The design of a single aggregate concrete on Cullinan Diamond Mine

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Synopsis

A single aggregate mix design was developed based on a slag/Portland binder blend and crusher sand. The primary design criterion, after performance, was the fluidity of the shotcrete and concrete product to ensure compatibility with existing manufacturing and shotcrete equipment as well as the pipeline transport system Cullinan Diamond Mine was investigating.

Initial work had determined an optimum slag/Portland to aggregate ratio while retaining a water to slag/Portland binder ratio of approximately 0.4 to maintain the flowability of the product. A super-plasticizer was used to further increase the flowability of the product as opposed to increasing the water content. Finally a polypropylene reinforcement fibre was included in the wet shotcrete product to improve the energy absorption characteristics of the shotcrete.

Previous work on the strength development of the slag/Portland based shotcretes and concretes suggests that strength class based on the EN 206 specification is C40/50 while the toughness classification based on the EFNARC plate test is *c*, or greater than 1000 joules[1].

Typically, Cullinan Diamond Mine wanted a shotcrete with a uniaxial compressive cube strength of 45 MPa and an energy absorption, based on the EFNARC plate test, in excess of 700 joules. This is an EN 206 strength class of C36/45 requiring a uniaxial compressive core strength of 30.5 MPa and a toughness classification of b[1].

In addition to the shotcrete development, Cullinan Diamond Mine required concrete products with a compressive strength range of between 25 and 60 Mpa for differing construction operations underground to be manufactured from the same mix design and raw materials as for the shotcrete.

Finally, Cullinan Diamond Mine carries out extensive dry shotcrete operations and an investigation into the possibility of using the single aggregate mix design for dry shotcreting was also entered into.

This paper presents data that indicates that, under the terms of reference, a wet and dry shotcrete and concrete product appears to be possible from a single aggregate less than 6.7 mm in size, and that a slag/Portland binder is suitable for use as the hydraulic binder in all the products, and that the necessary performance parameters of strength and energy absorption can be achieved.

Introduction

The objective of the work reported on in this paper, undertaken on behalf of Cullinan Diamond Mine of De Beers Consolidated Mines Limited, was to evaluate the ability of a single aggregate product, with a particle size less than 6.7 mm in size, and a slag-based binder to be used for the manufacture of shotcrete and concrete.

The shotcrete mix design using the slag/Portland blend was to meet the following criteria:

- ➤ A strength requirement of approximately 45 MPa
- ➤ Be based on locally available aggregates with a particle size grading to fit the EFNARC shotcrete grading and the DIN 8 mm grading envelopes
- ➤ Meet the required shotcrete energy absorption, or stress strain, requirements of a minimum of 700 joules energy absorption.

The concrete design criteria were based on a uniaxial compressive strength of between 25 and 60 Mpa,

The mix designs investigated were to simplify the current products used on the mine that contain two aggregate size ranges and types, and to use a blended hydraulic binder to reduce costs. The other requirements were based on typical concrete technology, i.e. a water to cement ratio of 0.4, or less, and a flow table measurement of approximately 650 mm for the shotcrete, and a slump of 180 mm for the concrete.

The aggregates selected were crusher sands from selected suppliers within a 30 to 40-kilometre radius of Cullinan Diamond Mine. The sands were selected to approximate the EFNARC shotcrete aggregate envelope. This fulfilled the requirement of simplifying

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the aggregate component. The amount of binder added was based on previous experience with shotcrete and concrete developments.

During initial testing if it was found that the final product did not meet the required flow and a superplasticizer was added in sufficient quantity to meet the flow requirements.

After the test work to develop a shotcrete and concrete mix design was completed, the most suitable product was tested further, comparatively, with the current shotcrete and concrete products used on Cullinan Diamond Mine in respect of:

- Wear rate
- Flexural strength
- Product stability
- Shrinkage.

The selected single aggregate product was also evaluated underground and *in situ* tests were carried out to investigate integration of the product with the existing mine equipment and to evaluate performance, uniaxial compressive strengths and energy absorption.

Further tests were carried out to determine whether the single aggregate mix design could replace the existing dry shotcrete product.

