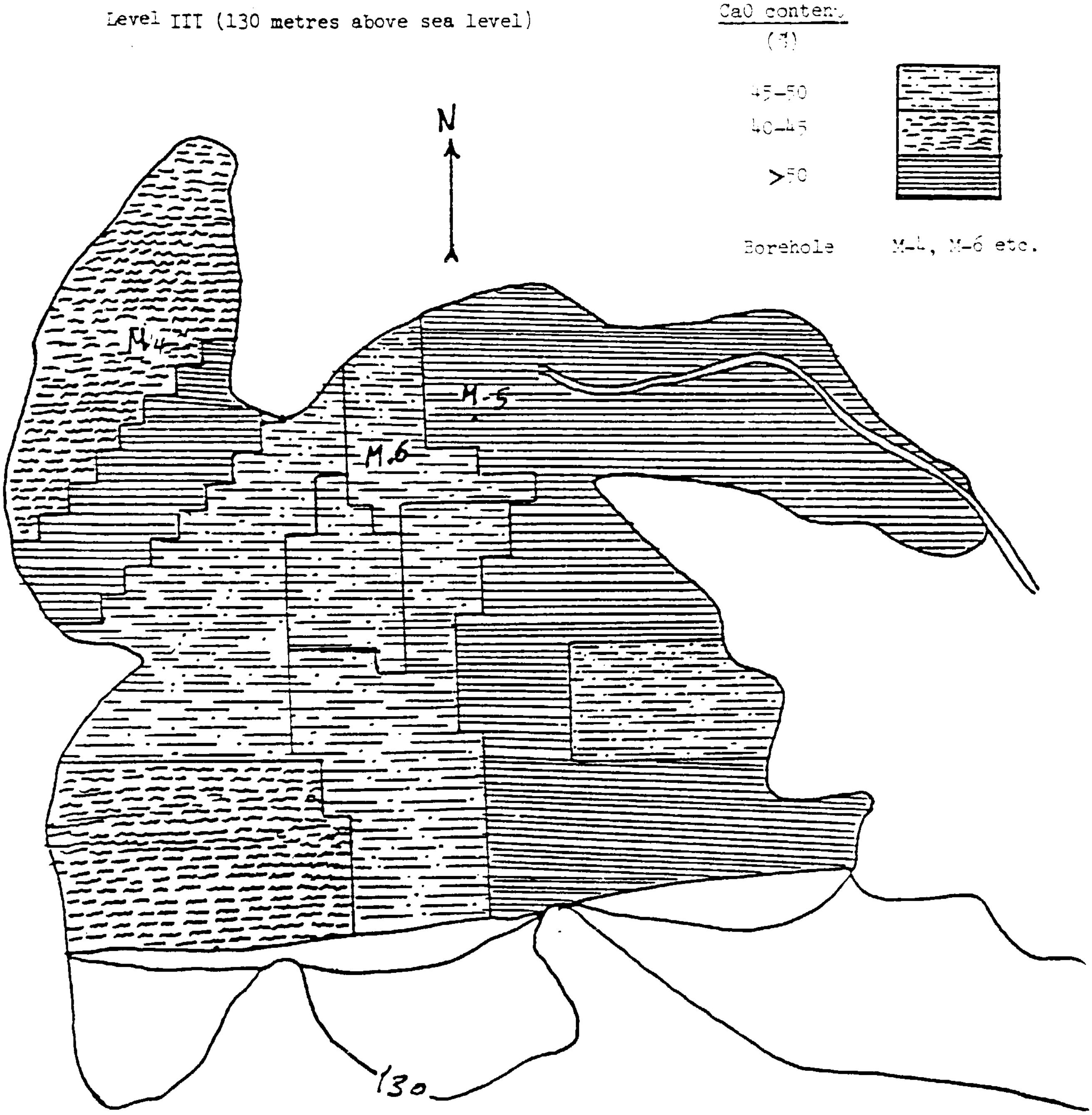

Figure IV. Cross-section of the Mannubia deposit at the level
of bench III

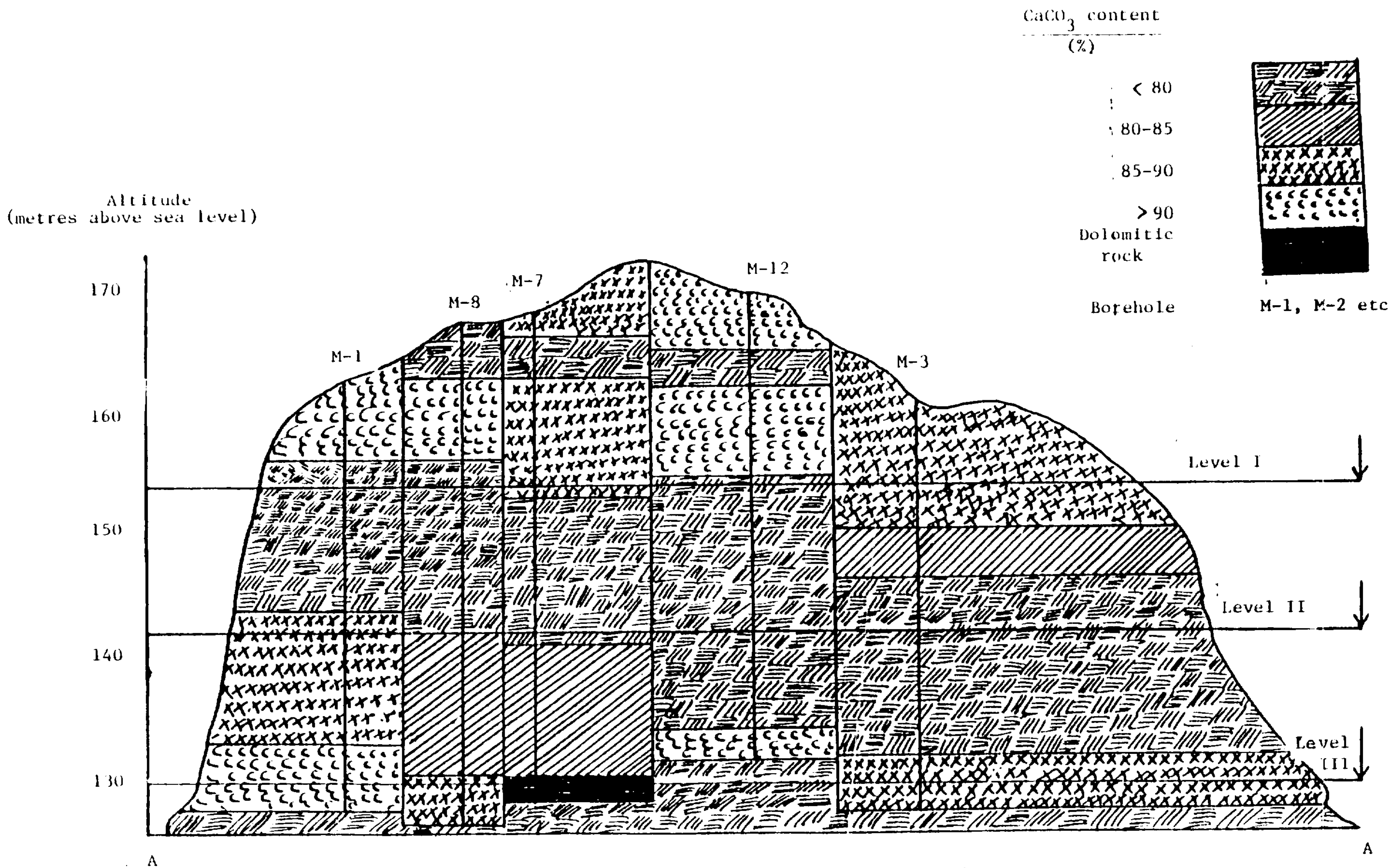

Figure V. Vertical cross-section A-A of the Manaubia deposit

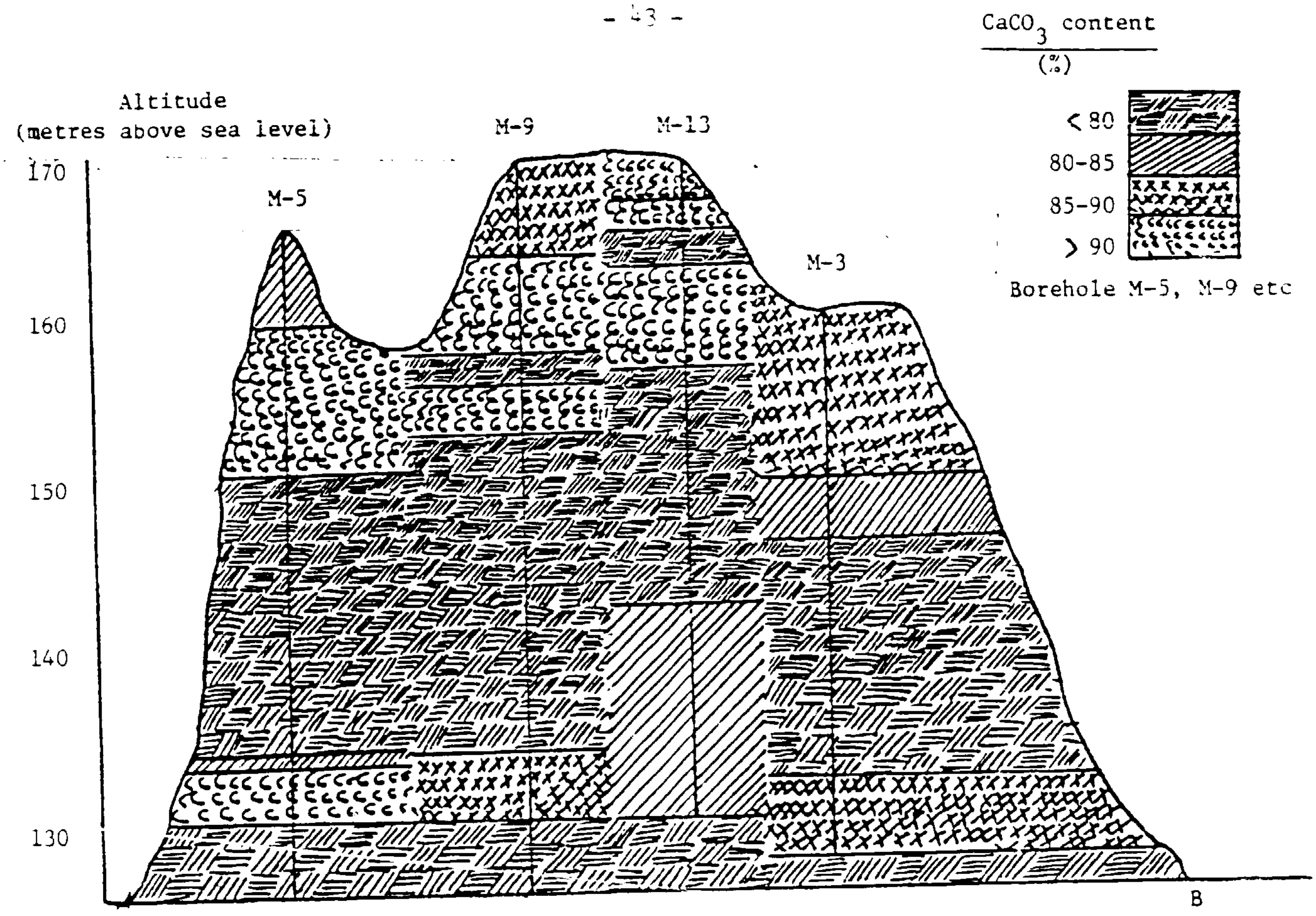

Figure VI. Vertical cross-section B-B of the Mannubia deposit

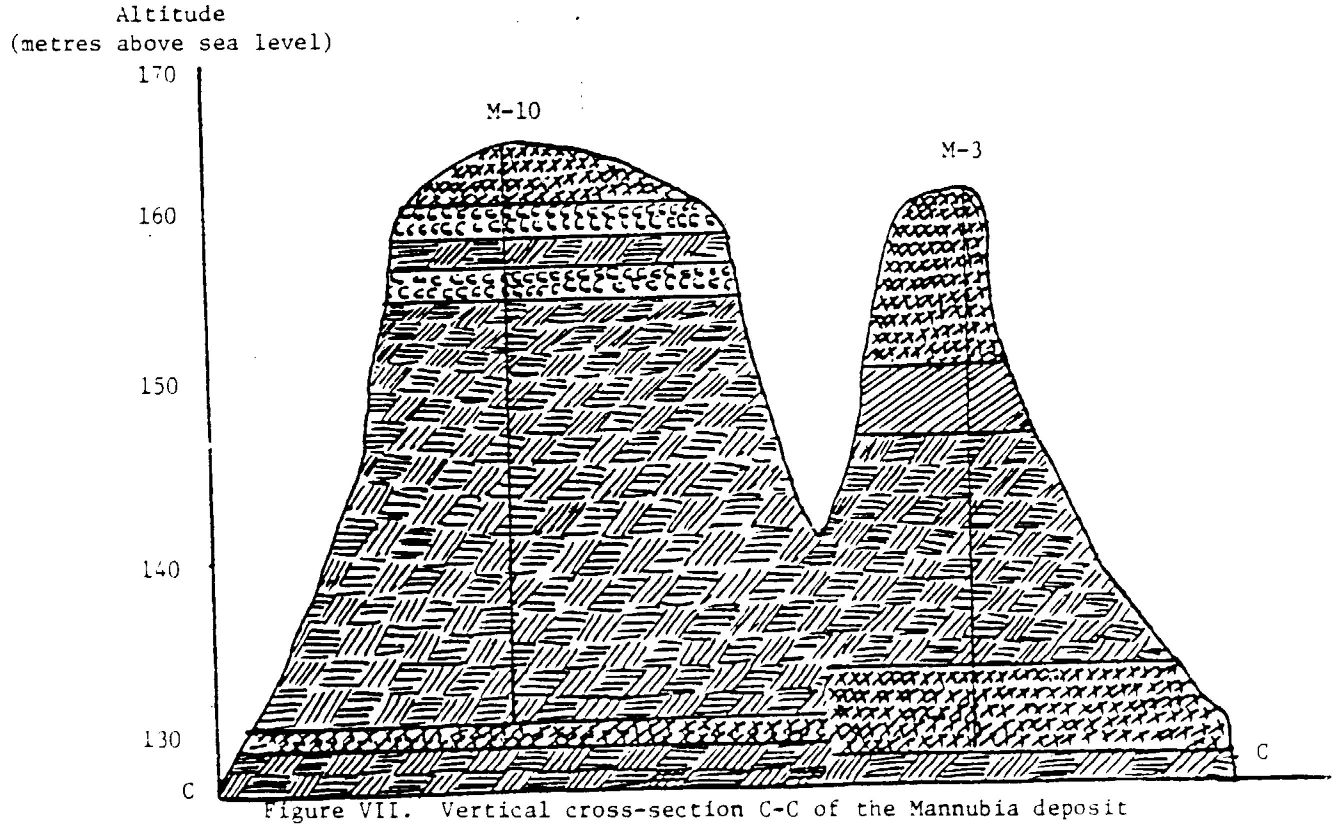

Figure VII. Vertical cross-section C-C of the Mannubia deposit

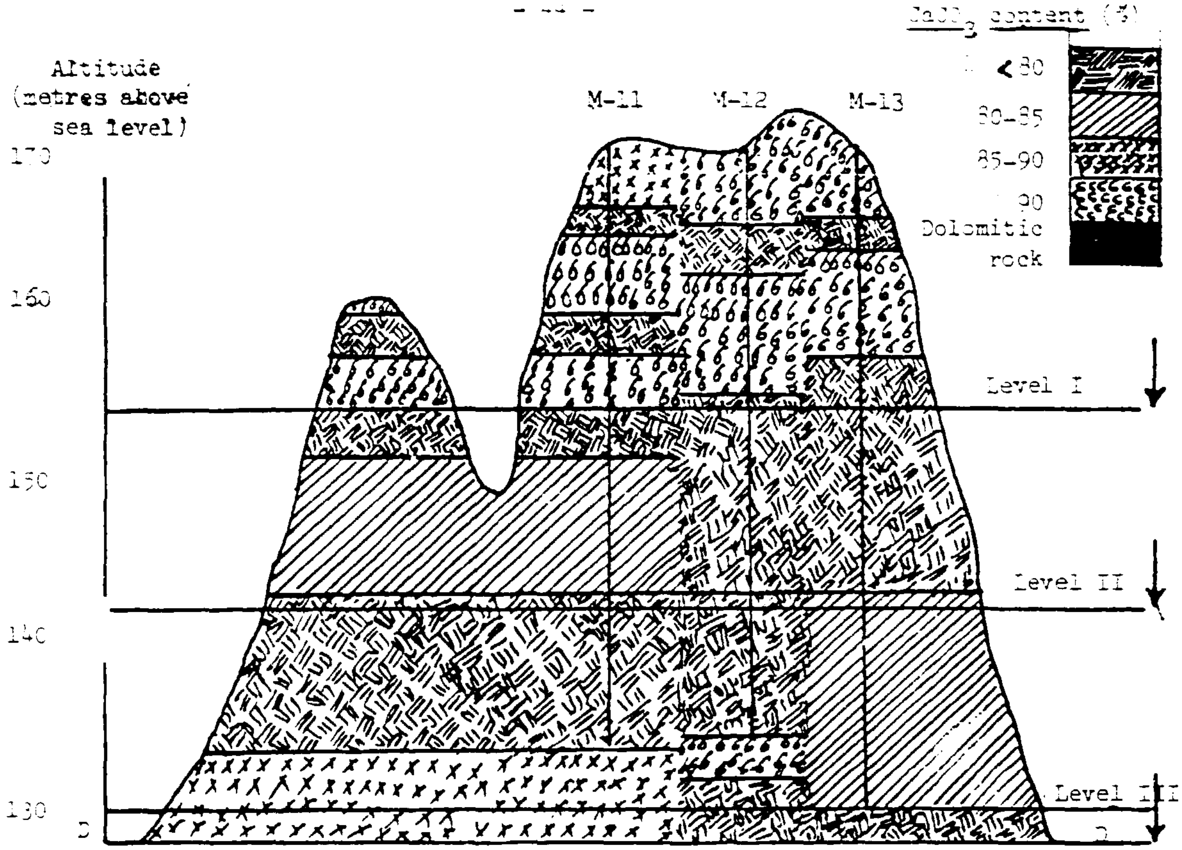

Figure VIII. Vertical cross-section D-D of the Mannubia deposit

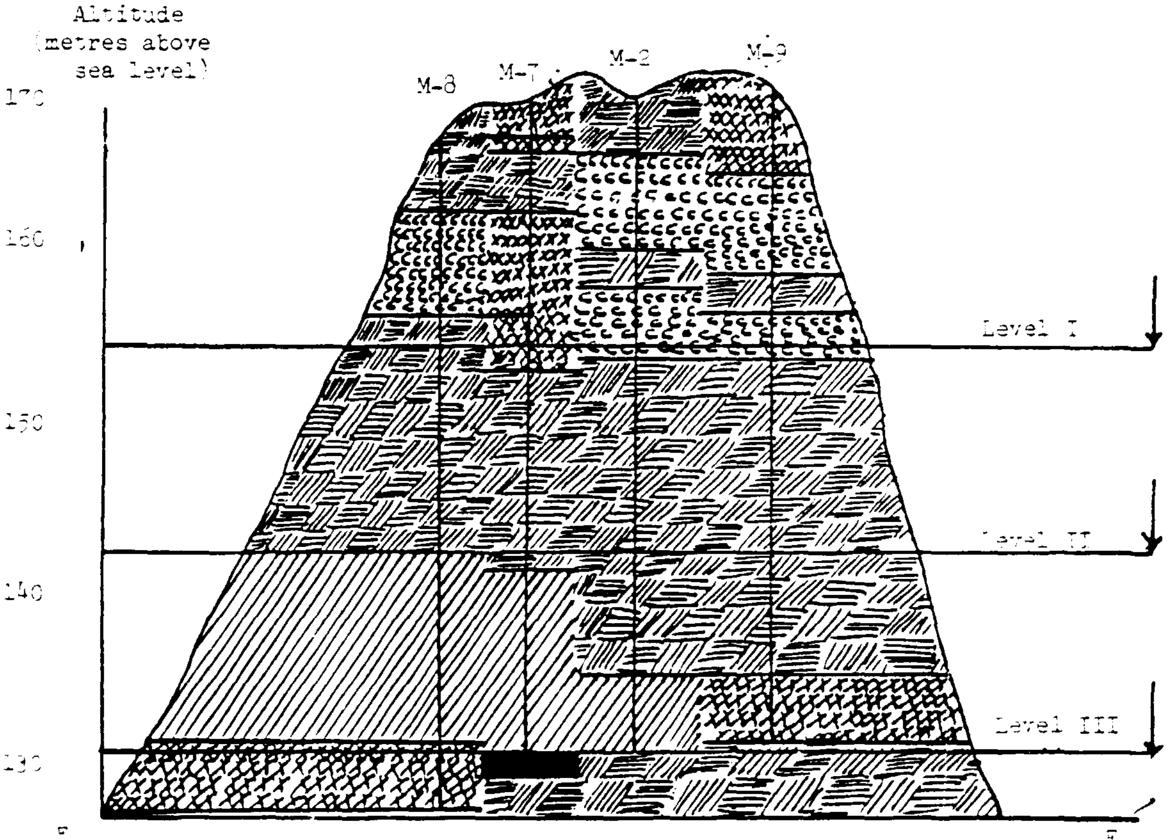

Figure IX. Vertical cross-section E-E of the Mannubia deposit

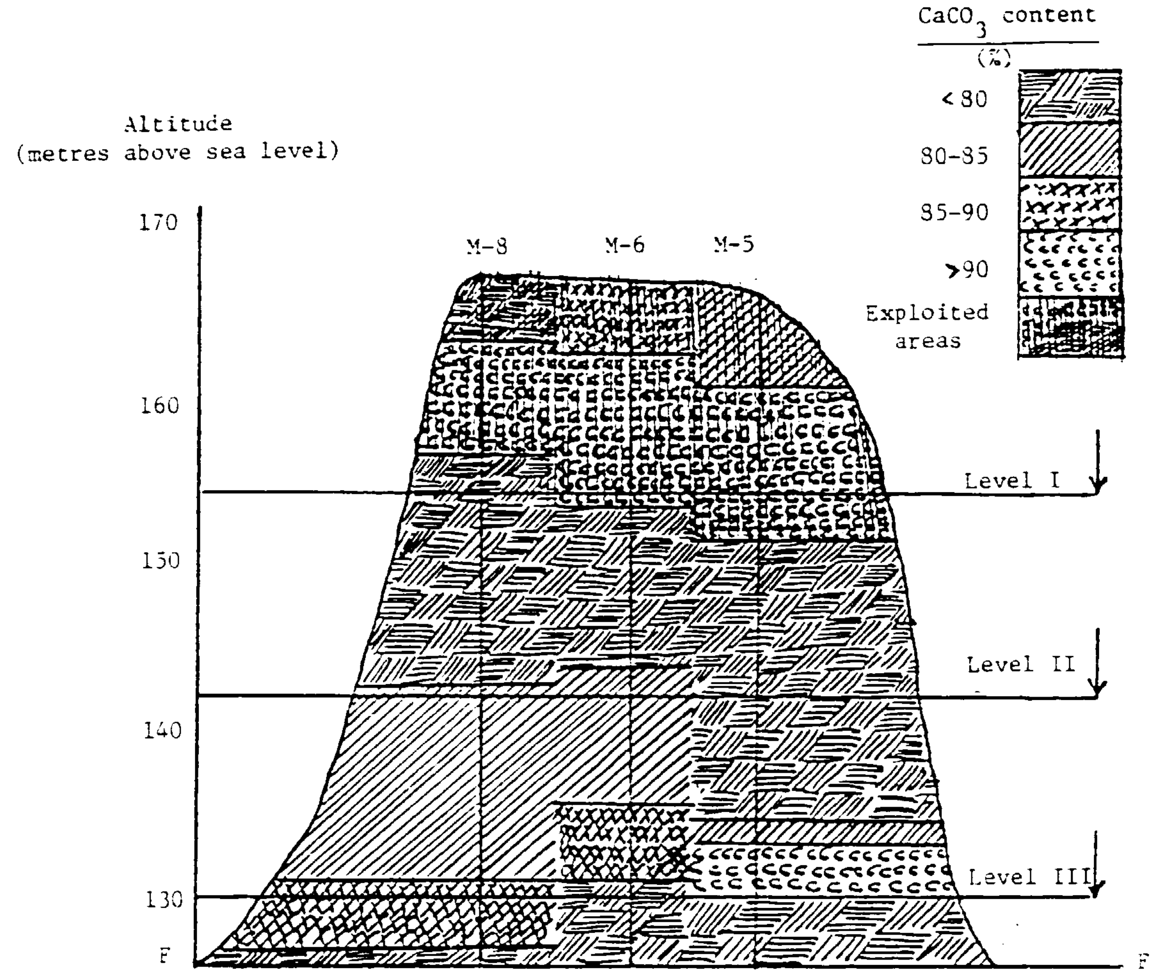

Figure X. Vertical cross-section F-F of the Mannubia deposit

These cross-sections are self explanatory and show clearly that, in any direction which could be chosen to start exploitation, after a few metres a limestone layer will change to calcareous marl, marl or a clayey layer or vice versa. The change will cause problems in the burning of clinker and kiln behaviour as the raw-mix composition will be always changing. For this reason, there is no point in discussing Polservice's proposal for bench openings in the quarry. The co-ordinator agrees with the method now used for exploiting the quarries and will discuss this further later on in the report.

All the upper limestone covering the area around boreholes M-5, M-6, K-7 and M-8 and part of the area around M-1 and M-2 has been extracted and used in cement production during the last years. (See figure II).

The co-ordinator will not comment on the exploitation of the available raw materials in the Kebir deposit as Polservice stated in their report that the structure of the Kebir deposit is even less regular than that of the Mannubia deposit. At Kebir, the individual members of the succession of strata show a wide range of variation both in base altitude and in thickness and the opening of quarry benches would be even more impractical.

## D. Quality control

The Portland cement raw materials, limestone, marl and clay, which are present in the Mannubia and Kebir areas, vary greatly in their mineralogial and chemical composition even in one area or in the same bed. Because of these variations in chemical composition, the proportions of the raw mix must be corrected at frequent intervals. These corrections involve frequent and time-consuming calculations of the mix ratios which requires also more personnel. These corrections should take place the the earliest stages, at the quarry work face, the preblending stores and the raw mills. This avoids serious production problems and unnecessary costs which may be incurred if the quality-control personnel have to intervene subsequently to make corrections at a later stage of the production process.

Polservice recommended that materials should be periodically sampled and tested at the work face in order to ensure a supply of raw materials in the proportions needed. At the end of the year, the actual reserves belonging to the exploitation front of each level should be confirmed. Polservice added that the quarrying operations like drilling, blasting and loading should be carried out only by workers with the necessary qualifications. All the work should be supervised by experts in mining and geology in order to ensure the correct grade of quality of the raw materials. Polservice also stated that the factory laboratory should exert continuous strict control on the work of the quarrying and production departments. A list of the mixes should be supplied which would enable the quarrying department to adjust the advance of the quarry faces in the indivdual benches so as to provide a proper proportion of the materials.

From these Polservice recommendations, it is clear that this company foresaw the serious problems that could arise in future when dealing with the limestone and marl deposits in their natural state in the Mannubia and Kebir areas in view of their inhomogeneity and variable quality.

In the co-ordinator's opinion it would have been better for Polservice at the time of the investigation to recommend the use of a process computer so that the components could be fed into the system in a constant composition. Deviations can be tolerated only within narrow limits as uniform kiln and material temperatures are fundamental conditions for achieving a high level of efficiency in the production plant and maintaining output at peak level. If this type of automation were used in the Al Khums I plant, it would mean that the material flow in this plant could be controlled for periods of several hours, or even days, by means of analog controllers or a process computer, without the need for such a large number of expert personal. In this plant, the minimum equipment required for mix control is a programmable table-top computer in conjunction with X-ray fluorescence equipment and controls for the following factors; lime standard, silica modulus and alumina modulus. In this system, the computer would give print-outs indicating the necessary readjustments to the weighing machines. The installation of such a process computer at that time (1974) would have been the most economical solution to the problems of mix control.

