The fabric of coal-mine refuse as backfilling material and its relation to grain-size distribution parameters

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Synopsis

This study aims at investigating the structural characteristics of backfilling material. In this regard, spatial arrangement of solid particles and associated voids in a unit mass of coal mine refuse as backfilling material were tested. The materials were produced from coal mine refuse of Zonguldak Colliery, Turkey. The experimental procedures were developed to determine their void ratio (or its equivalent porosity), bulk density and the shape properites of constituent particles. The orientation fabric and the co-ordination number were the other two fabric elements determined. The filling materials were sieved and their particle size distributions were found. The results obtained by experiments were related to the particle size distribution parameters, namely, the coefficient of uniformity and the effective size. It was concluded that mean value of void ratio is correlated with coefficient of uniformity. The standard deviation of porosity as an index of fabric heterogeneity is clearly correlated to effective size. By an original experiment, the frequency distribution of co-ordination number was observed as binomial in uniformly graded materials. Also, the co-ordination numbers of test mixtures were calculated by the Marsal method and results obtained showed a good correlation between the minimum particle size and number of contacts per unit area.

Introduction

The principal factors that affect the mechanical characteristics of non-cohesive materials are void ratio (void volume/solid volume) or porosity (void volume/total volume) and the number of interparticle contacts. Some researchers (Marsal 1963; Aberg 1992) have related these factors to the particle size distribution parameters. The investigations on the packing of granular materials in relation to the porosity or bulk density begin with the modelling of the packing of spherical particles (Duffy and Mindlin, 1959). Kapoly (1971) has carried out research on binary mixtures of granular soils in order to obtain mixtures with minimum voids. Aberg (1992), by using a simple stochastic model of void structure and void sizes, has established theoretical equations by means of which void ratio of a non-cohesive soil can be calculated from its grain-size distribution. A significant result was obtained by Oda (1972, 1980). He has defined the fabric of cohesionless soil as the spatial arrangement of solid particles and associated voids in its mass and he has introduced the two characteristics of fabric;

- orientation of individual particles (orientation fabric) and
- mutual relationships of individual particles to others (packing) (Figure 1).

In order to elucidate these two fabric characteristics, four fabric elements should be determined quantitatively.

- Orientation fabric, i.e. the preferred orientation of long axes of particles and the intensity of preferred dimensional orientation
- Packing
- Co-ordination number
- Three-dimensional distribution of normal directions perpendicular to tangential planes at the points of contacts.

Furthermore, Oda (1980) has reached some conclusions in his experimental work with sand samples. The number of contacts (N_c) per particle (co-ordination number) is inversely proportional to void ratio. He also found that the distribution of co-ordination number throughout the body is Gaussian and the long axes of particles are preferably oriented in the direction of gravity.

On the other hand, Ching (1990), has theoretically defined the distribution of co-ordination number as a spherical harmonic function in three-dimensional medium.

In fact, the investigations in literature are commonly related to sands and soils and there are only a few studies on the granular

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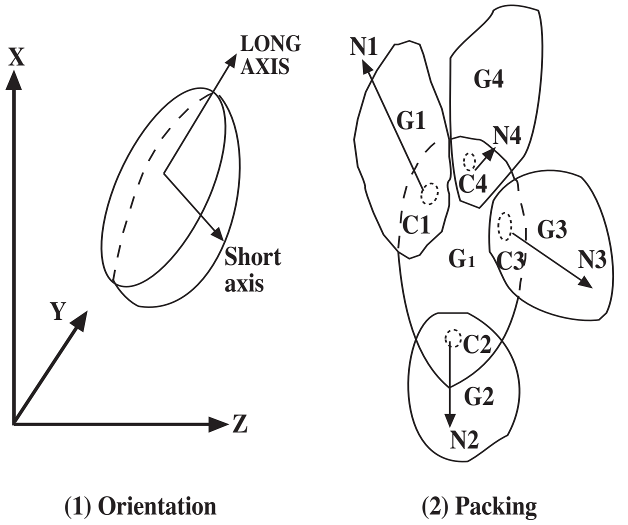

Figure 1—Orientation fabric and packing to show the spatial arrangement of solid particles and associated voids (Oda, 1977)

materials that can be used as backfilling materials in mines. This study has aimed at fulfilling the gap of knowledge about structural characteristics of backfilling materials of coal-mines. The objectives of this study are a systematic investigation of fabric properties of some model backfilling materials and to correlate the fabric material elements with particle size distribution parameters.

Material and method

The sampled material and preparation of sample mixtures

The materials to be tested were sampled from Zonguldak Colliery, Turkey. Different samples were collected from different areas. The block samples of limestone were sampled from Kozlu Mine, small blocks of sandstone were sampled from the waste disposal area of Kozlu Mine where rock excavated from underground operations is accumulated. Samples of washery rejects, mostly containing siltstone were collected from the disposal area near Armutçuk Mine, Zonguldak. These raw samples were transported to the laboratory, air-dried and crushed by using a jaw crusher to prepare samples for sieving. U.S. Standard sieves were used for separation of size fractions. The size fractions which were used in mixtures of crushed limestone are given below.

Fraction no.	Size range (mm)
I	19–9,5
II	9,5–4,75
III	4,75–2
IV	2–1,18
V	1,18–0,6
VI	-0,6

The first category of sample mixtures were prepared by mixing the fractions obtained from -19 mm crushed limestone. In the second category of samples, five compositions of binary mixtures of -19 mm sized sandstone and -1.18 mm sized siltstone were prepared with increasing ratios of -1.18 mm sized siltstone to -19 mm sized sandstone.

