USE OF ROCKDUST FOR ENHANCING DURABILITY OF CONCRETE

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ABSTRACT

Rockdust is an inevitable by-product of rock crushing for producing aggregates. In Mauritius, crushed basalt is a major source of aggregate for construction. The rockdust content of crushed basalt sand is typically in the range 18-25%. This excess fine material in the sand is considered to be harmful to the performance of concrete, and is therefore reduced to acceptable limits by washing. The objective of this study was to investigate how far the presence of rockdust in crushed sand is harmful or beneficial to concrete performance in the fresh and hardened conditions. Two test series were carried out. In the first, rockdust content in the crushed sand varied from 0 to 20% while the cement, water, coarse aggregate and fine aggregate contents were kept constant. In the second series, the water content was also allowed to vary in order to maintain the workability constant.

Slump of fresh concrete decreased significantly (from 90 to 25mm) with increase in rockdust content and water demand increased correspondingly when slump was maintained constant. Bleeding decreased from 9% to 3% of free water as rockdust increased from 0 to 20%, thus improving cohesion in the fresh concrete. In hardened concrete, the presence of rockdust did not significantly impair the compressive strength of specimens stored in air and in water up to a period of 1 year. There were no negative effects on the modulus of elasticity too. The drying shrinkage was increased by about 40% as rockdust content increased from 0 to 20%, even when the water content was kept constant. The most positive influence of rockdust was on the permeability of concrete. Initial Surface Absorption tests and water permeability tests both indicated significant improvements in durability with increasing rockdust contents.

KEYWORDS

Crushed aggregate; rockdust; concrete; workability; bleeding; compressive strength; modulus of elasticity; drying shrinkage; durability.

INTRODUCTION

Mauritius is a small island of volcanic origin and the only natural source of aggregate for use in construction is basalt rock, which occurs in the form of surface boulders, sub-surface boulders, bedrock and small hills. Thus, basalt, either quarried or in the form of boulders, is crushed to produce aggregates. The crushing process generates a significant quantity of rockdust which, if left in the crushed aggregates and crushed sand, is considered to be a harmful contaminant for making concrete. In practice, these fines in the crushed aggregates and especially in the rocksand are reduced by washing before using the aggregates for structural concrete.

The objective of this paper is to investigate how far the presence of rockdust in crushed sand is harmful or beneficial to the performance of concrete, both in the fresh and hardened conditions. Should all the fines be removed or can some be left behind, and if so, how much? The fresh concrete properties measured were workability and bleeding. The hardened concrete performance was assessed in terms of compressive strength, drying shrinkage, modulus of elasticity and durability, the latter by means of the Initial Surface Absorption test and the CLAM water permeability test.

THE ROCK CRUSHING PROCESS

Boulders from surface sources, or rock obtained by explosive blasting in quarries, are transported by lorry to stone crushing plants. The process typically involves three, sometimes four stages of crushing. A schematic layout of the stone crushing process is shown in Fig. 1. Primary jaw crushers reduce the rockfeed down to sizes of about 200 mm. This method of crushing tends to produce particle shapes and textures which are flaky, angular and rough.

Secondary crushers are fed with primary crusher material which reduce them to sizes in the range 0 - 50 mm. These crushers can also be of the jaw-type, but in most cases, are of rotary-type, such as impacters, which produce more abrasive crushing. The main advantage of the latter technique of crushing is a significant improvement in particle shapes, whereby these are more cubical and better suited for making fresh concrete workable and pumpable with lower water demands.

The tertiary crushers are invariably rotary-type crushers which reduce the output of the secondary crushers to sizes in the range 0 - 20 mm. The processes mentioned so far are typically dry crushing processes with only light water spraying to keep the dust down. The 0 - 20 mm crusher material is then fed onto a deck of vibrating sieves with simultaneous and relatively abundant water spraying so as to wash and to separate the particles into coarse fractions (20, 14 and 10mm nominal sizes) and fine aggregate (less than 5 mm).
The material passing 5mm (sometimes 4mm) is fed to decantation tanks and centrifugal suction extractors to remove excess fine material (dust, silt and clay) leaving washed rocksand. The fine particles are carried in the flow as a slurry and are allowed to settle in sedimentation tanks for disposal, while the water is recycled into the system.