The results achieved by the computer can be expressed in terms of increased rotary kiln throughput and reduced heat consumption. Savings were reported by other plants to be in the range of 5-7% where the computer performs kiln control and mix control. Indeed, mix problems have been solved in many cement plants all over the world, applying integrated control by process computer.

Another aspect is that the output of the basic raw materials used by the Al Khums I Cement Plant has to be increased and this method of quality control will offer substantial advantages in achieving this.

If it had been possible to introduce the process computer at the time of erecting the plant extension, the economic benefits would have been greater and the results better than if the installations are introduced step by step up to full automation.

As well as achieving integrated control of the raw-material flow, the necessity of blending the basic raw materials properly must also be considered. In dealing with this subject it is necessary to clarify the raw-material blending situation in Al Khums I as follows:

(a) Production line I is provided with a covered raw-material store with a set of reclaiming belt conveyors;

(b) Production line II is provided with an open stockpile for marl and limestone with two mobile, slewing, clamshell cranes. It also has a raw-materials proportioning station with hoppers, box-type feeders and weighing belt conveyors.

It is clear that there is no hope at all of getting proper blending of raw materials from the primitive raw-material stockpiles of both production lines as described above.

It has already been pointed out that the raw materials used have wide variations in quality. In such circumstances it is the co-ordinator's opinion that it will only be possible to obtain the grades of material suitable for cement production in Al Khums I by means of controlled selective quarrying, followed by homogenization of the loosened material. This latter operation is usually carried out by bedding, i.e. in a mixing bed. It is also necessary, especially when dealing with the basic raw materials, that the quality-control activities should be concentrated at the quarry work face and this will, of course, greatly affect the whole quarrying operation.

The other important factor is the use of a proper blending stockpile. A number of stockpile suppliers offer various systems of which the prices fluctuate widely. The degree of preblending offered is about proportionate to the installation costs. The co-ordinator recommends the installation of a stockpile with sufficient capacity to serve the production of both production lines. This stockpile ought to have practically all the layers piled by a flying belt conveyor (stacker). These layers are cut during reclaiming and consequently an even blend is obtained by slices being removed from the entire cross-sectional area. The stacker has to be equipped with an electronic-control flying system to regulate the stopping times automatically in the end zones, depending on the height of the pile. Very good homogenizing or blending can also be achieved by building a sub-surface stockpile (homogenizing tanks or troughs). The corresponding extra cost of investment will then lead to savings from the energy point of view as the calcination operation will be more regular.

An important development is the "Computerized Evaluation System" (CES) for raw materials recently developed by F.L. Smidth of Denmark. This has been successfully introduced in a cement plant which for a number of years had been processing a clay of greatly varying composition that caused fluctuations in the raw mix, disrupted the operation of the kiln and shortened the life of the refractory lining in the burning zone. The Al Khums authorities could ask Polservice to apply this method in future in exploiting the raw materials. The actual bench layout has to be calculated by CES so that it is possible to control the difference in $CaCO_3$ content and to adjust this content to the correct percentage required either when the basic raw materials are being mixed during excavation or when they are being processed. Moreover, to ensure smooth working conditions throughout the digging benches, the variations in composition of materials within benches should be kept to a minimum.