Shotcrete can be viewed simply as the application of a concrete product onto a surface using compressed air to both accelerate the concrete onto the surface and compact the concrete into a dense final product. The final product can be structural from both a compressive and flexural point of view.

A number of characteristics are required from a sprayable concrete over and above a consistent quality product meeting the performance specifications of strength:

- Flowability
- Bond strength
- Flexibility.

The test methods employed to develop the shotcrete for Cullinan Mine included both a uniaxial compressive strength test using 100 x 100 x 100 mm cubes and the French rail test, otherwise known as the EFNARC (European Specification for Sprayed Concrete) panel test to determine energy absorption. The EFNARC panel is a standard 600 x 600 x 100 mm thick[1]. In all cases the manufactured products were left under wet Hessian for 24 hours after which they were demoulded from either the cube moulds or EFNARC panels and transferred to a water bath at 27 degrees centigrade until testing. The results given in the following tables, unless otherwise stated, are the average of three test results.

Mix designs and test programme

The aim of this single aggregate development was to have a single mix design that through the addition, or removal, of water, or superplasticizer, the different performance requirements could be achieved to meet the shotcrete and concrete strength and performance requirements.

Table I gives proposed shotcrete particle size distributions from *Tunnelling the World* by M. Van Der Walle[2]. Further comments by Van Der Walle suggest:

- That for shotcrete with a particle size distribution less than 4 mm in size, 450 to 600 kg of cement should be used per m^3 of final product.
- A slump of 150 to 175 mm
- A water/cement ratio of between 0.4 and 0.45.

Table I

Proposed shotcrete graduations[2], Gradation limits for combined aggregates

Sieve size, US standard square	Per cent by weight passing individual sieves		
	Gradation No. 1	Gradation No. 2	Gradation No. 3
19 mm	—	—	100
12 mm	—	100	80–95
10 mm	100	90–100	70–90
4.75 mm	95–100	70–85	50–70
2.40 mm	80–100	50–70	35–55
1.20 mm	50–85	35–55	20–40
600 μm	25–60	20–35	10–30
300 μm	10–30	8–20	5–17
150 μm	2–10	2–10	2–10

Table II

Product mix designs

Product	Shotcrete				Concrete			
	Mass	Volume	Vol %	Mass %	Mass	Volume	Vol %	Mass%
Aggregate	1541.0	572	57	64.1	1566.0	580	58	64.4
Binder	660.0	228	22.8	27.5	673.0	232	23	27.7
Plasticizer	2.5	1.7	0.2	0.1	4.5	3.0	0.3	0.2
Water	200.0	200.0	20	8.3	188.0	188.0	18.7	7.7
Totals	2403.5	1001.7	100	100	2431.5	1003.0	100	100

The current Cullinan Diamond Mine wet shotcrete mix design is a proprietary mix design and it can be seen that the cementitious component is approximately 26% of the solids components.

Comparing the above with the final single aggregate mix design, given in Table II, for this development work it can be seen that the component quantities are in keeping with suggested mix design ranges proposed by Bekaert. The cost of all the products in the single aggregate mix design is lower than for the current mix design. The cost reduction was calculated at 30% (2004 costing). Tables III and IV give the concrete and shotcrete mix designs currently used by the mine for comparison and Table V gives the mines cost comparison with the single aggregate product.

The single aggregate mix design development included a single blended hydraulic binder, 4 types of crusher sand, two types of superplasticizer and filler, as well as various water to binder ratios.

The 4 crusher sand types were selected were based entirely on availability, transport distance and costs:

1. Willow Wonder Sand
2. Alpha – blended sand
3. Alpha – washed sand
4. Alpha – dust sand

The particle size distributions for these products are given in Figure 1–4.