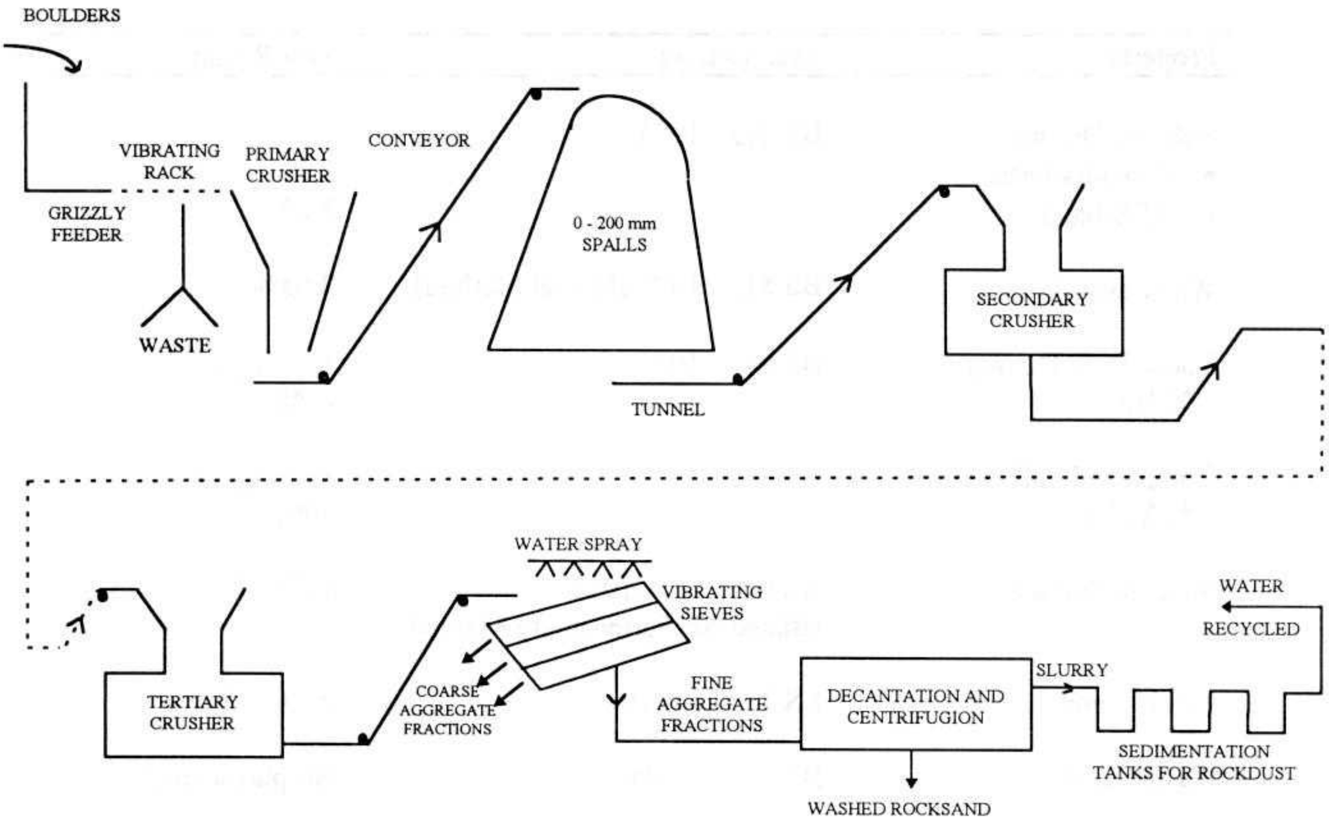

Fig. 1. Schematic diagram of the stone crushing process

PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCKDUST

Some physical properties of rockdust are shown in Table 1 and the particle size distribution is indicated in Table 2. Rockdust is mainly a coarse to medium silt, with a relatively low clay content varying between 1 and 5%. This is corroborated by the fact that it shows little or no plasticity and the liquid limit varies between 27 and 30%. The chemical composition of rockdust is very similar to that of rocksand (see Table 3), and not surprisingly so, because both products originate from the same parent rock material, that is, basalt.