Specific gravity and shape properties of particles

Specific gravity tests were conducted by using ASTM Standard C 127-84 (for +4.75 mm) and ASTM Standard C 128-84 (for -4.75). An electronic balance with 0.001 gr precision was employed for weight measurements.

The shapes of particles were evaluated according to the criterion provided by Marsal (1963) on 25 particles selected randomly from each fraction. By means of a caliper, three dimensions: length, d_1, breadth d_2, thickness d_3, were measured at approximately right-angles. The arithmetical average of these three measurements, was the measured diameter (mean diameter) d_m. A set of values was obtained from 25 particles representing the fraction. The averages of these values were taken as average dimensions $\overline{d_1}$, $\overline{d_2}$, $\overline{d_3}$ and $\overline{d_m}$. The other measure of size is nominal diameter d_n which is defined as the average of maximum and minimum sizes of each fraction. Thus, two volume estimations namely, dimensional V_m and nominal, V_n are possible by taking measured diameter d_m or nominal diameter d_n respectively. The two particle volumes may then be estimated by,

$$V_m = \frac{\pi}{6}\left(d_m\right)^3 \text{ and } V_n = \frac{\pi}{6}\left(d_n\right)^3 . \qquad [1]$$

On the other hand, the true volume of a particle (V_{true}) is computed by dividing its measured weight W_{me} by its specific gravity G_S $(V_{true} = W_{me} / G_S)$. The parameter which is of special interest is shape factor r_v and thus, two shape factors, namely dimensional r_v and nominal r_v' are defined as,

$$r_v = \frac{V_{true}}{V_m} \quad r_v' = \frac{V_{true}}{V_n} . \qquad [2]$$

Although for the fine size fractions dimensional shape factors could not be measured, nominal shape factors were estimated. For this purpose, a randomly selected group of particles were weighed, the weight was then divided by the number of particles in the group and measured weight of a particle and consequently its measured volume were obtained. The nominal shape factor was calculated according to equation [2]. A picture showing groups of particles selected from fractions is seen in Figure 2.

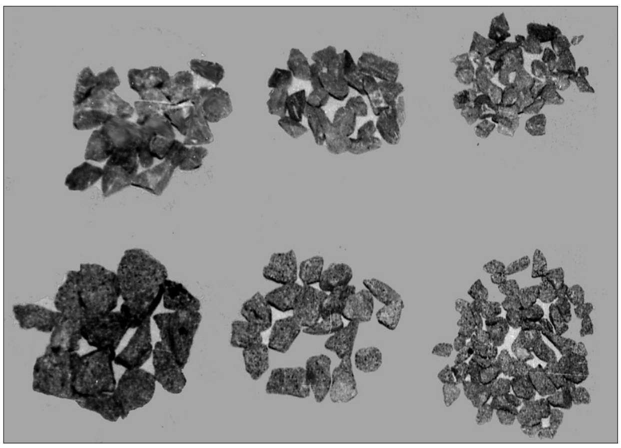

Figure 2—A view of particle groups
1st row : limestone particles
2nd row : sandstone particles

Unit volume weight, porosity and their variants

In this section, the methods applied to determine the unit weight and porosity and their variants when the sample is confined in a volume are described.

The unit volume weight which is defined as the mass (including all voids) of a unit volume of sample material, was determined on an oven-dry basis. The moisture content of the air-dried sample kept in the laboratory for a long time was found to be very low compared to the absorption capacity. Although each sample was not oven-dried, the amount of moisture separately determined in per cent by weight was subtracted from the total weight and the unit volume weight was given on an oven-dry basis.

A cylindrical measure for tests was designed following the criterion proposed by Senyur (1985). This criterion recommends that the diameter of the test chamber to be 8–10 times larger than the maximum particle size and in addition, the ratio of the height of material *(H)* in the test cylinder to the diameter of cylinder *(D)* to be lower than two i.e. $1 < H/D < 2$. The cylindrical measure seen in Figure 3 consists of three parts; a thin-walled steel cylinder, a base plate grooved to hold the cylinder firmly and a plate which is settled on the open face of material when it fills the cylinder to a certain level. The well-mixed sample material was put into the test container by hand shovel carefully to forestall differential settlement and so that the material was in its loosest state with maximum void volume.

The surface of the filled material was smoothed gently by finger pressure, and the loading plate was placed on the face of the material. The average depth of the plate's upper face from the top of the cylinder was measured by a vernier. The measurements were taken from three points on the top circumference of the cylinder selected so as to divide the circumference into three equal segments. If H_{av} denotes the average depth of the plate's upper face from the top cylinder, the height of material H in the cylinder is then,

$$H \cong H_c \pm \left(H_{av} \pm t_p\right) \qquad [3]$$

Figure 3—Cylindrical measure

where, H_c: Height of the cylinder (measurement is taken on the inner surface)
t_p: Thickness of the top plate

Having measured the height of material, its volume (V_f) was calculated and then its bulk unit weight (γ_f was then obtained by dividing the measured weight W_f by volume V_f i.e. ($\gamma_f = W_f / V_f$. The porosity n_a and then the void ratio, e, of each sample was calculated using the following relationships (Craig, 1986).

$$n_a = \frac{G_s \pm \gamma_f}{G_s} \quad e = \frac{n_a}{1 \pm n_a} . \qquad [4]$$

The specific gravity G_s in equation [4] is associated with sample mixture. ASTM C 127-84 was used to calculate the average specific gravity values G_s for sample mixtures of different materials.

Tests with each sample mixture was replicated 5 times and the average values and associated standard deviation related to γ_f, n_a and e were calculated.