If a prehomogenization stockpile is erected it would be possible to avoid chemical fluctuations over a period of at least several days. If the Al-Khums I Cement Plant is not equipped with a prehomogenization system, this will mean that the quarry has to be exploited with great care to avoid supplying the production line with raw materials of fluctuating characteristics and frequency, which is otherwise likely to happen all the time. This kind of quarry exploitation requires a great number and variety of machines and vehicles and this in turn leads to extra costs in quarry investment and also higher running costs.

## E. Raw-mix designs

The production of Portland cement by a clinkering process depends on the chemical composition of the mix, the physical state of the raw materials (such as fineness), the temperature and period of burning. The chemical composition of Portland cement must fulfill certain requirements to ensure its successful use and stability. For example, a limitation is placed on the lime content to ensure that the cement shall not contain an excess of lime over that which can combine with the acidic oxides. Such an excess would be liable to produce unsoundness. Accordingly, a proportioning formula, the "lime modulus", is provided for calculating the maximum amount of lime which can combine with the acidic oxides during burning. The relationship between the silica, alumina and iron-oxide contents of a cement is expressed as the "silica modulus" (SM) which usually lies between 1.5 and 3.2 and ideally should be between 2.2 and 2.6. As the silica modulus increases, chemical combination becomes more difficult, especially when the ratio exceeds 3. Thus an increase in the silica modulus impairs the burnability of the raw mix. Increasing the silica modulus produces cements with slow setting and hardening properties. On the other hand, cements with a low silica modulus have excellent early strengths. The ratio of alumina to iron oxide, known as the "alumina modulus" (AM) is in the range of 1.5 to 3.5 and as it increases chemical combination also becomes more difficult. When the alumina modulus is low, over-production of flux or liquid formation may occur which in turn narrows the range of temperature operation.

These fundamentals are described by the co-ordinator to stress the necessity of supplying the kiln with a steady flow of raw-mix constituents whose chemical and physical state will be suitable for burning. Any change in these factors will upset the behaviour of the kiln and react unfavourably on the kiln lining and the quality of the clinker produced.

Dealing with the Polservice recommendations on raw-mix design, the co-ordinator feels that Polservice has treated this part of the study in a theoretical way and there is too little comment on the practical application of these raw materials in the proportions suggested to produce clinker complying with the standard specifications. The co-ordinator's comments concentrate upon some practical applications and facts as follows.

The raw mixes used in the Al Khums I Cement Plant up till now were mainly dependant on limestone and marl (both from the Margheb deposit), imported bauxite and iron ore from the Galmoya region. The proportion of these were within the following ranges:

| | Percentage |
|---|---|
| Limestone | 50.0-62.0 |
| Marl | 35.0-45.0 |
| Bauxite | 1.5-1.7 |
| Iron ore | 1.4-1.5 |

The raw mill's hoppers, proportioning equipment, feeders and weighing belt conveyors were designed to deal with these percentages of the raw materials.

According to data from the Al Khums I plant, the carbonate content of the limestone used in the raw mix since the beginning of 1980 has been in the range 83.78-96.38%. The alumina content of the marl used in the same period has been in the range 1.7-7.58%. The same variatons existed in the contents of the other oxides in the limestone and the marl. Although the variations were not very great, they were reflected in the quality of the clinker produced, i.e. in the percentage of the clinker phases produced.

The system proposed by Polservice for proportioning the raw-mix designs given in their report, using the raw materials from the Mannubia and Kebir deposits, was very complicated and in practice could not be applied smoothly without the help of a preblending system, quality control and the introduction of some adjustments in the proportioning and weighing equipment. Their proposed raw-mix designs are shown below.

| | Raw-mix design number | | | | | | |
|---|---|---|---|---|---|---|---|
| Component | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Limestone | 53.8 | 15.3 | 69.7 | 80.4 | 95.3 | 21.4 | 95.0 |
| Marl | 41.5 | 80.1 | 25.3 | 15.0 | | 72.6 | |
| Iron ore | 1.7 | 1.6 | 1.5 | 1.3 | 1.2 | 1.5 | 1.5 |
| Clay | 3.0 | 3.0 | 3.5 | 3.3 | 3.5 | 3.5 | 3.5 |

From these raw-mix designs, it is clear that the percentages of iron ore and of clay in the raw mix will remain fairly constant. The iron oxide only varies from 1.2-1.7% and the clay from 3.0-3.5%. The major components, limestone and marl, are shown as varying in a very considerable way. The average percentage of the base rock (calcareous marl) could vary from 0.0% to 95.0%.