Table III

Concrete mix designs (kg/m3)

Product	60 MPa	40 MPa	25 MPa
Cement	488	394	301
Sand	673	755	836
Stone	975	975	975
Admixture	7.0	5.6	4.3
Water	205	205	205

Table IV

Shotcrete mix design

Product	kg/m3
CEM I 42.5	500
Condensed silica fume dust	40
Rayton sand	1558
Retarder and superplasticizer	9
Internal curing agent	5
Accelerator	25
Water	230

Table V

Cost comparison*

Product	Current shotcrete	Single aggregate shotcrete	60MPa concrete current	Single aggregate 60MPa concrete
Sand	131		68	
Aggregate		115		121
Stone			84	
Cemetitious plus fillers	330	276	256	289
Fibre	252	166		
Superplasticiser		35	62	63
Superplasticiser/ Retarder	139			
Curing agent	74			
Accelerator	162	169		
Total	R 1088	R 761	R 470	R 473

*2004 costing in rands, all values rounded up

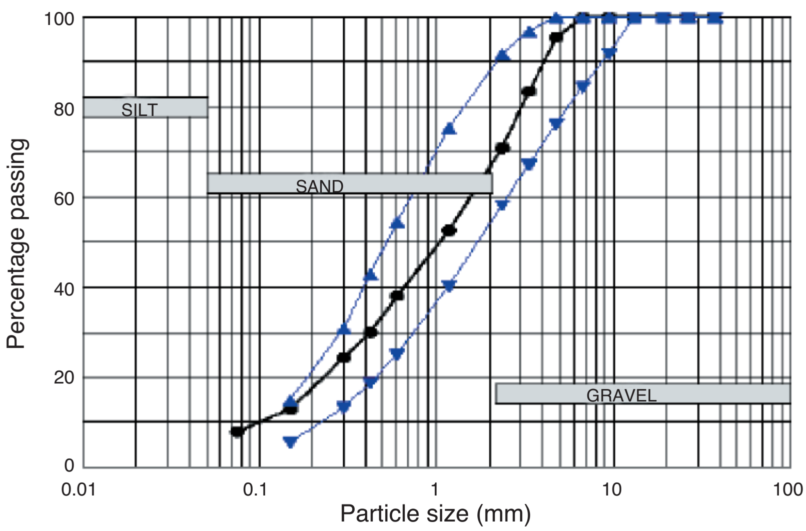

Figure 1—Willow wonder sand particle size distribution

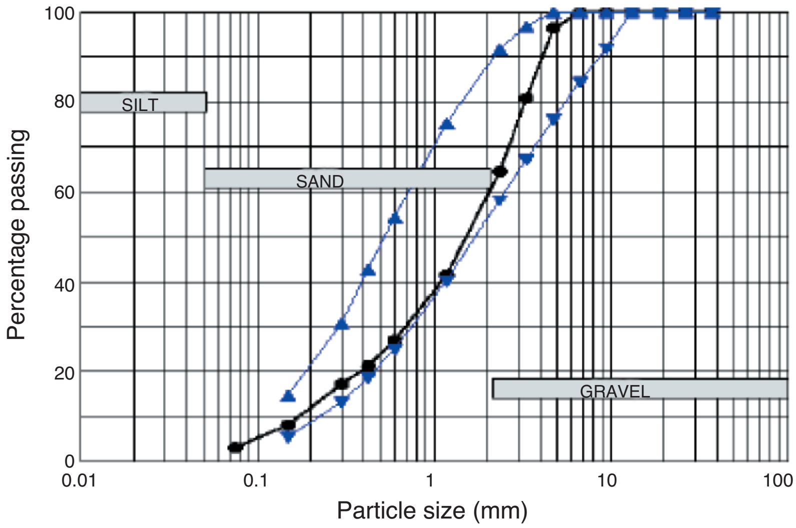

Figure 2—Alpha blended sand particle size distribution

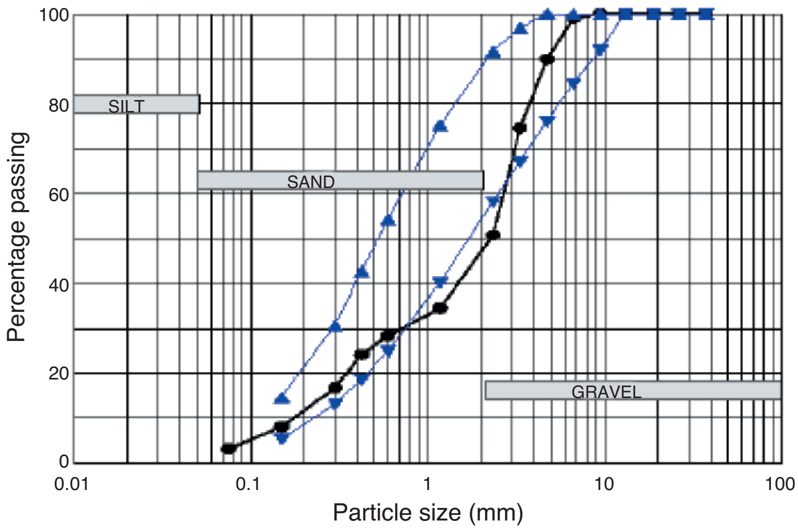

Figure 3—Alpha washed sand particle size distribution

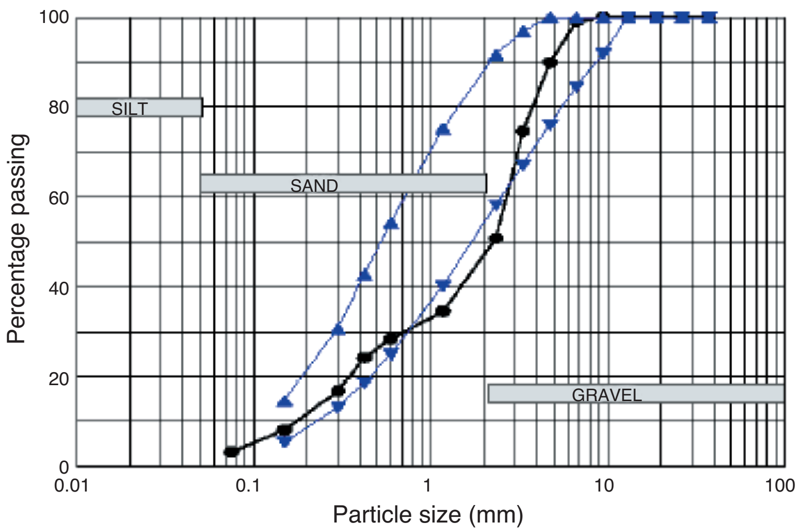

Figure 4—Alpha dust particle size distribution

Table VI

Selected crusher sand

Item	Result	
Uniaxial compressive strength 100 x 100 x 100 mm cubes	24 hours	3.3 MPa–3.1 MPa–3.3 MPa Average—3.2 MPa
	48 hours	6.7 MPa–7.2 MPa– 8.3 MPa Average—7.4 MPa
	7 day	31.4 MPa–28.1 MPa–34.4 MPa Average—31.3 MPa
	14 day	36.0 Mpa (single cube)
	28 day	55.1 MPa–37.6 MPa–38.1 MPa Average—37.9 MPa (outlier discarded)
28 day core	33.0 MPa–45.0 MPa– 38.5 MPa Average—38.8 MPa	
Energy absorption	698 J–921 J–1086 J Average—902 Joules	