Particle size distribution and parameters

The particle size analysis was performed by following ASTM C 136-84 standard. Three characteristic particle size gradation curves are shown in Figure 4 (Senyur, 1985). In soil mechanics, two coefficients, namely coefficient of uniformity C_u, and the coefficient of curvature C_c are given as indicators of particle size gradation,

$$C_u = \frac{d_{60}}{d_{10}} \text{ and } C_c = \frac{\left(d_{30}\right)^2}{\left(d_{60}\right)\left(d_{10}\right)} . \qquad [5]$$

Where, d_{60} is the particle size greater than 60 per cent (i.e. 60 per cent passing size), d_{30} is the size greater than 30 per cent and d_{10} is the size greater than 10 per cent of the material. That is, d_{10} is called the effective size.

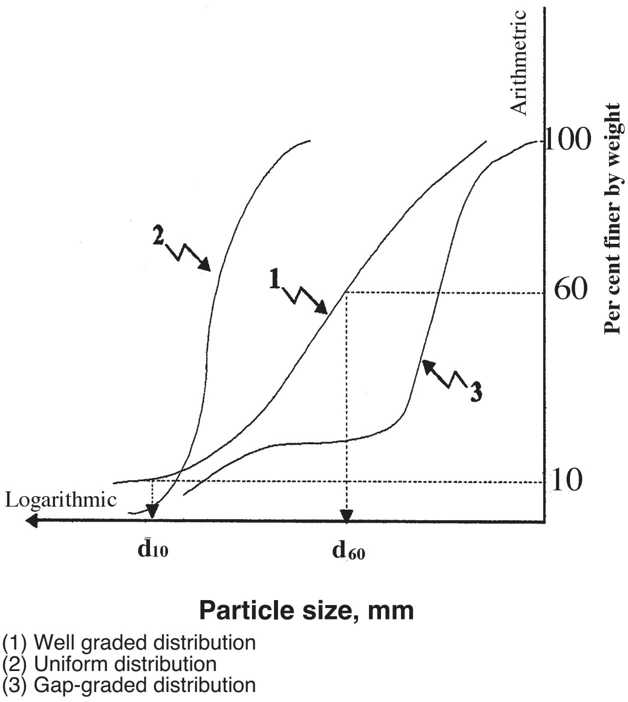

Figure 4—Characteristic particle size gradation curves (Craig, 1976)

Co-ordination number and fabric

The geometrical approach developed by Marsal (1963) provides estimations for co-ordination number based on the size gradation. Co-ordination numbers in model filling mixtures prepared in this study were estimated according to this method after obtaining their particle size distributions. Besides the theoretical approach of calculation given by Marsal, an experimental method was also developed to find the co-ordination number.

Marsal's method for determination of co-ordination number

On the basis of Marsal's approach, the number of particles (n_{vk}) contained in each fraction k per unit of total volume can be determined, assuming that the particles are spherical with a diameter d_{nk}. In order to take the real shapes of the particles into account, the individual volume is corrected by application of a factor (r_V), determined experimentally as explained previously (equation [2]).

The number of particles per unit of total volume in a material with a void ratio e, is then,

$$n_v = \frac{6}{\pi} \sum_{n=1}^{L} \frac{P_k}{1+e} \cdot \frac{1}{r_{v_k} \left(d_{n_k}\right)^3} . \qquad [6]$$

Where L is the number of component fractions and P_k is the percentage that passes the sieve of nominal diameter d_{nk} and is retained in the next smaller one,

$d_{n,\,k+1}$.

Assuming the material to be homogeneous, in the sense that all its parts have the same granulometric composition, the number of particles (n_S) per unit area of an arbitrary cutting surface is then,

$$n_S = n_V^{2/3}. \qquad [7]$$

The number of contacts per particle i.e. co-ordination number n_c in particles of fraction k is estimated by,

$$n_{c_k} = \pi \cdot \left(d_{n_k}\right)^2 \cdot n_s . \qquad [8]$$

This expression is valid for n_{ck}>6 contacts/particle (Marsal, 1963). Since each point of contact is shared by two particles, the number of contacts per unit of total volume is estimated by,

$$\sum n_{c_v} = \sum_{n=1}^{L} \frac{n_{V_k} \cdot n_{c_k}}{2} . \qquad [9]$$

The number of contacts per unit area is appraised by,

$$n_s = \left(\sum n_{c_v}\right)^{2/3} . \qquad [10]$$

Finally, the co-ordination number N_c in total volume is obtained by,

$$N_C = \frac{2\left(\sum n_{c_v}\right)}{n_v} . \qquad [11]$$

As an illustration to the methodology, the calculations carried out with the sample mixture number 11 (Table AIII; Appendix 1) is presented in Table I.

Table I

Number of contacts per particle, per unit area and per unit volume (-19 mm crushed limestone mixture, sample no. 11, void ratio, e = 0,492)