Table 1 : Some physical properties of rockdust

Property	Test Method	Test Result
Relative Density	BS 812 : 1975	
• Ovendry basis		2.79
• SSD basis		2.86
Water absorbtion	BS 812 : 1975 (Funnel Method)	2.65%
Loose Bulk Density	BS 812 : 1975	1530 kg/m^3
% Voids		45%
Compacted bulk density	BS 812 : 1975	1660 kg/m^3
% Voids		40%
Specific Surface	ASTM C-204-1975 (Blaine Air Permeability Method)	1655 m^2/kg
Liquid Limit	BS 1377 : 1990	27.3 - 30.6%
Plastic Limit	BS 1377 : 1990	No plastic limit
Linear Shrinkage	BS 1377 : 1990	0.9%

Table 2. Particle Size Distribution of Rockdust (M.I.T Classification)

Clay	Silt			Sand		
	F	M	C	F	M	C
0-2 microns	2-6	6-20	20-60	60-200	200-600	600-2000
1-5 %	2-5 %	17-20 %	60-64 %	11-12 %	2%	Nil

Table 3. Chemical Composition

Material	Rockdust	Rocksand
Constituents	% by weight	% by weight
SiO_2	80.96	81.79
$Al_2O_3+Fe_2O_3$	15.72	15.31
CaO	0.10	0.08
Cl_2	0.44	0.28
SO_4	0	0
MgO	2.19	2.43
P_2O_5	0.09	0.10
L.O.I	0.59	0.67
pH	8.3	7.9

EXPERIMENTAL DETAILS

Materials

The coarse aggregate consisted of equal proportions of 10mm, 14mm and 20mm nominal single sizes of crushed basalt. The fine aggregate was washed rocksand graded in the range 0 - 5mm. The particle size distributions of the individual aggregates are shown in Table 4. The cement used was ordinary Portland Cement.

Table 4 Grading of concrete constituents

SIEVE SIZE mm	PARTICLE SIZE DISTRIBUTION, % passing			
	Coarse aggregate			Fine aggregate
	20 mm	14 mm	10 mm	Crushed Sand
20	98.2			
14	2.6	97.4		
12.5	1.4	42.1	100	
10.0	0.2	2.4	97.6	
6.3			41.0	100
5.0			6.8	98.7
2.36				76.5
1.18				52.8
0.60				38.5
0.30				23.3
0.15				15.4
0.075				7.6

Mix Proportions

Two test series were undertaken, one in which the free water content was kept constant (Table 5), and another in which the workability was kept constant (Table 6). In the latter series the free water content varied so as to maintain the slump between 90 and 110mm. This was an attempt to simulate what is more likely to occur in practice, as on site, water is usually added until the required or desired workability is achieved.

In both test series, the cement content, coarse aggregate content and the fine : coarse aggregate ratio were kept constant. The variable was the fine fines content, that is the percentage of material passing 75μm sieve, in the fine aggregate. Thus, the first mix in each series contained fine aggregate which was washed free of all its fine fines. The remaining four mixes contained fine aggregate to which 5%, 10%, 15% and 20% rockdust material were added respectively. The mix designation indicates the test series ,followed by the percentage by weight of fine fines in the fine aggregate.