According to the co-ordinator's as well as Polservice's raw-mix calculations, it is clear that Margheb clay, despite its high silica content, will be suitable as a corrective material to replace the imported bauxite. This clay is located in the immediate vicinity of the cement plant which is a great advantage.

However, according to Polservice, the replacement of bauxite by clay will require certain modifications to the existing process technology and equipment in the cement plant. The modification of process technology involves:

(a) An increase in CaO content in the raw meal from 41.5-42.5% to 42.5-43.0% in order to saturate the silica introduced in the clay with lime;

(b) An increase in the lime saturation factor (LSF) from the present 90-92% to 92-94% since the clinker produced with the help of clay will contain less $C_3A$ which is responsible for the initial strength of cement. This can be compensated by increasing the $C_3S$ content obtained through the LSF;

(c) The above modification will require a raw meal with $CaCO_3$ content in the range of 75.5-76.5% instead of in the range 74.5-75.5% used at present.

The necessary modifications of equipment will involve:

(a) The installation of an appropriate type of crusher for clay (erected and under test);

(b) The construction of a clay store roofed for protection against rain;

(c) The installation of a transport and feeder system supplying clay to both raw materials mills.

The present feeder system, designed to supply bauxite and iron oxide, will be inadequate for supplying clay because of its construction and small capacity. The amount of clay needed will be three times greater than that of bauxite.

It has been suggested that, to change from 1.7% bauxite to 5.0% clay would require modifications of equipment while in order to change the percentages of marl and limestone in the mix, no modifications in the equipment are required. The co-ordinator believes that this is not correct and that variations in the carbonate content of both limestone and marl would also require modifications to the transport and storage systems.

In general, it will be very difficult for the quality-control personnel to control the oscillation of the carbonate content and kiln behaviour.

## F. Ore reserves

As shown in table 4, the workable reserves as calculated by Polservice (re-arranged and retabulated by the author) amounted to the following:

| | | (tonnes) | |
|---|---|---|---|
| Mannubia | Bench I | 3 391 125 | |
| | Bench II | 5 279 200 | |
| | Bench III | 8 709 123 | |
| | | Subtotal | 17 379 448 |
| Kebir | Bench I | 1 396 558 | |
| | Bench II | 3 430 923 | |
| | Bench III | 8 133 423 | |
| | | Subtotal | 12 960 904 |
| | | Total | 30 340 352 |

Polservice also established the existence of a fourth level in Mannubia which, if exploited, would increase the total workable reserves to 42 525 800

Polservice has estimated that the raw materials from the Mannubia-Kebir deposit will secure the production of the cement factory at Al Khums I for 40 years. This is based on the following assumptions:

(a) The workable reserves of the Mannubia deposit, as shown, amount to 17.4 million tonnes. This, together with 1.2 million tonnes from bench 1 of the Kebir deposit, gives reserves of 18.6 million tonnes. This would secure the production of the cement factory for 27 years at a yearly demand rate of 730 thousand tonnes;

(b) The reserves of benches II and III in the Kebir deposit are assessed as 11 million tonnes and, assuming that the marl of bench II and limestone of bench III will form 95% of the raw meal, these reserves will secure the production of the cement factory for another 16 years, i.e. a total of more than 40 years.

The co-ordinator has several comments to make on this calculation of reserves.

It was mentioned above that the raw mixes designed by Polservice could only be applied if preblending-homogenization and automated quality control were used. Failing this, since controlling the quality as proposed by Polservice would be so difficult, it appears that selective mining or quarrying would be the best way to control the quality of the raw meal entering the kiln.

In practice, the upper limestone in the Mannubia quarries was and still is being exploited selectively to provide the raw meal with its calcareous component and the marl was and still is being exploited only to supply the raw meal with the necessary siliceous and aluminous components. Using calcareous marl as the main component to replace limestone and marl would create serious problems in clinker production.

Because of these doubts about including calcareous marl in the reserves and because the uneven distribution of investigatory boreholes and the lack of adequate supplementary trenching may not have given an accurate picture of the reserves, the amount of reserves calculated by Polservice cannot be accepted as proven.

Even if it is agreed that the ore-reserve calculations carried out by Polservice were accurate, the following facts should be pointed out:

(a) All the upper limestone predominating in block II (represented by boreholes M-8 and M-6) has been completely exploited;

(b) The upper limestone covering blocks I, III, IV and V has been partly exploited;

(c) The clinker produced in the Al Khums I Cement Plant since 1979 (when the Mannubia quarry was opened) was 601,237 tonnes which consumed 700,000 tonnes of limestone extracted from the blocks mentioned above;

(d) Therefore, the workable reserves of limestone present in the Mannubia deposit after deducting the amount used will be:

| | |
|---|---|
| 3 391 125 | tonnes workable reserves |
| -700 000 | tonnes exploited limestone |
| 2 691 125 | or approximately 2 700 000 tonnes |

(e) As already explained, the lower marly zone underlying the upper limestone is very thick and it is impossible to use all of it in the raw meal because of the practical difficulties, at least until the introduction of preblending and automated-control methods or until future technological progress makes it possible to use this type of material without any harmful effects on clinker production. In the meanwhile, if the marly zone cannot be exploited, the lower limestone will not be exposed and this limestone would be needed to satisfy the proportions of approximately 70% limestone to 28% marl used at present in the plant's raw mix;

(f) The total limestone reserves in both the Mannubia and Kebir deposits amount to:

| | | |
|---|---|---|
| Mannubia | 2 700 000 | tonnes |
| Kebir | 1 400 000 | tonnes |
| Total | 4 100 000 | tonnes |

(g) As the yearly demand of raw materials amounts to 730,000 tonnes and as about 70% of this quantity is limestone, approximately 500,000 tonnes of limestone are required annually for the clinker production of 440,000 tonnes per year;

(h) The total limestone reserves given above will therefore only be sufficient for cement production at Al Khums I for approximately eight years (4,100,000 ÷ 500,000).

It must also be said that in order to extract the Margheb clay, the very thick marl overlying this clay ought also to be used in the raw-mix design or else it has to be discarded as useless material.

However, the ore reserves calculated by the co-ordinator as sufficient to supply the Al Khums Cement Plant's full production for eight years, could be extended to cover a lifetime of more than 25 years if the production lines are modified and overhauled and the following recommended procedures are adopted.

Drilling more boreholes in the Mannubia and Kebir deposits. This further investigation has to be carried out to determine the true bedding conditions, assess the suitability of every metre of depth according to its chemical properties and to select (especially in the marly zones) the most suitable areas in these deposits for future opening up. Information from these boreholes has to be supplemented by digging more trenches surrounding the limestone outcrops.

Evaluation of the geochemical data obtained from the exploration must be substantially speeded up by means of a suitable computation system such as the Computerized Evaluation System (CES) for raw materials recently developed by F.L. Smidth (Denmark). In this method, the chemical analysis of the drilled cores can be stored, section by section, with associated data relating to the co-ordinates of the borehole, the depth and the thickness of the deposit. By making use of appropriate programmes, it is moreover possible to store the results obtained from inclined boreholes, trenches and from trial pits and, taking into account the dip of the strata, to obtain a strata-related representation of the geochemical conditions.

Since the benches in the quarry are usually horizontal, the computer can, via the standard deviation, determine coefficients of variation and limiting concentrations for selected areas of the deposit. From this information, the bench height and bench sections can then in turn be obtained. This data collection can be regularly updated and supplemented by further analyses during the subsequent actual quarrying operations so that predictions of the chemical composition of the material found in the individual stages of quarrying can reliably be made. It is also possible to let the computer produce maps indicating lines of equal chemical concentration, which provide information for determining the direction of quarrying.

The erection of a suitable stockpile to provide finished products of constant quality whilst adapting production to the heterogeneous nature of the Mannubia and Kebir deposits should be studied as early as possible. The reasons for providing this intermediate device to make the raw mix homogeneous are:

(a) Better utilization of the predominantly inhomogeneous raw-material deposits in Mannubia and Kebir;

(b) Better uniformity of the raw meal and of the clinker produced so that the quality of the cement is more nearly constant and within the standard specifications;

(c) Automation of raw-mix proportioning has become essential for the lowering of costs.

The mean chemical composition of the prehomogenization stockpile has to be precisely known during its formation so that the necessary corrections can be made. This calls for:

(a) Installing a reliable apparatus to take samples of representative material placed on the bed (sampling station);

(b) Being able to analyse these samples rapidly to obtain their chemical composition (x-ray flourescence equipment);

(c) Having the computational means to transform the data obtained into concrete directions for blending, with a minimum response time (computer).

## G. Summary of the co-ordinator's comments

### Geological investigations

The 30 boreholes drilled by Polservice in both the Mannubia and Kebir deposits and the trenches dug were not so well distributed as to cover the entire area of these deposits. The depth of the boreholes drilled was more than sufficient but was also wasteful and unnecessary as it penetrated down to dolomitic rocks. The boreholes could be said to give sufficient information for such inhomogeneous deposits and such a shapeless area, but the two areas are still in need of more confirmatory trenches to be dug around the upper limestone outcropping boundary.

### Chemical analysis

The quantity and type of analyses carried out by Polservice was sufficient to get a good knowledge of the deposit from the chemical-constituents point of view. However, Polservice failed to include in their report the descriptive meanings of the chemical-analyses results. This part has been supplied by the co-ordinator.

## Exploitation of the raw materials

Selective mining as carried out by the Al Khums I Cement Plant was the easiest way to fulfill the specification requirements of the cement raw-mix design. The Polservice proposal to divide the Mannubia and Kebir deposit into four benches for exploitation could not be carried out unless the plant were to be equipped with some special facilities. From the co-ordinator's explanatory drawings and sections cutting the deposits in different directions, it can be clearly seen that, in any direction chosen to start exploitation, the materials excavated will change their carbonate content so frequently and to such an extent that it would affect the clinker burning, kiln behaviour and the quality of cement produced.

## Quality control

The investigated raw materials in both the Mannubia and Kebir deposits vary greatly, mineralogically and chemically, even in one place or in the same bed. If the Polservice proposal to open the quarries in four benches were followed, the proportions of the raw mix would have to be corrected at frequent intervals which would require more personnel to undertake the time-consuming calculations needed. It would have been better at the time of submitting the Polservice report, to recommend the introduction of a process computer in conjunction with x-ray fluorescent equipment to give automated control of the quality of the raw materials, raw-mix design and clinker produced. If the process computer had been introduced at the time of erecting the second production line, it might have been economically possible to implement the bench-excavation proposal. Polservice should also have included in their report a recommendation to use a proper blending stockpile as they were well aware of the poor conditions for storing and blending raw materials in production line I.

## Raw-mix designs

This part was dealt with by the contractor mainly on a theoretical basis as, in practice, the raw-mill hoppers, proportioning equipment, feeders and weighing belt conveyors were designed for a certain range of raw-mix design and could not cope with all the proposed designs with their very wide proportioning range. In order to meet such a wide proportioning range, all the equipment would have to be modified and in practice was not capable of so much modification. Apart from this, it is clear that a preblending system is required to supply the kilns with steady raw-mix constituents. The co-ordinator agrees that Margheb clay would be suitable to replace bauxite as a corrective material, but certain modifications to the existing technology and installations would be required to process the clay.