Fibre content	7.59 kg/m^3–8.49 kg/m^3–8.33 kg/m^3 Average—8.14 kg/m^3 (initial loading 9 kg/m^3)	
Crusher composition	Pretoria group quartzite of the Transvaal sequence	

All the samples were also tested according to SABS 10833 for grading, dust content clay content, fineness modulus, and organic content. The Willow Wonder sand and the Alpha blended sand were marginally outside the prescribed maximum dust limits, and the Alpha dust sand was marginally above the maximum fineness modulus.

There was similar data on the existing aggregates; the two aggregates were a washed river sand with a less than 10% retention on 4.75 mm sieve, less than 5% passing 0.075 mm and a less than 5% clay content. The 19 mm aggregate had less than 15% retained on a 19 mm sieve and a less that 2% clay requirement.

The starting point of the mix design was a water to binder ration of 0.4 with small changes in the water content on each side of this and a binder content of 30% of the total solids content, with small changes in the binder content on either side of this value.

Mix designs were achieved by producing a product that appeared visually to meet the requirements of flow and 'fattiness' required to make a shotcrete product stick to a surface.

The products produced in this manner were then evaluated according to flowability on a flow table. If the product did not meet the flow requirements, superplasticizer was added until the flow was approximately 650 mm. A number of mix designs were tried until a single product appeared successful with the respective crusher sands.