Table 5 : Test Series 1

	MATERIALS (kg/m^3)					
Mix Designation	**Cement**	**Coarse Aggregate**	**Fine Aggregate**	**Rockdust**	**Total Fine Aggregate**	**Water**
1.00	375	985	980	0	980	200
1.05	375	985	931	49	980	200
1.10	375	985	882	98	980	200
1.15	375	985	833	147	980	200
1.20	375	985	784	196	980	200

Table 6 : Test Series 2

	MATERIALS (kg/m^3)					
Mix Designation	Cement	Coarse Aggregate	Fine Aggregate	Rockdust	Total Fine Aggregate	Water
2.00	375	985	980	0	980	200
2.05	375	985	931	49	980	210
2.10	375	985	882	98	980	220
2.15	375	985	833	147	980	240
2.20	375	985	784	196	980	270

Properties Investigated

For each of the concrete mixes in test series 1 and 2, the properties investigated and the test details are shown in Table 7. All the test methods used were standard BS or ASTM methods, except for the water permeability tests, which were carried out using the Germanns Water Permeability (GWT) apparatus. This test measures the influx of water into the concrete at a chosen pressure. The conception of this apparatus is almost identical to the Autoclam which was developed at the Queen's University of Belfast, except for a difference in contact area between water under pressure and the surface of the specimen. A correction has been applied to the test results so as to obtain clam water permeability indices.

Table 7 Test details

PROPERTY	SPECIMENS/TEST DETAILS	PROCEDURE
• Workability (Slump)		BS 1881: Part 102:1981
• Plastic density		BS 1811: Part 107:1983
• Bleeding		ASTM C232-87
• Hardened density	100 mm cubes	BS 1881: Part 114:1983
• Compressive Strength and Strength development	100 mm cubes cured in water at 23° C and tested up to 1 year and in ambient air conditions	BS 1881: Part 116:1983
• Elastic deformation	150 mm ∅ x 300 mm cylinders cured in water at 23°C and tested at the age of 28 days for stress-strain curve and elastic modulus	BS 1881: Part 121:1983
• Drying shrinkage	75 x 75 x 300 mm prisms cured in water at 23°C and tested by oven-drying at the age of 28 days	BS 1881: Part 5:1970
• Durability	150 mm cubes and cured in water at 23°C for 28 days	BS 1881: Part 5: 1970
- Initial Surface Absorption Test	Preconditioned by oven-drying at 105°C for 4 days prior to testing	
- Water Permeability		GWT: Germanns Water Permeability test

RESULTS

Fresh Concrete

The plastic density increased very slightly in Series 1 mixes as the percentage of rockdust increased from 0 to 20% in the fine aggregate while the free water content remained constant (Table 8). In the Series 2 mixes there was a tendency for the plastic density to decrease as the water demand increased in order to maintain the workability constant. But, the plastic density achieved in all the fresh concretes indicates that adequate compaction was achieved in all the mixes investigated. Slump decreased significantly with increase in rockdust content when the free water was maintained constant. And conversely, when the slump was maintained constant, the water demand increased, but more significantly with rockdust contents greater than 10%.

Bleeding decreased with increasing rockdust content especially for the mixes in which the free water was kept constant, where bleeding was reduced to about 1/3 its initial value as rockdust increased from 0 to 20%.

Fresh Table 8 : concrete results

Mix Designation	Plastic Density (kg/m³)	Slump (mm)	Bleeding % of free water
1.00	2530	90	9.3
1.05	2540	75	7.7
1.10	2550	50	5.8
1.15	2560	40	4.3
1.20	2560	25	3.1
2.00	2530	90	9.3
2.05	2530	95	7.8
2.10	2540	95	6.1
2.15	2520	100	5.0
2.20	2510	105	4.3

Hardened Concrete

Strength and Strength Development

Both strength and strength development of concrete are a function of the storage condition that follows casting. Table 9 shows the cube strengths, measured from the age of 3 days up to one year, of specimens for both test series, stored either continuously in water until testing or continuously in air following demoulding, in ambient laboratory conditions. The temperature varied inside the laboratory over the range 20 - 29° C while the relative humidity varied over the range 60 - 90% during the one year period.

The Series 1 test results indicate that as long as the water content was kept constant, the presence of some rockdust in concrete yielded slightly higher strengths especially at the early ages (Fig.2). Although this difference tended to become less at the later ages, rockdust contents up to 20% did not adversely affect the strength achieved in the concrete.