## Ore reserves

The ore reserves calculated by the contractor cannot be accepted as proven reserves for the reasons given in detail previously. According to the co-ordinator, the workable ore reserves of limestone available in the Mannubia and Kebir deposits after subtracting the quantity already used, amount to about 4 million tonnes, which is sufficient to last the Al Khums I Cement Plant for approximately eight years.

## III. OTHER NEW DEPOSITS INVESTIGATED

Polservice investigated some other areas to the south of the main coastal road and said that their investigations resulted in the discovery of limestone reserves larger than those specified in the contract. In their opinion, this discovery created the possibility of further development of the cement industry in the Al Khums area. It was decided at that time by the General Director of the National Cement and Building Materials Company that the limestone deposits situated north of the main coastal road (Mannubia and Kebir) would be reserved for the cement factory, Al Khums I. The deposits in the area situated south of the main coastal road would form the raw-material base for the planned new cement factory, Al Khums II. The two new areas were known as the Juma and Cretaceous limestone deposits.

Although both these deposits were situated south of the main coastal road and therefore were allocated to the planned new cement factory, it was felt to be of interest to comment here upon the data given by Polservice on each of these two areas. It is possible that their reserves may be rescheduled to supply the Al Khums I plant.

### A. Juma limestone deposit

Polservice investigated this deposit, situated south of the main coastal road, by drilling six boreholes. Polservice stated that the succession of strata here is upper marl, upper limestone, lower marl and lower limestone, on average totalling 20 metres in thickness. Polservice added that the analysis of samples collected from boreholes showed good quality materials in this deposit. They assessed the surface area as 0.425 square kilometres, the mean thickness of the deposit as 20 metres and the bulk density as 2.2 tonnes per cubic metre so that the reserves of the Juma deposit were then estimated conservatively as amounting to 17 million tonnes.

The co-ordinator has collected the data on the chemical analyses and these are presented in table 8.

The co-ordinator's comments on all the findings on the Juma deposit are as follows.

The chemical analyses and the descriptions of the bore-hole logs indicates the true similarity between both successions as the Tertiary rocks consist here of the upper marl, the upper limestone, the lower marl and the lower limestone.

The co-ordinator disagrees with Polservice's conclusion that the mean thickness of the deposit is 20 metres and that all the deposit is of good raw-material quality and is suitable for cement production. He gives the following reasons:

(a) The figures for $CaCO_3$ content, as indicated in table 8, show that the materials in this zone vary from pure limestone containing 96.00% $CaCO_3$ to clayey material. This oscillation of $CaCO_3$ content in the raw materials supplied to the raw mills and kilns is undesirable;

Table 8. Chemical analyses of borehole samples from the Juma deposit

| Borehole no. | Thickness | | Full analyses | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (CaCO$_3$) (%) | MgO (%) | S$_1$O$_2$ (%) | Al$_2$O$_3$ (%) | Fe$_2$O$_3$ (%) | SO$_3$ (%) | Na$_2$O (%) | K$_2$O (%) |
| J-1 | | | | | | | | | | | |
| Spot level[a] | 155.0 | | | | | | | | | | |
| | 0.0 | 6.2 | 37.28 | 45.50<br>(83.0) | 0.50 | 11.61 | 3.04 | 0.00 | 0.15 | 0.14 | 0.28 |
| | 6.2 | 18.8 | 34.27 | 42.33[b] | 0.91 | 14.97 | 4.65 | 0.00 | 0.17 | 0.14 | 0.52 |
| | 18.8 | 33.2 | 36.10 | 43.44<br>(84.35) | 0.91 | 12.45 | 4.42 | 0.00 | 0.17 | 0.12 | 0.46 |
| | 33.2 | 35.8 | 40.60 | 47.24 | 3.44 | 5.43 | 2.09 | 0.00 | 0.14 | 0.14 | 0.16 |
| Depth of borehole | 70.0 | | | | | | | | | | |
| J-2 | | | | | | | | | | | |
| Spot level | 157.6 | | | | | | | | | | |
| | 0.0 | 10.3 | 42.95 | 53.77<br>(96.00) | 0.31 | 1.16 | 1.25 | 0.14 | 0.06 | 0.09 | 0.12 |
| | 10.3 | 21.7 | 36.38 | 44.49[b]<br>(80.54) | 0.70 | 12.26 | 4.32 | 1.51 | 0.12 | 0.11 | 0.39 |
| | 21.7 | 30.0 | 36.32 | 45.10<br>(92.73) | 0.57 | 12.61 | 3.24 | 0.97 | 0.15 | 0.12 | 0.23 |
| | 30.0 | 33.6 | 41.64 | 51.93 | 0.54 | 3.97 | 0.94 | 0.38 | 0.06 | 0.10 | 0.15 |
| Depth of borehole | 60.0 | | | | | | | | | | |
| J-3 | | | | | | | | | | | |
| Spot level | 161.2 | | | | | | | | | | |
| | 0.0 | 5.3 | 30.33 | 34.94[b]<br>(94.25) | 2.18 | 23.88 | 5.17 | 1.93 | 0.09 | 0.25 | 0.63 |
| | 5.3 | 12.0 | 42.15 | 52.78 | 0.28 | 3.21 | 0.82 | 0.23 | 0.06 | 0.14 | 0.16 |
| | 12.0 | 25.0 | 34.77 | 41.31[b] | 1.25 | 16.76 | 3.48 | 1.57 | 0.07 | 0.16 | 0.56 |
| | 25.0 | 36.1 | 35.16 | 42.49[b]<br>(89.00) | 1.10 | 14.72 | 3.95 | 1.71 | 0.07 | 0.16 | 0.56 |
| | 36.1 | 39.1 | 40.03 | 49.84 | 0.38 | 7.08 | 1.30 | 1.06 | 0.05 | 0.14 | 0.16 |
| Depth of borehole | 70.0 | | | | | | | | | | |

continued

Table 8 (continued)

| Borehole no. | Thickness | | Full analyses | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | From (m) | To (m) | LOI (%) | CaO (CaCO$_3$) (%) | MgO (%) | $S_1O_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) |
| J-4 | | | | | | | | | | | |
| Spot level | 157.4 | | | | | | | | | | |
| | 0.0 | 7.2 | 40.45 | 49.68<br>(88.70) | 0.45 | 7.00 | 1.65 | 0.55 | 0.06 | 0.16 | 0.16 |
| | 7.2 | 20.4 | 32.79 | 39.09 b/ | 1.57 | 19.31 | 4.64 | 1.65 | 0.03 | 0.16 | 0.6 |
| | 20.4 | 32.0 | 35.06 | 42.37 b/ | 1.00 | 14.43 | 4.61 | 1.55 | 0.07 | 0.16 | 0.6 |
| | 32.0 | 35.6 | 40.22 | (89.38)<br>50.05 | 0.38 | 6.39 | 1.85 | 0.90 | 0.07 | 0.14 | 0.25 |
| Depth of bore-hole | 70.0 | | | | | | | | | | |
| J-5 | | | | | | | | | | | |
| Spot level | 158.9 | | | | | | | | | | |
| | 0.0 | 2.7 | 41.41 | 49.32<br>88.96 | 1.32 | 3.98 | 2.01 | 0.32 | 0.08 | 0.05 | 0.16 |
| | 2.7 | 10.1 | 42.75 | 53.40<br>(95.35) | 0.76 | 1.15 | 1.25 | 0.14 | 0.06 | 0.03 | 0.15 |
| | 10.1 | 19.0 | 35.27 | 42.05 b/ | 2.05 | 15.28 | 3.5 | 1.05 | 0.10 | 0.03 | 0.05 |
| | 19.0 | 32.0 | 35.02 | 41.38 b/ | 1.31 | 15.01 | 3.91 | 1.12 | 0.10 | 0.05 | 0.70 |
| | 32.0 | 38.6 | 39.64 | (88.30)<br>49.45 | 0.65 | 8.18 | 0.99 | 0.32 | 0.06 | 0.07 | 0.26 |
| Depth of bore-hole | | | | | | | | | | | |
| J-6 | | | | | | | | | | | |
| Spot level | 151.4 | | | | | | | | | | |
| | 0.0 | 5.2 | 40.28 | 50.38<br>(89.96) | 0.40 | 6.19 | 1.76 | 0.76 | 0.07 | 0.12 | 0.22 |
| | 5.2 | 15.5 | 34.36 | 42.41 b/ | 0.93 | 14.53 | 4.62 | 1.67 | 0.07 | 0.17 | 0.59 |
| | 15.5 | 21.5 | 35.92 | 43.59 b/ | 1.12 | 12.56 | 4.45 | 1.57 | 0.17 | 0.12 | 0.48 |
| | 21.5 | 28.7 | 35.12 | 42.92 b/ | 0.75 | 14.85 | 4.06 | 1.75 | 0.07 | 0.17 | 0.52 |
| | 28.7 | 33.4 | 40.15 | (89.52)<br>50.13 | 0.35 | 6.35 | 1.82 | 0.31 | 0.07 | 0.11 | 0.20 |
| | 33.4 | 38.5 | 37.06 | (81.57)<br>45.68 | 0.77 | 11.70 | 3.17 | 0.91 | 0.15 | 0.14 | 0.28 |
| Depth of bore-hole | 53.5 | | | | | | | | | | |

a/ Spot levels are given in metres above sea level.

b/ Marly limestone.

(b) The upper limestone beds (containing more than 80% $CaCO_3$) are confined, as in the Mannubia and Kebir deposits, to the uppermost layers and its thickness ranges from 5.2 metres as shown in borehole J-6 to 10.3 metres and 10.1 metres as in boreholes J-2 and J-5 respectively. Accordingly, the average thickness can be conservatively estimated as 7.3 metres.

(c) The lower limestone beds (containing more than 80% $CaCO_3$), as in the Mannubia and Kebir deposits, are overlain by marly limestone or marly beds. The thickness of these limestone beds as shown in table 8 ranges from 11.9 metres as seen in borehole J-2 to 2.6 metres as in borehole J-1. Accordingly, the average thickness of the lower limestone deposit in all the drilled boreholes can be conservatively estimated as 6.25 metres.

Taking these thicknesses for the upper and lower limestone beds, the limestone reserves can be calculated as follows:

The surface area of the deposit = 0.425 $km^2$
The bulk density = 2.2 $t/m^3$
Therefore the reserves in the <u>upper limestone deposit</u> will
be 0.425 x 2.2 x 7.3 (average thickness) = 6,825,500 t.
Limestone reserves in the <u>lower limestone deposit</u> will
be 0.425 x 2.2 x 6.25 = 5,843,750 t.
Total reserves = 12,669,250 t.

The average chemical analyses shown in table 8 indicate that, although marly strata are found in between the upper and lower limestone strata, these are of a calcareous character i.e. the $CaCO_3$ content ranges between 70-76%. This means that, with a well-chosen system of exploitation and quarry opening, all the calcareous marl can be exploited and the pure limestone used in correcting any deficiency found in the $CaCO_3$ content of this calcareous marly zone.

If all the calcareous marl is added to the reserves of pure limestone, then the co-ordinator agrees with the reserves of basic raw materials calculated by Polservice to be 17 million tonnes. However, this quantity must be confirmed later by drilling more boreholes around the six previously drilled by Polservice. The number of new boreholes ought to be not less than 20 and the spacing between them ought not to be less than 150 metres.

## B. Cretaceous limestone deposit

This deposit lies in an unnamed hill, south of the main coastal road and south of Juma. Polservice only gave a few descriptive lines on this deposit in their report. The co-ordinator feels that these lines are not sufficient and that it would be very useful to analyse and evaluate the logs of boreholes drilled by Polservice as this information would be of value to the Al Khums Cement Company.

Seven boreholes with a total depth of 406.5 metres and an average depth of 58 metres were drilled in this area. It is important to give a brief description of each borehole to cover some of the necessary data not provided in the Polservice report. The chemical analyses of the samples taken from the limestone beds in these boreholes are given in full in table 9.