These mix designs were tested using 100 x 100 x 100 mm UCS cubes and as EFNARC panels using polypropylene fibre as the reinforcement. During the EFNARC panel evaluation to determine energy absorption, the degree of fibre rebound was evaluated by taking cores and crushing them, enabling the fibre to be removed from the crushed material and evaluated based on mass. The cores were also tested for 28 days compressive strength.

This constituted the design feasibility from which a single mix design and additive combination was selected.

Table VII

Initial 24 and 48 hour strength developments

Mix design		24 h strength (MPa)	48 h strength (MPa)
Fly ash Plasticizer 1 w/c ratio Slump	 0.076 kg 0.30 180 mm	9.8	22.5
Fly ash Plasticizer 2 w/c ratio Slump	 0.085 kg 0.32 190 mm	10	19.3
CSF Plasticizer 2 w/c ratio Slump	 0.12 kg 0.28 170	9.5	23.5
Fly Ash Plasticizer 2 w/c ratio Slump	 0.12 kg 0.28 180 mm	6.8	19.7

Owing to availability and cost of condensed silica fume a further investigation into the use of condensed silica fume versus fly ash as an additive was carried out. This involved a strength generation comparison based uniaxial compression tests of 100 x 100 x 100 mm cubes.

Test results

The results of the design feasibility for the selected crusher sand are given in Table VI. Table VII gives the initial strength results at 24 and 48 hours for the selected superplasticizer with fly ash and condensed silica fume. This test was carried out to allow replacement of the silica fume with fly ash.

Table VIIIa and VIIIb gives the underground results of energy absorption from panels sprayed underground and cubes manufactured underground.

Discussion

The aim of this study was to reduce the manufacturing costs, raw material and additive requirements of the mines shotcrete. A further development was to produce a single mix design that could also be used as a structural concrete as well as a dry shotcrete.

The design methodology was to use a single aggregate and reduce the binder costs by using a blended product binder, slag, Portland, fly ash and additives, that would also reduce the additive requirements through hydrating more slowly, thereby increasing the product pot life. The addition of slag also improves the final product's resistance to impurities in the water or the aggregates that may retard cement hydration and strength development.

The shotcrete requirements have been met by the single aggregate mix design as shown in Tables VI, VII, VIIIa and VIIIb. These requirements are:

- 45 MPa uniaxial compressive strength on a cube
- 27 MPa uniaxial compressive strength on an *in situ* core
- An EFNARC energy absorption of greater than 700 joules
- Compatibility with the existing mine infrastructure and equipment.

The reinforcement fibre used to achieve the energy absorption requirements was a profiled monofilament polypropylene fibre.

This mix design although discussed as shotcrete is equally available as a concrete. In order to increase the strength of the concrete, it would be possible to decrease the water content by increasing the superplasticizer content. This reduction in the water to cement ratio will automatically increase the strength. The use of a slag based binder will also result in a strength increase over and beyond 28 days. The mix design used to achieve the required concrete strengths is the same as that for the shotcrete. It was the design aim to achieve a uniaxial compressive strength in excess of 60 MPa, which is the mine's requirement for ore pass lining. To achieve strengths lower than this to meet the 25 and 40 MPa requirements will be a function of either increased water or decreased binder content.

Table IX gives the uniaxial strength achieved on 100 x 100 x 10 mm cubes for the 60 MPa concrete mix design. It will be noted that an average maximum strength of 67.25 MPa was achieved 12% greater than the required 60 MPa.

In terms of concrete technology specifications where 95% of the cubes tested for a target strength need to be 1.645 times the standard deviation greater than the target strength, the objective is also achieved as the standard deviation for the results is 1.32, which means that 95% of the samples need to be above 62.18 MPa.

In order to develop increased confidence for the single aggregate concrete product, it was decided to compare the currently used 60 MPa concrete with the new single aggregate product.

The comparisons were to include:

- A wear comparison using both a tumbler abrasion test, involving a rotating box with the sides made from the test materials in which steel balls are dropped from panel to panel during rotation as per C&CI Test Method 7.84, and a wire brush test in which a wire brush is dragged back and forth over the test material surface as per C&CI Test Method 7.115. In both cases the wear is measured by mass loss.
- Durability tests of oxygen permeability, water sorptivity and chloride conductivity[6]
- Flexural strength.