In the second test series, however, the increased water demands required to maintain workability of the higher dust content mixes produced strength reductions which were more evident at the later ages (Fig.3). This strength reduction was more significant in mixes containing more than 10% rockdust in the fine aggregate.

Table 9 : Strength development

Mix Designation	Compressive Strength (N/mm²)									
	3d		7d		28d		90d		365d	
	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
1.00	21.6	17.2	25.7	24.0	43.1	44.8	52.4	55.2	54.1	57.5
1.05	20.8	22.4	30.9	33.0	42.2	45.9	47.3	56.5	53.3	57.0
1.10	31.0	27.0	40.9	40.8	48.4	49.3	52.6	60.1	58.1	66.1
1.15	32.2	31.1	39.7	42.2	51.7	53.4	56.8	63.9	63.8	66.6
1.20	29.3	30.4	39.0	41.1	51.2	52.2	56.0	63.3	64.0	65.9
2.00	21.6	17.2	25.7	24.0	43.1	44.8	52.4	55.2	54.1	57.5
2.05	17.0	17.5	28.0	27.0	36.0	41.0	44.0	51.0	48.9	57.7
2.10	17.5	18.0	25.5	27.0	36.5	39.0	48.0	56.0	52.1	61.6
2.15	16.0	17.5	23.5	26.5	30.5	33.5	38.5	43.5	45.5	53.0
2.20	14.5	14.5	26.0	25.5	30.5	33.0	35.4	36.2	41.4	42.9