Fraction	Per cent weight (W)	Nominal diameter (d_{ni})	Shape factor (r_v)	Particle volume $(\pi/6)(d_{ni})^3$ =	Surface of particle $A_{mi} = \pi(d_{ni})^2$	Number of particle in each fraction (n_{vi})	Number of contacts per particle n_d=A_{mi}xn_s	Contacts per unit of total volume $N_i = (n_d * n_s)/2$
	%	cm		cm³	cm²	particle/cm³	contacts/ particle	contacts/cm³
(19 mm)-(9.5 mm)	38.6	1.425	0.72	1.595	6.38	0.24	21564	2587
(9.5 mm)-(4.75 mm)	33.3	0.7125	0.61	0.19	1.595	1.93	5391	5202
(4.75 mm)-(2 mm)	7.6	0.34	0.63	0.02	0.36	3.92	1216	2383
(2 mm)-(1.18 mm)	1.3	0.16	0.80	2.1×10^{-3}	0.08	5	270	675
(1.18 mm)-(0.6 mm)	6.4	0.09	0.80	3.8×10^{-3}	0.025	140	85	5950
(0.6 mm)-(0.3 mm)	3.8	0.045	0.80	4.8×10^{-5}	6.4×10^{-3}	667	22	7337
(0.3 mm)-(0.15 mm)	4.0	0.022	0.80	5.6×10^{-6}	1.5×10^{-3}	6011	6*	18033
(-0.15 mm)	5.0	7.5×10^{-3}	0.80	2.21×10^{-7}	1.8×10^{-4}	189640	6*	568920

$$n_{v_i} = \frac{\%W \times 6}{\pi \times r_V \times (1+e)\left(d_{n_i}\right)^3} \qquad n_1 = \frac{0.386 \times 6}{\pi \times 0.72 \times 1.492 \times (1.425)^3} = 0.24$$

$n_2 = 1.93$ $n_6 = 667$

$n_3 = 3.92$ $n_7 = 6011$

$n_4 = 5$ $n_8 = 189640$

$n_5 = 140$

$$n_v = \sum N_{v_i} = 196470$$

$$\sum N_{c_i} = 611087$$

Volumetric grain concentration, n_V = 196470

Surface grain concentration, n_s = 3380

n. of contact per unit area, N_s $= \left(\sum N_{c_i}\right)^{2/3}$ = 7201

Co-ordination number, N_c $= \frac{2\sum N_{c_i}}{n_v} = 6.2$

Experimental procedure

The scope of tests includes the determination of co-ordination number, its distribution in total volume and orientation fabric of particles. Since, the fine particles are problematic in the sense of detecting the contacts, the sample mixture numbered 7 (Table AIII, Appendix 1) which is uniformly graded and composed of coarse particles was tested.

In order to measure the co-ordination number by counting the traced marks on each particle, an experiment with the following procedure was performed.

The well-mixed test sample (Sample no. 7) was put gently, using a hand shovel, into a mould of 184 mm in diameter and 343 mm in height with drainage holes at its bottom. Black oil paint was permeated into voids among particles for a few minutes and then was carefully drained without disturbance of particle arrangement. A small ring of liquid was still retained due to the effect of surface tension at each contact. In order to coagulate the liquid at each contact, the particle assembly in the mould was air-dried for 24 hours and then oven-dried at low temperature for 10 hours. Traced marks of the following two types were found:

- ➤ irregular ring enclosing a small surface with a clear centre conserving the original background
- ➤ a spot in the original colour of the particle.

About 150 particles were randomly selected from the central part of the mould in order to avoid the effect of fabric disturbance due to the wall-effect. The co-ordination number was counted for each of 150 particles and their frequency histograms were prepared.

Test results

The test results related to specific gravity and shape properties of particles are displayed in Table AI (Appendix 1).

The variation of shape factor r_v with the ratio of thickness/mean diameter (d_3/d_m) was investigated with 25 randomly selected particles of Fraction (no. 1) which were chiefly prismatic with sharp edges. The distribution of data is seen in Figure 5 where it is observed that the distribution does not correlate well with Marsal's curve (Marsal, 1963).

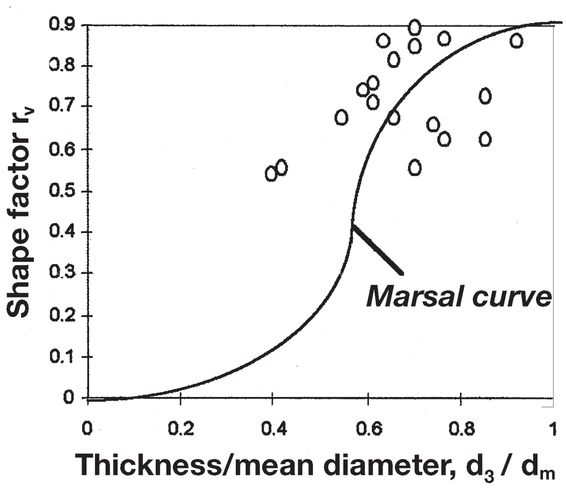

Figure 5—r_v versus d_3 / d_m (-19 mm crushed limestone, fraction no 1

The results of mechanical grading by means of a series of standard sieves are presented graphically, showing the percentage by weight of the material which passes each mesh (k) in terms of nominal diameter(d_{nk}); a logarithmic scale is used for the latter. The results of particle size analysis by sieving carried out with sample mixtures are presented in Figure A1 (Appendix 1). The values related to coefficient of uniformity C_u, (60 per cent passing size d_{60} / effective size d_{10}) for each of the sample mixtures are presented in Tables AII and AIII (Appendix 1).