Table 9. Chemical analyses of samples from the limestone beds in the cretaceous limestone deposit.

| Log. of borehole No. | Thickness |  | Full analyses |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | From (m) | To (m) | LOI (%) | CaO (%) | MgO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $SO_3$ (%) | $Na_2O$ (%) | $K_2O$ (%) |
| C-1 Spot level[a] | 112.4 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 5.5 | 41.9 | 53.02 | 0.4 | 3.12 | 0.61 | 0.39 | 0.12 | 0.12 | 0.2 |
|  | 5.5 | 13.1 | 42.79 | 50.8 | 2.59 | 1.24 | 1.2 | 0.62 | 0.10 | 0.07 | 0.3 |
| Depth of borehole | 70.0 |  |  |  |  |  |  |  |  |  |  |
| C-2 Spot level | 114.4 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 8.5 | 32.78 | 38.88 | 1.34 | 19.4 | 5.08 | 1.29 | 0.06 | 0.12 | 0.75 |
|  | 8.5 | 18.6 | 42.08 | 51.55 | 51.55 | 2.37 | 1.16 | 0.54 | 0.06 | 0.08 | 0.45 |
| Depth of borehole | 70.0 |  |  |  |  |  |  |  |  |  |  |
| C-3 Spot level | 106.0 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 9.2 | 42.44 | 48.07 | 3.83 | 4.00 | 0.92 | 0.52 | 0.10 | 0.08 | 0.10 |
|  | 9.2 | 20.0 | 39.20 | 48.17 | 1.00 | 6.61 | 3.16 | 1.24 | 0.09 | 0.08 | 0.50 |
|  | 20.2 | 31.7 | 42.81 | 53.38 | 0.60 | 1.59 | 0.86 | 0.40 | 0.07 | 0.08 | 0.16 |
| Depth of borehole | 56.5 |  |  |  |  |  |  |  |  |  |  |
| C-4 Spot level | 102.7 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 6.8 | 42.18 | 51.58 | 0.98 | 3.03 | 0.82 | 0.8 | 0.1 | 0.08 | 0.2 |
|  | 6.8 | 13.7 | 41.60 | 50.94 | 0.96 | 3.50 | 1.67 | 0.8 | 0.03 | 0.08 | 0.2 |
| Depth of borehole | 58.0 |  |  |  |  |  |  |  |  |  |  |
| C-5 Spot level | 99.5 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 8.9 | 41.87 | 48.88 | 2.74 | 4.36 | 1.2 | 0.72 | 0.13 | 0.08 | 0.16 |
|  | 8.9 | 14.6 | 39.9 | 48.92 | 1.00 | 5.34 | 3.11 | 1.00 | 0.12 | 0.08 | 0.72 |
|  | 14.6 | 25.0 | 42.84 | 53.74 | 0.30 | 1.34 | 0.86 | 0.6 | 0.12 | 0.08 | 0.20 |
|  | 25.0 | 33.8 | 43.61 | 54.85 | 0.30 | 0.48 | 0.50 | 0.19 | 0.13 | 0.08 | 0.04 |
| Depth of borehole | 47.0 |  |  |  |  |  |  |  |  |  |  |
| C-11 Spot level | 101.6 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 10.2 | 39.59 | 48.47 | 1.25 | 6.46 | 2.17 | 1.08 | 0.06 | 0.1 | 0.5 |
| Depth of borehole | 50.0 |  |  |  |  |  |  |  |  |  |  |
| C-12 Spot level | 84.4 |  |  |  |  |  |  |  |  |  |  |
|  | 0.0 | 6.0 | 40.18 | 46.74 | 3.03 | 6.98 | 1.87 | 0.5 | 0.03 | 0.03 | 0.21 |
|  | 6.0 | 12.9 | 38.13 | 47.34 | 0.81 | 10.33 | 2.52 | 0.48 | 0.03 | 0.05 | 0.16 |
| Depth of borehole | 55.0 |  |  |  |  |  |  |  |  |  |  |

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[a] Spot levels are given in metres above sea level

## Borehole C-1

Limestone predominates in the upper beds with a total thickness of 13.1 metres. The limestone is covered with a calcrete crust of one metre thickness. The limestone is greenish-buff or yellowish in colour with intercalations of calacreous silt. The lower part of the limestone is pink in colour and hard with caverns filled with yellow silt. The limestone analyses showed that it is suitable for cement production as the $CaCO_3$ content of the upper stratum (0.0-5.5 m) is 94.68% and the carbonate content of the lower part (5.5-13.1 m) is 90.7%. In this part, there are two dolomitic bands from 6.2-8.2 metres and from 8.2-10.3 metres, with a total thickness of 4.1 metres. These two bands contain 4.06% and 3.04% MgO respectively. All the underlying strata down to 70 metres depth are rich in magnesia content which reaches more than 20%. Therefore, all these rocks are dolomitic in character.

## Borehole C-2

Limestone suitable for cement production predominates in the upper parts underlying the calcareous marly stratum which in turn is covered with a calcrete crust of 0.8 metres. The uppermost strata (0.0-8.5 m) are greenish and buff in colour. It is calcareous marl yellowish and silty at the lower part. Its $CaCO_3$ content reaches 69.4%. The underneath stratum (8.5-18.6 m) is limestone of 92% $CaCO_3$ content. This limestone is buff in colour with calcite veins, locally silty. All the underlying strata down to the lowest part of the borehole contain high percentages of MgO.

## Borehole C-3

The limestone strata are represented by three zones. The uppermost (0.0-9.2 m) limestone is creamy, pinkish or greyish in colour. This limestone is traversed with calcite veins. The underlying zone of limestone (9.2-20.0 m) is greyish, pinkish buff and silty in some places. The lowest limestone zone (20.0-31.7 m) is greyish, pinkish crystalline or silty in different places. The $CaCO_3$ content of these limestone zones is 85.84%, 86.02% and 95.32% respectively. All the lower strata are rich in MgO content, i.e. most of the rocks are dolomitic.

## Borehole C-4

The upper part of the borehole (0.0-6.8 m) consists of limestone, pinkish or buff in colour. It is traversed throughout with calcite veins. Numerous intercalations of yellow silt are present. Its $CaCO_3$ content reaches 92.1%. The underlying limestone strata (6.8-13.7 m) are creamy-yellow or buff. The limestone is usually crystalline and silty in some places. Its $CaCO_3$ content reaches 90.96%. All the strata below this are dolomitic in character.

## Borehole C-5

The limestone strata can be differentiated into four zones. The uppermost (0.0-8.9 m), with a $CaCO_3$ content of 87.28%, is buff crystalline with calcite veins and few silt intercalations. The covering layer, 2.5 metres thick, is made of calcrete crust and yellowish marl. The average MgO content is 2.74% but the magnesia increases locally to 3.57% in the area 4.7-8.9 metres deep. The underlying second limestone layer is buff or light yellow, silty with intercalations of crystalline limestone and calcite veins. The $CaCO_3$ content reaches 87.35%. The third limestone layer has 95-96% $CaCO_3$, is buff in colour, oolitic in character with few calcite veins intercalating the rock. The fourth limestone layer (base) has 97-94% $CaCO_3$, is pink or reddish and crystalline. From this layer down to the bottom of the borehole (47.0 m deep), the rocks are of dolomitic character.

Borehole C-11

The limestone in the top layers of the borehole cannot be differentiated into more than one zone. The limestone predominating in this zone (0.0-10.2 m) has a $CaCO_3$ content of 86.55%, is buff, light yellow or brownish in colour. It is oolitic limestone with an MgO content within the normal range except in a band 5.3-7.0 metres deep which contains magnesia up to 5.67%. The rocks underlying the oolitic limestone are of dolomitic character. Polservice continued drilling and penetrated the strata down to 50.0 metres in depth. It is worth noticing that the uppermost layer, one metre thick, represents a soil bed partially contaminated with limestone fragments.

Borehole C-12

Limestone suitable for cement production occupies the capping strata of the borehole. Its thickness reaches 12.9 metres. This part is differentiated into two zones. The upper zone has a 83.46% $CaCO_3$ content, is creamy-white and locally yellow in colour. The upper part of this zone is crumbly in character with intercalations of hard, greenish limestone. The lower part is of tough fossilliferous limestone. A calcrete crust with white marl covers the uppermost part of the zone. The underlying limestone stratum has a 84.53% $CaCO_3$ content, is creamy white and locally yellowish in colour. The limestone is tough and fossilliferous. The lowest strata down to 55.0 metres in depth are of dolomitic limestone character.

Comments

This area is of vital importance to the Al Khums Cement Plant as the high-quality limestone in the Mannubia and Kebir areas is not sufficient to supply their cement production for very many years.

Polservice assessed the quantity of limestone reserves in the cretaceous area to be 10 million tonnes since they considered the thickness of the high-quality limestone to range from 17 to 58 metres with an average thickness of 30 metres. The co-ordinator believes that the mean thickness of the limestone which is apparently suitable for cement production is not more than 18.0 metres. Therefore, the limestone reserves should be recalculated as follows:

Surface area investigated = 144,927 $m^2$
Average depth of limestone = 18 m
Weight of 1 $m^3$ = 2.3 t
Therefore reserves = 144,927 x 18 x 2.3 = 5,999,977.8
= 6,000,000 t

Although this brings down the estimated limestone reserves by 30%, it is still a very sizeable deposit.

The area is poisoned by the presence of high percentages of magnesia especially in the underlying strata. In the co-ordinator's opinion, drilling seven boreholes to cover an area of 144,927 $m^2$ was not sufficient and he proposed the drilling of not less than 15 additional boreholes with a spacing of at least 100 metres between them to cover the area more adequately. At first, it was proposed to concentrate the new boreholes around the ones already drilled. Unfortunately, Polservice has only indicated the position of one of their seven boreholes on a survey map.

The co-ordinator began to represent the first seven boreholes diagrammatically in order to decide the proper depth to which drilling should continue. In doing this, he came across some unexpected facts and results which are shown in figure XI and which can be summarized as follows:

(a) The high percentage of magnesia content in the dolomitic limestone is haphazardly distributed through the limestone strata and is not confined to one level. It is not easy to determine at which level the magnesia starts to be concentrated in the limestone strata;