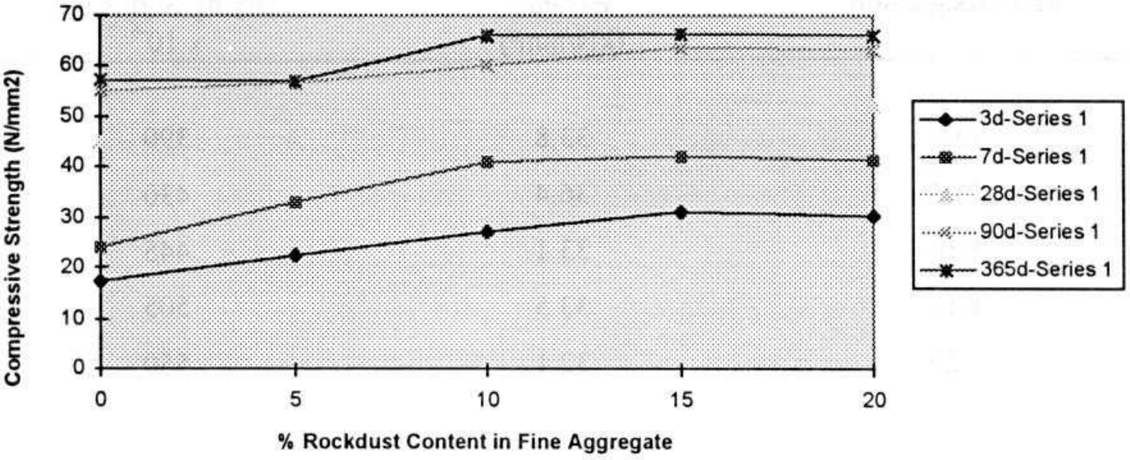

Fig.2 Strength Development of Series 1 Specimens

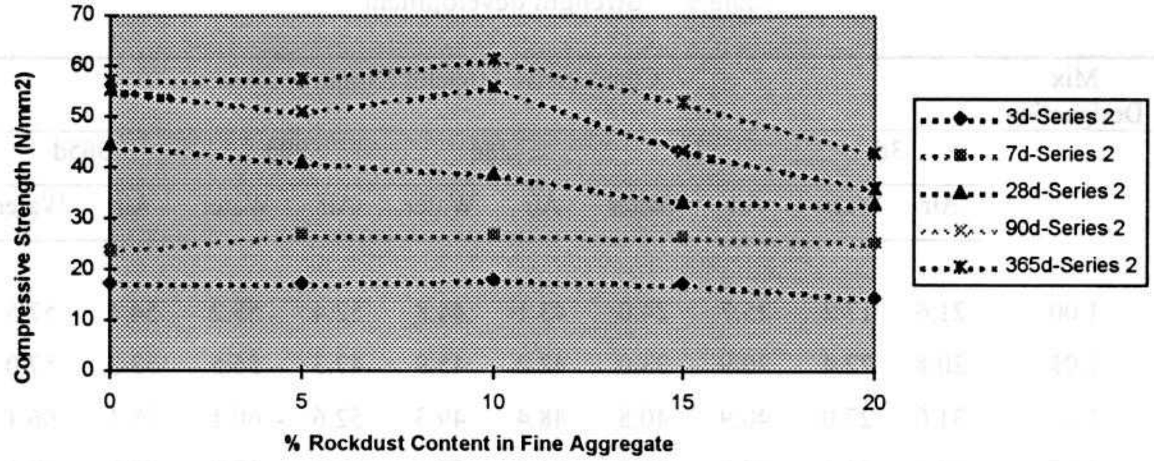

Fig. 3 Strength Development of Series 2 Specimens

Deformation

The static modulus of elasticity underwent no noticeable changes in the Series 1 specimens, showing little susceptibility of this property of concrete to the presence of rockdust (Table 10). In the Series 2 specimens, the modulus of elasticity decreased by 10 - 12% in the mixes which had 40 - 70 L/m^3 more water.

Table 10 : Deformation and volume change

Mix Designation	E-value (kN/mm²)	Drying Shrinkage x 10^{-6}
1.00	33.8	390
1.05	36.4	430
1.10	33.1	445
1.15	33.5	505
1.20	32.1	550
2.00	33.8	390
2.05	31.2	495
2.10	34.6	585
2.15	30.8	710
2.20	29.4	760

Drying shrinkage of concrete increased very significantly as rockdust content increased while water content remained constant (Fig. 4). Thus, the concrete with 20% rockdust had about 40% higher drying shrinkage than concrete with no rockdust. In the series 2 tests, as rockdust content and water content increased, drying shrinkage was even more adversely affected. Thus, the concrete with 20% rockdust and 70 L/m^3 more water than concrete without rockdust almost doubled its drying shrinkage value.