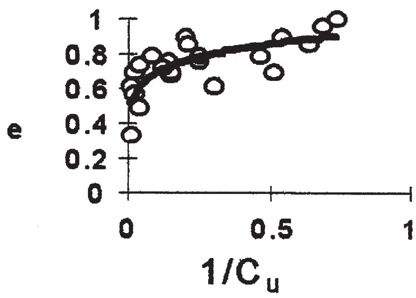

Figure 6—Void ratio, *e* versus coefficient of unifomity, C_u

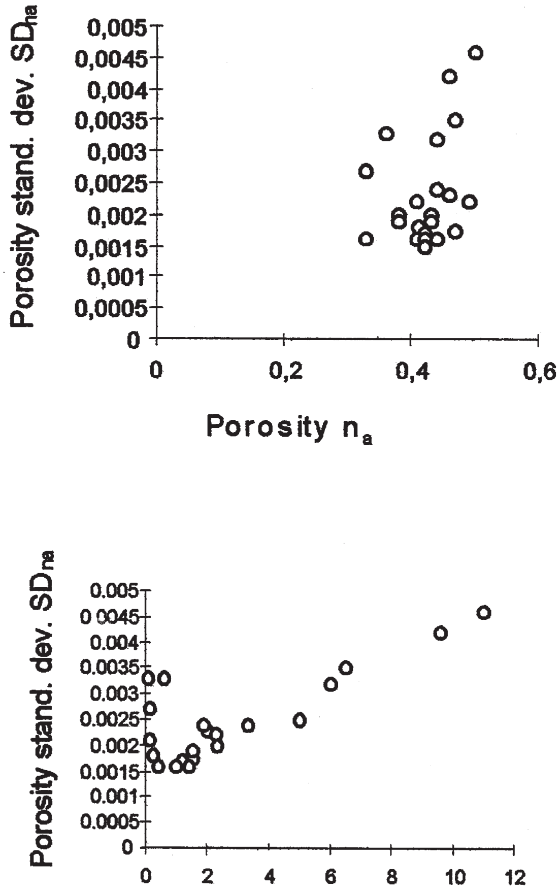

Figure 7—The relationship between standard deviation (SD_{na}) of porosity measurement and porosity n_a and relationship between SD_{na} and effective size d_{10} (mm)

The results of the tests carried out for determination of unit volume weight γ_f and associated porosity n_a and void ratio e, are presented in terms of mean and standard deviation in Tables AII and AIII (Appendix 1), where the compositions of sample mixtures with two important fabric parameters namely, the co-ordination number N_c and number of contacts per unit area N_s are also presented respectively.

An attempt was made to relate the values of void ratio e, to gradation parameters and a meaningful relationship is observed with the coefficient of uniformity C_u as is seen in Figure 6. Additionally, standard deviations (SD_{na}) of porosity measurements are related to effective size d_{10} and porosity n_a as is seen in Figure 7. The number of contacts per unit area N_s is a significant parameter influencing the mechanical behaviour of materials. The obtained values of N_s are attempted to be correlated with particle size distribution parameters. Coefficient of uniformity, C_u and especially minimum particle size d_{min}, correlate with N_s, (Figures 8, 9).

The frequency distribution of co-ordination number obtained by the experiment with the sample no. 7 (Table AIII, Appendix 1) is indicated in Figure 10.

During this experiment which was carried out for determination of co-ordination number, the orientations of particles were visually observed. The tendency was the long axes of the particles were oriented in the direction of gravity.

Evaluation of results

The frequency distribution of co-ordination number N_c throughout the granular mass of sample material tested

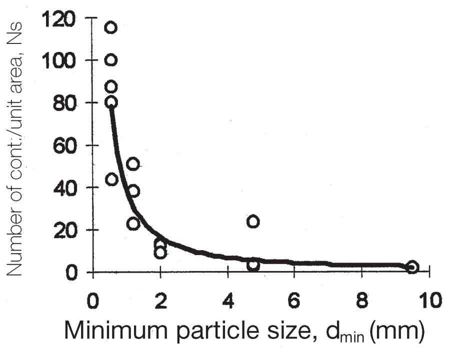

Figure 8—The relationship between number of contacts per unit area N_s and minimum particle size d_{min} (>0.6 mm)

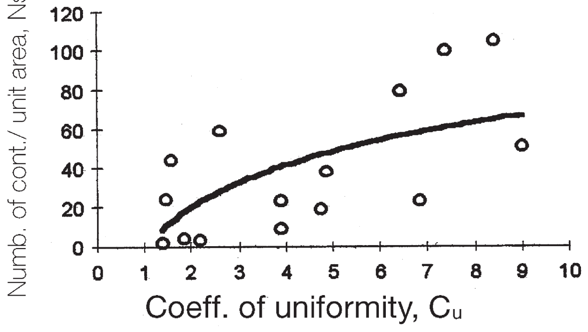

Figure 9—The relationship between number of contacts per unit area N_s and co-efficient of uniformity C_u (d_{min} >0.6 mm

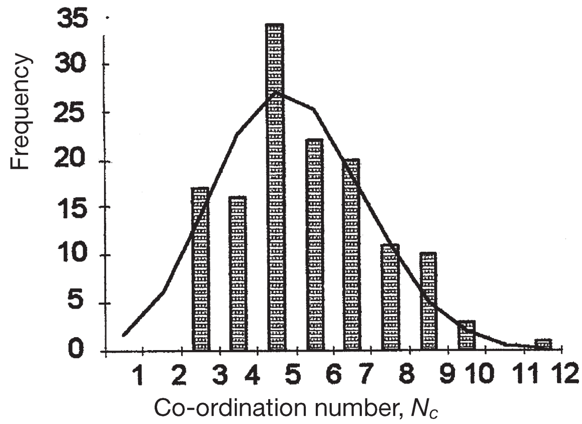

Figure 10—Distribution of co-ordination number, N_c

(no. 7, Table AIII) is best fitted to a binomial distribution (level of significance $\propto = 0.05$; calculated $\chi^2 = 10.71 < \chi^2$ table) (Figure 10). This implies that, for the uniformly graded coarse-grained materials, the distribution of co-ordination number is binominal which reveals a significant difference from the normal distribution model obtained by Oda (1977) related to experimental study on sands. However, in the tested sample (Sample no. 7) the mean value of coordination number is found to be six which approximates to that reported with sands. This similarity may be attributed to uniform gradation of both materials. Differentially high co-ordination number is expected for well-graded material, but the results obtained by Marsal's calculation method in this study are not in good agreement with this expectation.