Table VIIIa

Uniaxial compressive results from underground tests

	Compressive strength (MPa)				
	4 Day	7 Day	14 Day	28 Day	56 Day
Mine tests Cured cubes (average of three readings, cured under water at 25°C)		40.2	47.0	50.0	
Mine tests Uncured cubes Average	19.8 21.0 21.1 20.6	29.1 29.9 28.5 29.2	33.6 34.3 33.5 33.8	34.5 34.5 37.1 35.4	
NS Consultancy Cores		25.5 30 27.5 28	31.5 32 27.5 29	36 34.5 34 37 36	38 39.5 42.5 41.5 43.5 40 41.5
Average		27.8	30.0	35.5	41
Cube conversion		41.4	44.6	52.8	61

Table VIIIb

EFNARC panel results from underground trials

Underground tests 28 Day—joules	Surface tests 56 Day—Joules	
	Cast	Sprayed
1943/ 1493/ 1315/ 1386	822/ 956/ 833	751/ 909/ 726
Average 1398 joules (Outlier discarded)	Average 870 Joules	Average 795 Joules

Table IX

Results for 7, 14 and 28-day compressive strength tests

Age (Days)	Compressive strength (MPa)
7	37.0–38.0–39.5–38.5 Average 38.3
14	45.0–45.4–44.5–46.0 Average 45.2
28	66.5–66.0–69.0–67.5 Average 67.25

Table III gives the current 60 MPa mix design used by Cullinan Diamond Mine against which the single aggregate mix design was evaluated.

Table X gives the results for the wear tests. In the case of the tumbler abrasion test, the single aggregate concrete is marginally better than the current 60 MPa concrete. In the case of the wire brush test, the single aggregate concrete is significantly worse than the current 60 MPa concrete. The poor performance of the single aggregate product is both a function of the slag-based binder being only 28 days old and still curing to full strength and the larger surface area of paste when compared to the current 60 MPa concrete. The tumbler abrasion test, however, more closely resembles the environment in an ore pass. Table XI gives the performance classes of the durability tests and Table XII gives the performances of the two concrete products.

Table X

Wear results

Test	Single aggregate	Current Cullinan
Wire brush test (mm)	1.07, 1.09, 1.00	0.41, 0.42, 0.42
Average	1.05	0.42
Tumbler abrasion Test (g/mm^2)	0.1	0.1
Abrasion index from the tumbler test	1.7	1.8

Table XI

Performance indicators

Durability class	OPI (Log scale)	Sorptivity (mm/√h)	Chloride conductivity (mS/cm)
Excellent	>10	<6	<0.75
Good	9.5–10	6–10	0.75–1.5
Poor	9.0–9.5	10–15	1.5–2.5
Very poor	<9.0	> 15	>2.5

Table XII

Durability results of the two concretes

Test	Single aggregate	Current Cullinan
Oxygen permeability	10.1 (Excellent)	9.4 (Poor)
Water sorbtivity	9.32 (Good)	9.75 (Good)
Chloride conductivity	0.44 (Excellent)	0.37 (Excellent)

The durability tests show both products to performing between what is considered good and excellent with the exception of the current concrete and oxygen permeability, which was considered poor. These tests are a measure of the stability and durability of the concretes, again indicating that the single aggregate concrete will perform as well as or better than the current 60 MPa concrete.

The flexural strength results are given in Table XIII. It is clear that the single aggregate concrete outperforms the current 60 MPa concrete.

A final issue of shrinkage was evaluated for the two products based on SABS method 1085: Edition 2.1 of 2002[10]. Shrinkage results are also based on a sliding scale where concrete has a shrinkage typically between 0.02% and 0.065% with an average of approximately 0.045%.

The shrinkage results were 0.038% for the single aggregate mix design and 0.029% for the current Cullinan Mine Mix design. Both these results are better than average.

This development and test work concluded that the single aggregate mix design would not result in a 60 MPa product that was inferior that the current 60 MPa product and in some instances was significantly superior.

The use of the single aggregate product as a dry shotcrete was evaluated using A 350 CFM compressor operating at a pressure of 700 kPa connected to a Rockcreter type dry shotcrete machine.