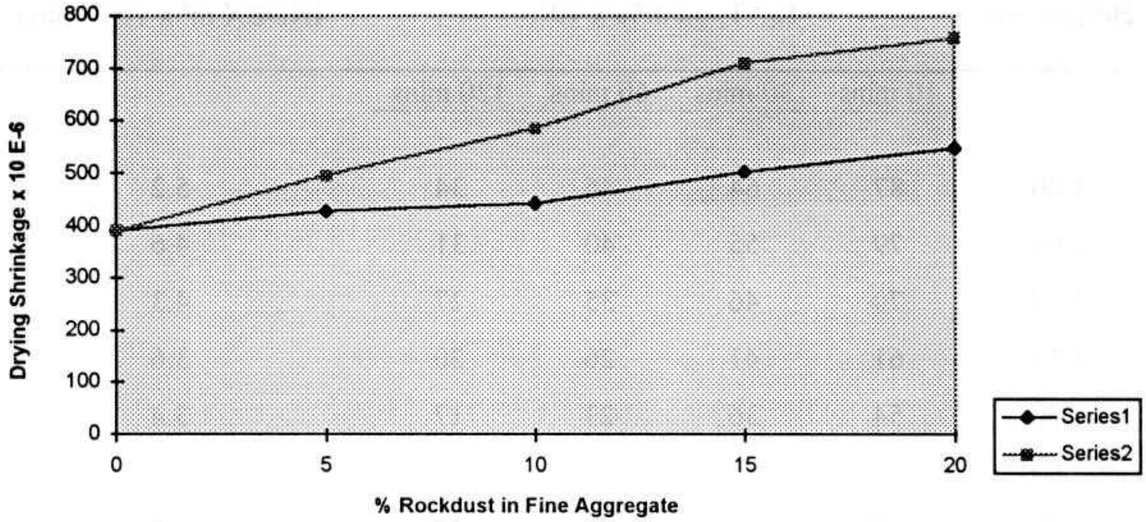

Fig. 4 Change in Concrete Drying Shrinkage with Rockdust Content

Durability

Durability of concrete is dependent on its ability to resist the penetration of materials which can react harmfully with the concrete constituents or the embedded reinforcement. The ingress of these materials, whether in liquid or gaseous forms, into the concrete is closely related to the surface characteristics of the concrete, and in particular, its pore structure and permeability. Two test methods have been used to measure the durability property of concrete, namely, the Initial Surface Absorption Test (ISAT) and the Water Permeability Test.

The ISAT constitutes an indirect measure of durability. It measures the rate of flow of water under a small constant head, into oven-dried concrete per unit area after a stated interval of time after the beginning of the test. This inflow decreases with time until eventually the surface becomes saturated and no more water is absorbed. The water permeability test measures the volume of water penetrating into the concrete at a constant pressure of 0.5 bar. As moisture content of concrete influences this water inflow, the concrete cubes were oven-dried prior to carrying out the permeability test. When the quantity of water flowing into the concrete is plotted against the square root of time, it is found to be linear, and the slope of the plot between 5 and 15 minutes is used to specify a water permeability index with units of $m^3/\sqrt{\min}$.

Both ISAT and water permeability index values (Table 11) show that the durability of concrete increased with increasing rockdust content. Thus, with a rockdust content of 20% in the fine aggregate, the permeability index decreased by about 35% when water was kept constant, and by about 25% when water was added to restore workability.

Table 11 : Permeability

Mix Designation	ISAT, ml/m²/s x 10^{-3}				CLAM PERMEABILITY INDEX m^3 x 10-7/√min
	10 mins	30 mins	60 mins	120 mins	
1.00	87	64	46	34	5.2
1.05	79	55	40	31	4.6
1.10	70	46	35	27	4.3
1.15	61	41	26	20	3.6
1.20	54	36	23	17	3.4
2.00	87	64	46	34	5.2
2.05	78	64	41	30	4.6
2.10	72	60	39	28	4.4
2.15	62	46	28	24	3.8
2.20	56	51	39	24	3.8

Discussion

Rockdust is an inevitable by-product of rock crushing. In Mauritius, basalt rock crushing is the major source of aggregate for construction. In crushed basalt sand the rockdust content, that is, the percentage of the material passing 75µm, is typically in the range 18 to 25%. This exceeds the maximum limit of 16% set for crushed rock fines in BS 882 : 1992. The excess fines in the crushed sand is considered to be potentially deleterious to the performance of concrete, the main fear being the increased risks of drying shrinkage cracking. Thus, in practice all rocksand intended for use in structural concrete is washed with water to reduce the fines content to more acceptable limits of between 5 and 8%.

To investigate the effects of rockdust on the properties of fresh and hardened concrete, two series of tests were performed. In the first series, the only variable was rockdust content in the crushed sand (0 to 20% by weight). All the other mix parameters, namely, cement, water, coarse aggregate and fine aggregate contents were kept constant. The second test series was the same as the first, except that the water content was also allowed to vary in order to maintain workability constant.

As rockdust content increased from 0 to 20%, the slump decreased from 90 to 25 mm, while the free water content was kept constant at 200 L/m^3. The plastic density was not significantly affected by the presence of rockdust, but bleeding decreased from 9% to 3% of the total free water. Thus, the presence of rockdust increases cohesion and stability of the fresh concrete.

When both the rockdust content and the water content were allowed to increase in the concrete there were noticeable reductions in compressive strength particularly over the longer term. For example, with 20% rockdust content and 270 L/m^3 free water in the mix, the strength was about 25% lower than the concrete which was free of rockdust. But, when the water content was maintained constant, the presence of rockdust up to 20% had no negative effect on the strength or the strength development of concrete over the test period up to one year. In fact, the lowest strengths were obtained in concretes that had no rockdust in the fine aggregate. Thus, from the point of view of strength it is preferable to have some dust in the concrete than no dust at all, provided the water/cement ratio is kept constant.