The void ratio, e, is correlated with coefficient of uniformity, C_u, (Figure 6) by the following relationship,

$$e = 0.925\ (1/C_u)^{0.123} \qquad r^2 = 0.58. \qquad [12]$$

Even though the value of the regression coefficient is not high, the above relationship implies that the void ratio, e, is inversely proportional to the coefficient of uniformity. This means that, with well-graded material, as C_u increases, void ratio decreases which is the expected behaviour.

The standard deviation of porosity SD_{na} is a measure of heterogeneity in spatial arrangement of particles when the placement of the sample in a container is replicated. No correlation between the standard deviation of porosity measurements (SD_{na}) and mean values of porosity measurements (n_a) was found, implying that the materials with high porosity should not necessarily display high SD_{na} in replicated placements. On the other hand, standard deviation of porosity SD_{na} surprisingly displays a good correlation with effective size d_{10} ($r^2 = 0.981$) (Figure 7). This hyperbolic relationship in conical form is given as,

$$211{*}10^{-7} \cdot d_{10}^2 - 0.503 \cdot SD_{na}^2 + 4.23{*}10^{-7} \cdot d_{10} - 11.3{*}10^{-4} \cdot SD_{na} - 11.26 \cdot SD_{na}^2 \cdot d_{10} + 22.6{*}10^{-7} = 0. \qquad [13]$$

The significant property N_S, the number of contacts per unit area, is well correlated with the parameters of the coefficient of uniformity (C_u) and minimum particle size d_{min} ($r^2 = 0.923$) (equation [14]).

$$N_S = 26.3\ d_{min}^{-1.4} \ln (C_u). \qquad [14]$$

Conclusions

The results of this study imply that, for uniformly graded materials, the frequency distribution of co-ordination number N_C best fits to binomial distribution and the mean value of co-ordination number obtained experimentally is smaller than the calculated value from the size gradation and has a value equal to the generally accepted value for granular materials ($N_c = 6$).

The conclusion drawn about the orientation fabric is that if a material is placed in a volume by gravity, the preferred orientation of long axes of particles is in the direction of gravity. This conclusion is in good agreement with the prediction of other researchers.

The results of unit-volume-weight tests verifies that void ratio, *e*, is related to coefficient of uniformity (equation [12]) and the standard deviation of porosity is related to effective size (equation [13]).

The number of contacts per unit area that are significant for the mechanical behaviour of this type of granular materials were calculated for all the test materials by the Marsal method. An important result obtained, given by equation [14], is that the number of contacts per unit area in total volume is related to minimum particle size and coefficient of uniformity.

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Appendix 1—Experimental results

Table AI

Some properties of particles

Material	Nominal diameter d_n cm	Mean length $\bar{d}_1$ cm	Mean breadth $\bar{d}_2$ cm	Mean thickness $\bar{d}_3$ cm	Mean diameter $\bar{d}_m$ cm	Specific gravity	Shape factor r_v	Nominal shape factor r_v
(-19 mm) Crushed Limestone	1.42	1.92 SD=0.32	1.42 SD=0.25	1.00 SD=0.25	1.45 SD=0.46	2.668	0.72 SD=0.11	0.80 SD=0.32
	0.71	1.10 SD=0.32	0.65 SD=0.17	0.47 SD=0.15	0.74 SD=0.36	2.663	0.61 SD=0.20	0.63 SD=0.29
	0.34	0.52 SD=0.13	0.33 SD=0.10	0.30 SD=0.05	0.35 SD=0.15	2.664	0.63 SD=0.24	0.66 SD=0.28
	0.158	-	-	-	-	2.665	-	0.80
	0.084	-	-	-	-	2.665	-	0.80
	0.025	-	-	-	-	2.665	-	0.80
(-19 mm) Crushed sandstone	1.42	2.05 SD=0.51	1.40 SD=0.31	0.95 SD=0.15	1.43 SD=0.60	2.54	0.70 SD=0.30	0.71 SD=0.35
	0.71	1.12 SD=0.48	0.58 SD=0.30	0.48 SD=0.11	0.72 SD=0.31	2.55	0.75 SD=0.24	0.78 SD=0.31
	0.34	0.54 SD=0.21	0.36 SD=0.15	0.28 SD=0.08	0.35 SD=0.17	2.55	0.64 SD=0.24	0.69 SD=0.28
	-	-	-	-	-	2.55	-	0.80
	-	-	-	-	-	2.55	-	0.80
	-	-	-	-	-	2.55	-	0.80
(-1.18 mm) Siltstone	0.06	-	-	-	-	2.59	-	0.80

Table AII

Properties of test samples ((-19 mm) crushed sandstone –(-1.18) mm siltstone mixtures)

Sample no.	Sandstone (-19 mm) %	Siltstone (-1.18 mm) %	d_{60} mm	d_{10} mm	C_u	Unit volume weight (γ_f) (SD) gr/cm3	Porosity (n_a) (SD)	Void ratio *e*	Average number of contact/ particles (N_c)	Number of contact/ area (N_s) conts./cm2
1	100	-	12.2	0.940	13	1.42 $4x10^{-3}$	0.442 $1.6x10^{-3}$	0.792	6.2	5422
2	85	15	11,0	0.210	52	1.50 $5x10^{-3}$	0.412 $1.8x10^{-3}$	0.700	6.2	10365
3	70	30	9.5	0.310	74	1.59 $5x10^{-3}$	0.379 $2x10^{-3}$	0.610	6.2	13836
4	60	40	7.1	0.090	79	1.72 $7x10^{-3}$	0.328 $2.7x10^{-3}$	0.490	6.4	17336
5	50	50	3.6	0.075	48	1.64 $8.8x10^{-3}$	0.362 $3.3x10^{-3}$	0.567	6.5	18268