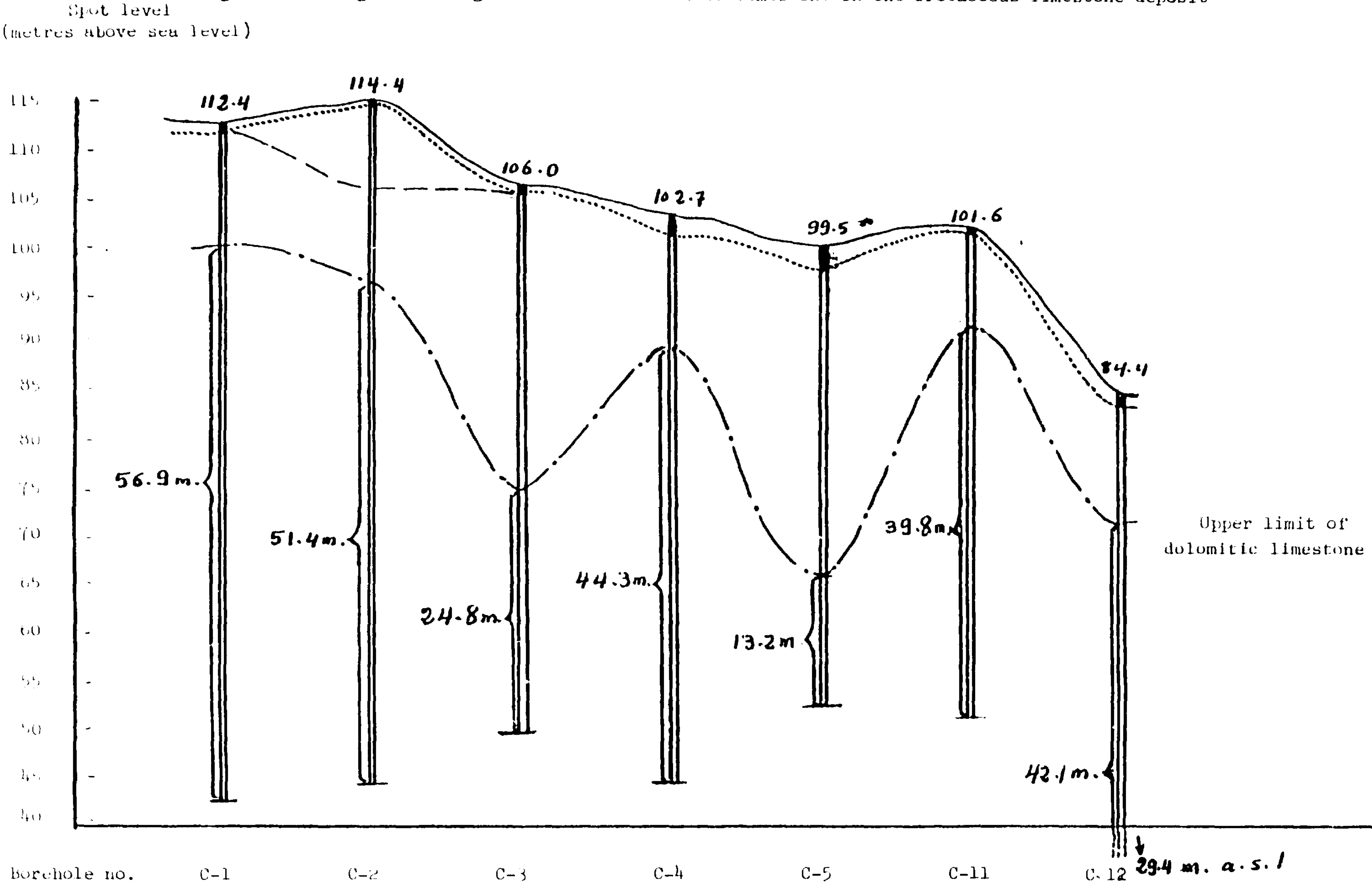
(b) Although the magnesia content starts to increase in boreholes C-1, C-2, C-4 and C-11 at levels between 89.0 and 99.3 metres above sea level, in the other boreholes, C-3, C-5 and C-12, it began to increase only much deeper at levels of 65.7-74.3 metres above sea level (no geological data concerning dipping of strata, faults, etc. were given);

(c) The limestone which is suitable for cement production only predominates regularly above 100.0 metres above sea level as shown in figure XI. It is very difficult to extract limestone in such a corrugated basin-like quarry to give a smooth supply to a cement plant.

For these reasons, it is recommended that the additional boreholes to be drilled ought to avoid penetrating the strata below 95.0 metres above sea level as penetrating deeper would create many problems arising from the introduction of limestone with a high magnesia content into the cement production which upsets the kiln operation.

It was a cause of much surprise to the co-ordinator that the boreholes had been drilled to such a depth in spite of the high magnesia contents found. It is well known that abbreviated analyses for $CaCO_3$ and $MgCO_3$ content have to be carried out on the spot when drilling for cement raw materials. They have a decisive influence on what further action is taken. The abbreviated analyses of these deposits showed that the MgO content increased to such an extent as to form dolomitic rocks. Nevertheless, the contractor proceeded to continue drilling to great depths which could produce no valuable results. This involved excess drilling of about 272.5 metres. The co-ordinator assumes that even when there is a contract to drill to such a depth, the contractor ought to inform the authorities of the results of his abbreviated analyses in order to change their work procedure and save money and time.

Figure XI. Diagram showing the level of dolomitic limestone in the cretaceous limestone deposit



## C. Development and exploitation of the quarry

The superficial deposits cover the entire area, as stated by Polservice, and their thickness is variable, mainly between 0.2 and 2.6 metres but increasing to 4 metres locally along the slopes. The surface material consists of calcrete crust and limestone rubble and shows a fairly high chloride and alkali content. Polservice advised that this superficial material should be stripped off at the opening of the quarry face. For this purpose, a bulldozer can be used to push the material down over the edge of the quarry at a suitable place. The overburden can only be removed economically if the right equipment is chosen and the direction of the excavation is planned so that the transport vehicles reach the main road in the shortest possible distance. The tipping area to be used for the disposal of the overburden along the edges of the wadis must be prepared before the work begins.

### Drilling

Because of the hardness of the limestone, it has to be broken out by blasting. The most economical method for this is large-diameter borehole blasting using a rotating, multi-stage, crawler-mounted drilling machine. A borehole diameter of 80 millimetres is recommended to suit the depth chosen and the blasting techniques. Compressed-air-operated percussion drills or down-the-hole drills are often used. However, their variable costs are considerably higher than those of rotary-drilling machines.

### Blasting

The blasting must be carried out as single-row blasting. The size of the blasts will follow Polservice recommendations and will be determined by the length of the quarry face opened and also by the vibration level permitted to avoid any side effects on the neighbouring buildings.

To achieve good fragmentation of the rock and an easily-loaded rock pile, a borehole grid should be chosen that is not too large. For this reason, many operations put up with a relatively high consumption of explosives and a grid size of 12-16 square metres is seldom exceeded. For best utilization of the energy of the blast, the spacing must be greater than the burden, particularly with ammonium nitrate-fuel oil (an-fo) and slurry explosives, mostly because of the expansion energy of the gases generated by the explosion. An-fo explosive, filled in bulk into the drilled borehole is universally the most cost-effective method of blasting. However, it is not water-resistant and ought to be used in dry boreholes only. Mixing of an-fo can be done on site in the proportion of 94:6 (ammonium nitrate:diesel oil). This mixed material can then be injected directly into the borehole which is an efficient and safe procedure. A primary cartridge or a heavy detonating fuse of 40-100 grammes per metre has to be used for detonation. The optimum face angle for perfect stability of the quarry face and the cleanest break at the foot proved to be 70° according to trials where the burden was 4-5 metres. Small single-row blasts on an approximately 12 square metre grid can be fired out on a 10-metre face using bulk an-fo explosive. The base charge consists of two electric detonators inserted into 5 kilogrammes of gelatinous explosive for a borehole of up to 12 metres depth, as recommended by Polservice. The detonation consequently takes place at the bottom of the borehole. This blasting technique has proved to give satisfactory results over a great many years and has the following three kinds of advantage:

(a) In terms of environmental protection and safety:

(i) Low vibration from the blast because of the short charge columns and the small amount of explosive per detonation;

(ii) Low noise nuisance as the detonator is in the borehole and no detonating fuse is used. The explosion itself is only apparant by a scarcely obtrusive muffled noise;

(iii) The danger of fragments of rock being thrown from the mouth of the borehole is slight as no detonating fuse passes through the tampings and the borehole remains better sealed;

(iv) The consequences of the borehole running out of true are not so severe with low faces. The desired burden is maintained and the risk of outward projection of pieces of the rock face caused by too small a burden is obviated;

(v) The danger of shearing of the detonating fuse in neighbouring boreholes cannot occur. The explosive is always detonated and there are no longer any dangerous unexploded base charges;

(vi) Because of the relatively small size of the grid the limestone is very well fragmented. Only a few oversize boulders are produced which can be broken up with a hydraulic breaker (or by secondary blasting);

(b) In terms of economic advantage:

The bottom of the face is removed more efficiently by the explosion. There are hardly any toes left, which removes the need for expensive additional work. The surface is well suited to wheeled loaders if these are used in loading. The level rock pile and the small amount of interlock of the fragments ensure high loading efficiencies and greater safety for the loader driver;

(c) In terms of selective quarrying:

(i) The separation of limestone and dolomite or marl is carried out in the actual quarry. Only small blasts are fired and their lateral extent is determined by the position of the dolomite vein or marly layers;

(ii) Even if the rock pile is mixed, with small single-row blasts there is still the possibility of sorting it during the loading.

If the double-row system is used for blasting on 20 metre faces, the consumption of explosive is about 120 grammes per tonne of limestone produced. This system can produce rock piles of up to 80,000 tonnes. In using this system, the base charge consists of 25 kilogrammes of high-energy slurry. A somewhat weaker slurry explosive is loaded on top of it up to 4 metres below the mouth of the borehole and tamped with drillings. It is fired by detonators in stages 0-18 at 30 millisecond intervals, with the explosive phase carrying right to the bottom of the borehole. Double-row blasting used in combination with slurry explosive produces good fragmentation in heavily stratified deposits. The rock pile is characterized by small lump size with only 0.6 tonnes oversize material per 100 tonnes of rock.

Attempts to control the quality of limestone using either single-row or multi-row blasts on high faces have had no success. Where there were distortions in the deposit, qualitatively different sections of the face were so severely mixed together that separation during loading is impossible. single-row blasting with a face height of 10 metres as opposed to 20 metres involves the lowest drilling and blasting costs. With a 10 metres face and detonation from the bottom of the holes, sub-drilling is reduced or eliminated and blast-hole capacity and explosive energy are better utilized.

It must be pointed out that it is only possible to control the quality of limestone during quarrying, as the negligible deviations in specific weight and similar physical properties of both limestone and marl do not permit separation during processing.

## Secondary fragmentation

Every blast produces some oversize material, particularly where there is pronounced stratification with heavy cross-fissuring. There has been no lack of attempts to get away from secondary blasting. In the last decade, fairly large plants have turned to hydraulic breakers for secondary fragmentation. These breakers would be efficient in the Al Khums limestone quarry as the predominating limestone is a hard brittle rock. The breakers are not recommended for use in limestone quarries with soft or medium-hard rock as this type of limestone resists even heavy breakers. Breakers have the disadvantage of large size and high repair costs and represent no reduction in cost compared with secondary blasting. However, the danger of flying rock is removed, downtime and non-productive time are reduced and neighbours are no longer troubled by the noise of the detonations. It is also possible to dispense with heavy and dangerous handworking with hammer drills for which trained labour is almost unobtainable locally. Some quarries use high-pressure water to split the rock boulders into small fragments.

## Loading

For loading work in quarries, the most important machines available are track-mounted loaders, wheeled loaders, cable-operated and hydraulic excavators. While track-mounted loaders only play a secondary role in limestone quarries, wheeled loaders have in many instances superseded the conventional cable-operated excavator.

Wheeled loaders are suitable for light to medium-heavy loading work in quarries. Cable-operated and hydraulic excavators are preferred for severe operating conditions as wheeled loaders are not sufficiently robust or rugged to be able to hold their own in continuous operation as the main loading machines. Loaders have a fairly short life, low breaking-out force, high energy consumption and, in contrast with the excavators, the total loaded weight has to be moved continuously while they are in operation. Even today, many operators of large open-cast quarries prefer the cable-operated excavator on account of its reliability and long life. Operating experience has shown that cable-operated excavators have 2.5 times the life of wheeled loaders and 1.5-2.0 times that of hydraulic excavators. In spite of this, a universal trend can be seen in which at least the smaller types of cable-operated excavators are being replaced by hydraulic excavators and wheel loaders.

In this case, the co-ordinator recommends the use of hydraulic excavators with a bucket size of more than 2.5 cubic metres and a corresponding gross weight of about 50 tonnes. These excavators should suit this job on both technical and economic grounds. Electro-hydraulic excavators are preferable as electricity can be supplied very easily. By comparison, the overall costs for diesel excavators are two to three times those for electric excavators.

# IV. MODIFICATION OF THE AL KHUMS I CEMENT PLANT

## A. Modifications originally proposed

The Al Khums I Cement Plant has never been able to achieve its rated production capacity. In 1980, therefore, the Heavy Industries Secretariat invited tenders for the modification of this plant. The planned modification was based on two alternatives. Alternative A, which is dealt with here, was to change the plant production from normal Portland cement to rapid-hardening, early-strength cement complying with the Italian specification for rapid-hardening, early-strength cement, type 525.