As for strength, the static modulus of elasticity of concrete was hardly affected by the presence of rockdust in the mix, except for those mixes where the increases in water/cement ratio were significant enough to lower the strength and concomittantly the modulus of elasticity as well. But, drying shrinkage is the property of concrete that was most affected by the presence of rockdust and increased even more when the water content was also allowed to increase. Even if chemical water reducing and plasticing admixtures had been used to achieve the desired workability while maintaining the water content constant, the drying shrinkage would have increased almost linearly with increases in rockdust content. Therefore, in order to mitigate the effects of rockdust on drying shrinkage of concrete, more powerful water reducers must be used so as to achieve the least practicable amount of water in the mix. The less water the concrete has to start with the less it will shrink. Alternatively, measures such as adequate spacing of contraction joints, provision of adequate steel reinforcement and careful detailing of the reinforcement will have to receive the necessary attention of the designer and the constructor.

The most significant benefit to concrete performance resulting from the presence of rockdust is in terms of improved durability. This is most likely due to the fine rockdust particles acting a pore fillers thus sealing the porosities that would otherwise have been present to a greater extent in the concrete (ACI Committee 210.2R-92). The resulting reduced permeability was evident even in the mixes where the water content was allowed to increase.

The results of this investigation support the guidelines given in BS 882 with respect to the maximum allowable fines content of 16% in crushed rock fine aggregate for use in structural concrete. The major limitation of high crushed fines content in concrete is the increased risk of drying shrinkage cracking. The other properties investigated, namely, compressive strength and modulus of elasticity are not detrimentally affected, while permeability is very significantly enhanced.

In countries where water scarcity is a problem, washing of crushed aggregates or even natural aggregates for making concrete may not be a feasible option from the practical or financial points of view. There may be a positive trade-off in leaving some excess fines in the aggregates, provided these aggregates do not incorporate other deleterious contaminants, such as salts, to produce concrete with adequate structural performance and enhanced durability. Mitigative measures must necessarily be taken at the level of the concrete mix design to reduce the potential drying shrinkage of such concrete , and also at the level of conception and design of the structural application of the concrete.

In other countries, the possibility of using crushed recycled concrete as an aggregate in new concrete has been investigated (Hansen, 1992), (Wainwright,1995). These researchers have ascertained that it is possible to produce concrete of satisfactory strength when using crushed concrete as replacement for the coarse aggregate, but the strength is impaired when the fine fraction of the crushed material is utilized. In addition when both the coarse and fine fractions of the recycled materials are used together, there is, in most cases, considerable reductions in the quality of the new concrete. Drying shrinkage was also found to be the most affected property of concrete resulting from the use of recycled aggregates, (Wainwright et al.,1994).

CONCLUSIONS

1. The results of this investigation tend to support the fact that the maximum limit of 16% set by BS 882 for fine material in crushed sand is a reasonable value for ensuring adequate performance of structural concrete made with crushed aggregates.
2. As rockdust content increases from 0 to 20% in crushed sand, slump of fresh concrete decreases significantly if the water content is maintained constant. Alternatively, the water demand increases appreciably if the workability is restored. The presence of rockdust improves cohesion and decreases bleeding of fresh concrete.
3. Compressive strength and modulus of elasticity of hardened concrete are not adversely affected by increases in rockdust contents of up to 20%, as long as the water content of the mix is controlled. Drying shrinkage increases significantly with increase in rockdust content even when the water content is kept constant. The most beneficial effect of the presence of rockdust is in terms of improved durability.
4. There can be a positive trade-off in leaving some excess fines in the aggregates, provided these aggregates do not incorporate other deleterious contaminants, such as salts, to produce concrete with adequate structural performance and enhanced durability. However, measures must be taken in the concrete mix design to reduce the potential drying shrinkage of such concrete.

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