Table AIII

Properties of test samples (-19 mm crushed limestone mixtures)

Sample no.	Fraction I	II	III	IV	V	VI	d_{60}	d_{10}	C_u	Unit volume weight (γ_f) $\overline{SD}$	Porosity (n_a) $\overline{SD}$	Void ratio *e*	Ave. num. of contact/ particles (N_c)	Number of contact/area (N_s)
%	%	%	%	%	%	%	mm	mm		*gr/cm3*				contacts/*cm2*
1	30	30	20	20	-	-	7.30	1.50	4.86	1.41 $4.8x10^{-3}$	0.47 $1.75x10^{-3}$	0.887	6.8	38
2	30	30	20	10	10	-	7.60	1.18	6.40	1.54 $1x10^{-3}$	0.42 $1.7x10^{-3}$	0.734	6.8	87
3	35	30	30	5	-	-	9.00	2.30	3.90	1.51 $5.4x10^{-3}$	0.43 $2x10^{-3}$	0.754	6.9	23
4	40	30	30	-	-	-	9.50	2.00	4.75	1.44 $7x10^{-3}$	0.46 $2.3x10^{-3}$	0.852	6.0	14
5	40	30	15	-	15	-	9.50	1.40	6.80	1.57 $4x10^{-3}$	0.41 $1.6x10^{-3}$	0.695	6.7	100
6	51.5	40	-	-	8.5	-	9.70	5.00	1.94	1.57 $6.7x10^{-3}$	0.412 $2.5x10^{-3}$	0.695	6.8	80
7	70	30	-	-	-	-	13.00	6.00	2.17	1.49 $8.8x10^{-3}$	0.44 $3.2x10^{-3}$	0.786	7.0	3
8	70	-	30	-	-	-	13.00	2.00	6.84	1.53 $5.4x10^{-3}$	0.43 $1.9x10^{-3}$	0.754	6.8	13
9	70	15	15	-	-	-	13.00	3.30	3.90	1.50 $6x10^{-3}$	0.44 $2.4x10^{-3}$	0.786	6.9	9
10	20	65	-	-	15	-	8.00	0.95	8.40	1.56 $4x10^{-3}$	0.42 $1.6x10^{-3}$	0.724	6.7	115
11	45	35	-	-	7.5	12.5	10.00	0.40	25.00	1.79 $4x10^{-3}$	0.33 $1.6x10^{-3}$	0.492	6.2	7201
12	100	-	-	-	-	-	15.00	11.00	1.36	1.34 $12x10^{-3}$	0.50 $4.6X10^{-3}$	1.000	9.0	2
13	-	100	-	-	-	-	3.30	2.25	1.46	1.35 $6x10^{-3}$	0.49 $2.2x10^{-3}$	0.960	6.0	24
14	70	-	-	30	-	-	13.50	1.50	9.00	1.66 $5x10^{-3}$	0.38 $1.9x10^{-3}$	0.610	6.5	51
15	50	50	-	-	-	-	12.00	6.50	1.85	1.41 $10x10^{-3}$	0.47 $3.5x10^{-3}$	0.887	6.3	4
16	95	-	-	-	5	-	15.00	9.60	1.56	1.44 $11x10^{-3}$	0.46 $4.2x10^{-3}$	0.852	6.6	44
17	90	-	-	-	-	10	15.00	0.60	25.00	1.54 $4x10^{-3}$	0.42 $1.5x10^{-3}$	0.733	6.1	5531