The Italian standard requires the following characteristics:

| | Bending strength ($kg/cm^2$) | Compressive strength ($kg/cm^2$) |
|---|---|---|
| After 24 hours | 40 | 175 |
| After 3 days | 60 | 325 |
| After 28 days | 80 | 525 |

Residue:
on 180 micron sieve, 2% maximum
on 90 micron sieve, 10% maximum

Setting time (Vicat):
initial, 45 min minimum
final, 12 hours maximum

Loss on ignition, equal to or less than 5%

Insoluble residue, equal to or less than 5%

$SO_3$ content, equal to or less than 3.5%

MgO content, equal to or less than 4%

Fineness (blaine) 3,900-5,800 $cm^2/g$ (depending on the quality of the clinker).

The production capacity should be the same as the rated capacity of the production lines, that is 1,330 tonnes per day over 330 days a year.

The co-ordinator has the following comments to make on the proposed Alternative A.

It would not be so difficult to switch to production of rapid-hardening, high-early-strength cement in the Al Khums I Cement Plant as the raw materials used can satisfy the specifications. The raw-mix design must be changed slightly to increase the lime-saturation factor, since in high-quality rapid-hardening cements (RHC), the lime-saturation factor should be higher than 95%. This means that more calcareous components must be added to the raw meal.

The equipment used for producing RHC is the same as that used for producing normal Portland cement, the only difference being in the fineness of the cement produced, i.e. more grinding is required for RHC. For example, ordinary Portland cement of approximately 2,800 $m^2/g$ (blaine) requires 35 kWh/t in grinding, whereas RHC of approximately 4,000 $m^2/g$ (blaine) requires about 65 kWh/t. This means that the equipment used in grinding cement in the Al Khums I Cement Plant will only be capable of producing RHC at somewhat over 50% of the rated capacity of the cement mills. Accordingly, cement production will drop drastically as the grinding operation will take longer using the same mills.

RHC clinker should be cooled rapidly on leaving the kiln to keep the tricalcium silicate ($C_3S$) crystals in the clinker very small in size as this will be reflected in the higher initial strength and easier grinding of the cement produced. In this plant, especially on the second production line where a satellite cooler is used, the clinker produced is of a high temperature (not less than 150-250°C).

In RHC production, the raw-meal blending, homogenization and kiln operation must be carefully conducted as the $C_3S$ phase is required in a higher percentage. Any failure in preparing the raw meal and operating the kiln will tend to transform the $C_3S$ to dicalcium silicate ($C_2S$) and free calcium oxide ($CaO$). In this plant, preblending of the raw materials is rudimentary, indeed no controlled preblending is carried out at all in the Al Khums I Cement Plant.

If the raw mix is designed according to the Polservice proposals, oscillations in carbonate content will be present as the raw meal enters the kiln and this will cause severe production problems.

Because of all these factors, the co-ordinator thinks it preferable not to change over to RHC production but to introduce the production of sulphate-resisting cement instead.

## B. Proposal for introducing the production of sulphate-resisting cement

The co-ordinator believes that the materials already available and in use at the Al Khums I Cement Plant are more suitable to the production of sulphate-resisting cement (SRC) than to that of rapid-hardening cement (RHC). The latter requires a higher alumina and iron-oxide content than is supplied by the marl from the plant's quarry and this deficiency would have to be made up by adding imported bauxite or Marqheb clay and an iron-rich ore.

A look at the chemistry of SCR will show how well-suited it is to the materials available at Al Khums I.

### The chemistry of sulphate-resisting cement

After adding water to cement (hydration), a reaction starts between the tricalcium aluminate ($C_3A$) and gypsum ($CaSO_4.2H_2O$) forming calcium sulphoaluminate. The calcium aluminate hydrate in hardened cement is able to react with any sulphate salts coming into contact with the concrete, also forming sulphoaluminate within the framework of the hydrated cement paste.

The volume of the solid phase increases 227 per cent and therefore disintegration of the concrete takes place. Another type of reaction can take place through an exchange of bases between calcium hydroxide and sulphates to form gypsum accompanied by an increase in the volume of the solid phase of 124 per cent.

These reactions are known as sulphate attack. Active salts like magnesium and sodium also have an attack action. The sulphate effect is greatest if accompanied by alternating wetting and drying, as for instance in the tidal zone.

Based on laboratory tests and applied research on normal Portland cement and its behaviour when treated with sulphates, salts etc., it was found that there is a definite relationship between the calculated $C_3A$ content and sulphate resistance.

After the raw-mix design of the kiln feed was modified by decreasing the potential $C_3A$ content and increasing the potential tetracalcium aluminoferrite ($C_4AF$) content it was found that the cement produced after this modification showed resistance to sulphate and salt-water attack. Therefore, the remedy lies in the use of cement with a low $C_3A$ content, and such cement is known as sulphate-resisting Portland cement. The British Standard for this cement, BS. 4027:1966, stipulates a $C_3A$ content of 3.5 per cent. The minimum fineness is 2,500 $cm^2/g$. In other respects, sulphate-resisting cement is expected to conform to BS. 12:1958 for ordinary Portland cement. In the United States, sulphate-resisting cement is known as Type V cement and is covered by A.S.T.M. Standard C150/72. This specification limits the $C_3A$ content to 5%, and also restricts the total content of $C_4AF$ plus twice the $C_3A$ content to 20%. The magnesia content is limited to 5%.

The role of $C_4AF$ is not quite clear. From the chemical standpoint, $C_4AF$ would be expected to form calcium sulphoaluminate, as well as calcium sulphoferrite, and thus cause expansion. It seems, however, that the action of calcium sulphate on hydrated cement is smaller the lower the $Al_2O_3$ to $Fe_2O_3$ ratio. Some solid solutions are formed and they are liable to comparatively little attack. The $C_4AF$ is even more resistant and it may form a protective film over any free calcium aluminate.

Since it is often not feasible to reduce the $Al_2O_3$ content of the raw material, $Fe_2O_3$ may be added to the mix so that the $C_4AF$ content increases at the expense of $C_3A$.

The low $C_3A$ and comparatively low $C_4AF$ contents of sulphate-resisting cement means that it has a high silicate content and this gives the cement a high strength. However, because $C_2S$ represents a high proportion of the silicates, the early strength is low. The heat of hydration developed by SRC is not much higher than that of low-heat cement. It seems therefore that sulphate-resisting cement is theoretically an ideal cement, but, because of the special requirements for the composition of the raw materials used in its manufacture, SRC cannot be cheaply made everywhere.

The raw materials available at the Al Khums I plant are particularly suitable as the raw mix is anyway deficient in $Al_2O_3$, and Galmoya iron ore can easily be supplied to the plant to increase the $Fe_2O_3$ percentage in the mix.

It is thought that the cost of producing SRC will not exceed that of normal Portland cement. Firstly, bauxite will not be used as a component. As this raw material is imported, it represents an expensive ingredient. Secondly, the percentage of iron oxide will be increased within the range of 1-2% and this can be supplied locally and cheaply. Thirdly, sand will be used as a third or a fourth component according to the chosen raw-mix design. Fortunately, the co-ordinator found a source of sand along the Tripoli-Al Khums road, about 70 kilometres from the cement plant. He asked the Al Khums authorities to analyse some sand samples from the area. A representative sample was analysed chemically on 1 March 1983. The chemical analysis of this sample was as follows:

| | Percentage |
|---|---|
| LOI | 0.87 |
| $SiO_2$ | 93.26 |
| $Fe_2O_3$ | 1.00 |
| $Al_2O_3$ | 2.48 |
| CaO | 1.14 |
| MgO | 0.44 |
| Carbonates | 0.75 |

As well as the suitability and availability of the raw-materials for SRC production, there would be no need to modify the machinery or equipment already working in the plant. Whereas, if RHC production is introduced, various modifications and additional equipment would be necessary, particularly to satisfy the fineness specifications.

In summary, the introduction of SRC production would have the following advantages.

1. It would be a great advantage to the Libyan Arab Jamahiriya to produce SRC in the western region of the country where SRC is still imported in large quantities at a relatively high price.

2. The cost of producing SRC at Al Khums I should not exceed that of producing normal Portland cement. The same machinery can be used without modification and the raw materials already in use would be suitable. Only the iron oxide in the raw mix will have to be increased.

3. It will not be necessary to use imported bauxite or the Margheb clays since it is not necessary to increase the $C_3S$ content to the high level required in RHC.

4. In SCR production, it would be possible to use large amounts of the calcareous marls in the limestone deposits since they have a low alumina content. Similarly, the marl covering the Margheb clay can be used as part of the raw-mix components, thus exposing the clay for exploitation if needed.

5. It would be easy to revert to producing normal Portland cement at any time if the market required it.

## REPORTS ISSUED UNDER THE PROJECT TF/LIB/75/002 OR TF/LIB/82/002

| | |
|---|---|
| UNIDO/IOD.37<br>24 May 1976 | Report on the first part (February to April 1976) of a year's mission by a building-materials adviser to the cement industry in Benghazi<br>Aly Afify |
| UNIDO/IOD.174<br>11 July 1977 | Report on the second part (November 1976 to August 1977) of a year's mission by a building-materials adviser to the cement industry in Benghazi<br>Aly Afify |
| UNIDO/IOD.264<br>1 August 1978 | Planning a system of mechanical maintenance<br>Alfred Madsen |
| UNIDO/IOD.345<br>16 March 1979 | Preventive maintenance planning in the mechanical maintenance service<br>Mehmet A. Basman |
| UNIDO/IOD.354<br>15 August 1979 | Assistance in instrument maintenance<br>Boguslaw J. Walczenko |
| UNIDO/IOD.361<br>12 December 1979 | Report of the project co-ordinator for the period up to October 1979<br>A.M. Afify |
| UNIDO/IOD.383<br>16 September 1980 | Assistance to the electrical engineering staff in organizing and carrying out electrical maintenance<br>Boguslaw J. Walczenko |
| UNIDO/IO.437<br>16 January 1981 | Report on a one-month mission (from 11 November 1980) to review and evaluate the progress of the project<br>A.M. Afify |
| UNIDO/IO.475<br>13 March 1981 | Instrument maintenance systems at the Benghazi complex: final summary<br>Boguslaw J. Walczenko |
| UNIDO/IO.472<br>6 July 1981 | Report of a one-month mission (from 19 May 1981) to review and evaluate the progress of the project<br>A.M. Afify |
| UNIDO/IO/R.7<br>30 July 1981 | Raw materials deposits at Wadi Ash Shati and Al Jufrah<br>Abd El R. Marei |
| UNIDO/IO/R.14<br>17 December 1981 | Preliminary study for long-term technical advice<br>A.M. Afify |

| | |
|---|---|
| UNIDO/IO/R.33<br>28 October 1981 | Progress of the project from 10 May 1980 to 31 July 1981<br>A.R. Marei |
| UNIDO/IO/R.17<br>2 November 1981 | Feasibility of producing sulphate-resisting cement<br>A.R. Marei |
| UNIDO/IO/R.29<br>26 March 1982 | Replacing cylpebs by grinding balls in Benghazi I and Hawari cement mills<br>A.R. Marei |
| UNIDO/IO/R.34<br>26 March 1982 | Progress of the project from 1 August 1981 to 31 December 1981<br>A.R. Marei |
| UNIDO/IO/R.42<br>26 March 1982 | Formation of cement lumps and aggregation in cement silos<br>A.R. Marei |
| UNIDO/IO/R.53<br>26 March 1982 | New gypsum deposits<br>A.R. Marei |
| UNIDO/IO/R.84<br>24 January 1983 | Progress of project from 1 January 1982 to 30 June 1982<br>A. R. Marei |
| UNIDO/IO/R.85<br>24 January 1983 | Feasibility study on plant for ready-mixed concrete and prefabricated concrete products<br>A.R. Marei |
| UNIDO/IO/R.99<br>27 October 1983 | Evaluation of the raw material situation of the Al Khums I Cement Plant<br>A.R. Marei |