The bags of single aggregate shotcrete mix were opened and combined on a tarpaulin. Good mixing was achieved by shovelling the products together into a barrel type concrete mixer.

The blended product was then introduced into the rotor dry shotcrete machine that introduced the dry product into the delivery hose through which the compressed air transported the product to the shotcrete nozzle.

At the nozzle water is introduced in a sufficient quantity to get the product to stick to the surface being coated.

In this case EFNARC panels were filled both for energy absorption tests and for taking core for compressive strength testing.

Table XIII

Flexural strength tests

Mix	Slump, mm (SABS method 862-1)[7]	Compressive strength, MPa (SABS method 863)[8]		Flexural strength, MPa (SABS method 864)[9]	
		7 day	28 day	7 day	28 day
Single aggregate	240	43.5	84.0	6.05	11.50
Current	190	49.5	68.5	4.90	6.45

Table XIV
Tabulated test results

Core compressive strength (MPa)					Energy absorption Joules)
24 Hour	48 Hour	7 Day	14 Day	28 Day	28 Day
4 /4/ 4/ 4	7/ 7/ 8/ 6.5	16.5/18/18.5	25.5/31/24	35/37.5/ 37	861/650/780
Average 4.0	Average7.1	Average 17.7	Average 26.8	Average 36.5	Average 763.7
Cube compressive strength (MPa)					
Average 5.9	Average10.6	Average 26.3	Average 39.8	Average 54.3	

Table XIV gives the results of the test work. From the results it can be seen that, in terms of the compressive strengths, the shotcrete requirement laid down for wet shotcrete can be achieved with a dry shotcrete machine and the single aggregate shotcrete mix design.

A steel reinforcing fibre was added to the single aggregate mix as opposed to a polypropylene fibre to prevent the polypropylene fibres from being entrapped in the air flow and 'blown' out of the shotcrete. The energy absorptions are also reported in Table XIV. It can again be seen that the single aggregate mix design used as a dry shotcrete can achieve the minimum requirements laid down for wet shotcrete, i.e. 700 Joules.

Conclusions

It has been possible to develop a cementitious product from a single aggregate size range together with a blended binder and reduced additives that meet the mine's requirements for:

➤ Wet shotcrete
➤ Dry shotcrete
➤ Concrete up to 60 MPa in strength.

This has been achieved while reducing costs over the current shotcrete and approximating the current 60 MPa concrete costs but simplifying manufacture to a single aggregate.

The Single aggregate 60Mpa product was further evaluated to approximate or outperform the existing 60Mpa 19 mm stone concrete in all but a wire abrasion test.

The developed single aggregate product also benefits from increased fluidity and therefore makes transport, especially through pipelines, more viable with less risk of blockage.

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References

1. European Specification for Sprayed Concrete EFNARC 1996, ISBN 095224831X.
2. Tunnelling the World, M. Vandewalle, N.V. Bekaert S.A., Six Edition 1998.
3. SABS 1083:2002, Edition 2.01, Aggregates from natural sources - Aggregates for concrete, ICS 91.100.15–91.100.25, ISBN 0-626-13623-7.
4. C&CI Test Method 7.8, Abrasion Resistance of Cast panels (Tumbling Method).
5. C&CI Test Method 7.11 Abrasion Resistance of Concrete using a wire brush or Silicon Carbide grit.
6. Alexander, M.G., Ballim, Y., and Mackechnie, J.R. Concrete durability index testing manual, Research Monograph No. 4. Departments of Civil Engineering, University of Cape Town and University of the Witwatersrand, March 1999.
7. SABS SM 862-1:1994, Edition 2, Concrete tests—Consistence of freshly mixed concrete - Slump test, ICS 91.100.30, ISBN0-626-09965-X.
8. SABS SM 863:1994, Edition 2, Concrete tests—Compressive strength of hardened concrete, ICS 91.100.30, ISBN 0-626-09969-2.
9. SABS SM 864:1994, Edition 2, Concrete tests—Flexural strength of hardened concrete, ICS 91.100.30, ISBN 0-626-09970-6.
10. SABS SM 1085:2001, Edition 2.01, Concrete tests—Initial drying shrinkage and wetting expansion of concrete, ICS 91.100.30, ISBN 0-626-12963-X. ◆