$\overline{SD}$ = Standard deviation

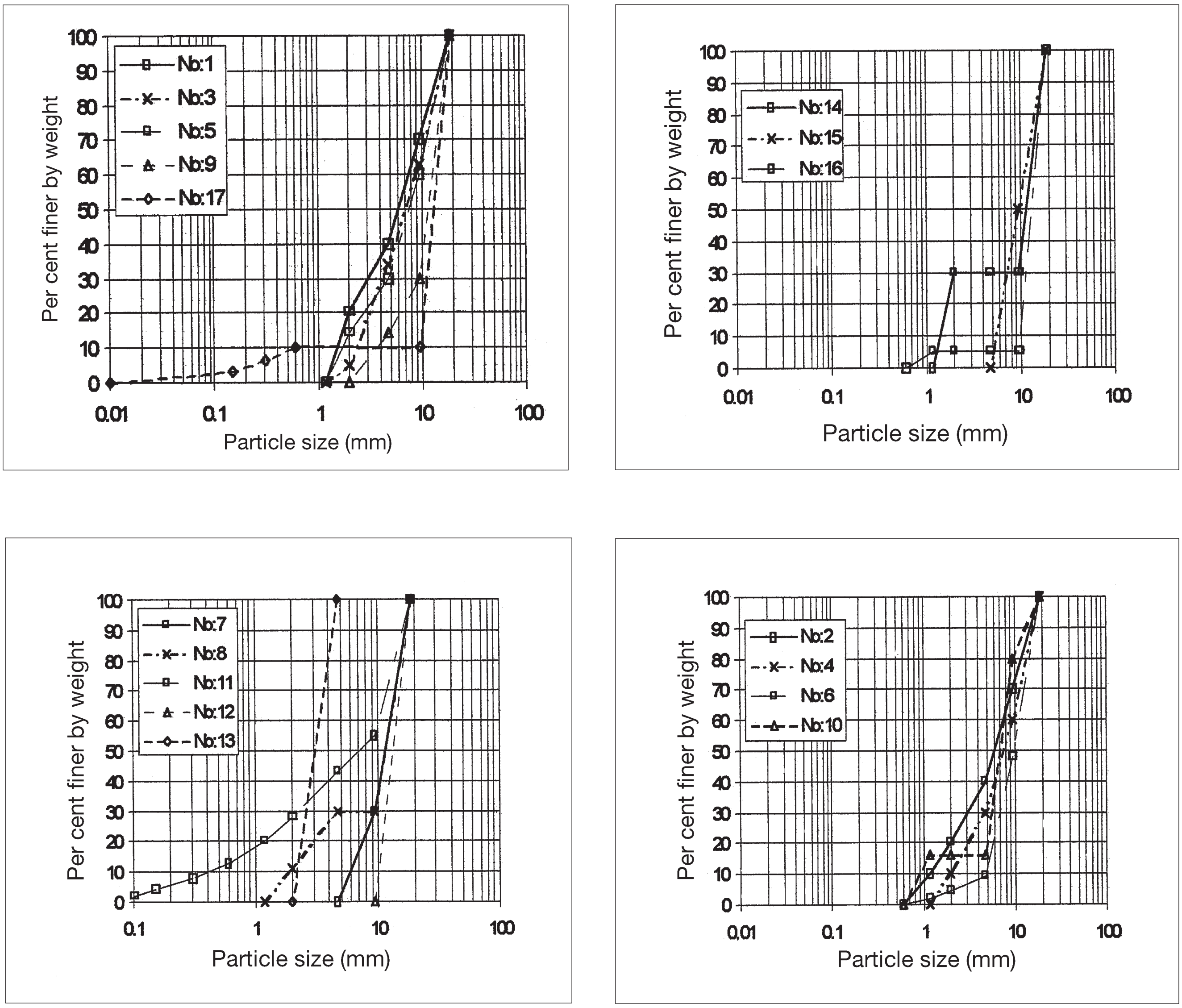

Figure A1a—The particle size distributions of test samples (mixtures of -19 mm crushed limestone fractions)

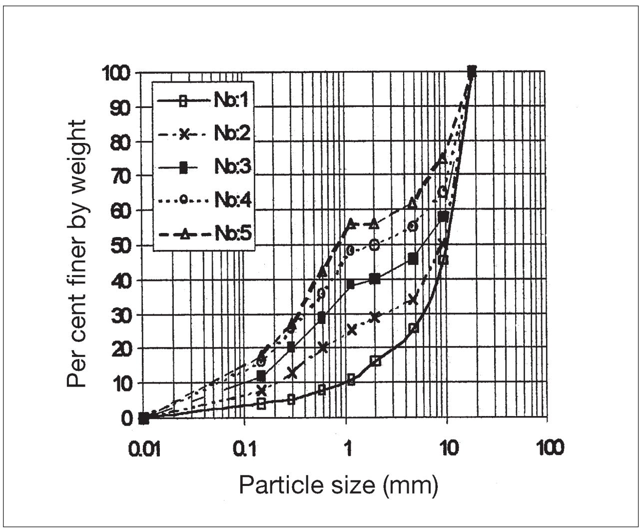

Figure A1b—The particle size distributions of test samples (mixtures of -19mm crushed sandstone and -1.18 mm crushed siltstone)

Mintek leader bullish about minerals future*

In his foreword in Mintek's 1997 Annual Review, Mintek President Dr Aidan Edwards comments that since 1989 State support for the parastatal had fallen steadily (from R116 million in that year to R77 million in the year ending March 1996—a reduction of 33% in real terms). In 1996/97 Mintek's 'own' income reached an all-time high (of 35% of the total income) and 10 per cent per annum increase is forecast for the next three years.

'It is significant to note', says Edwards, *'that Mintek, as a world leader in the metallurgical field, is increasing its international work to the extent that income from beyond South Africa's borders will dominate in the years ahead.*

'On the home front, Mintek's support for the small and developing mining sector continued to gather momentum. A network of relationships has been established with the aim of expanding the number of job-creating small mines in the country, and Mintek is increasingly providing small operators with advice on technical matters, the evaluation and development of viable deposits, and benefication opportunities.'

Dr Edwards said that undoubtedly the most exciting achievement during the year under review had been the successful transfer of Mintek's solvent-extraction (Minataur) process to Randgold's Harmony Gold Mine in the Free State. Indications are that material savings have been effected, both at the operational level and in financial turn-around time, possibly as much as R10 million per annum.

He predicts that the utilization of this technology at the Harmony Pure Gold project, which had marked a number of milestones in the South African gold-processing industry, will become commonplace as an essential component in gold metallurgy. ◆

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Mintek quiz to promote science and technology*

Minquiz, an important element in Mintek's efforts to promote careers in science and technology at high-school level, will be held on 4 March (at regional level) and 7 and 8 April (the national final) this year.

The preliminary rounds of the contest will be held at educational institutions in all nine provinces, and the national final will take place at Mintek's auditorium in Randburg where 30 semi-finalist teams, each consisting of three students, will compete for science council bursaries for studies in minerals-related topics at South African universities.

This, the 11th Minquiz to be held at Mintek, coincides with the national launch by the Department of Arts, Culture, Science and Technology of 1998 as the first Year of Science and Technology.

For more information, please contact Dr Glyn Moore at Mintek on (011) 709-4271 ◆

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