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The effect of material composition on the properties of dry shotcrete

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The rebound of dry shotcrete mixes can be a large 'add-on' cost in construction projects and it is in the interests of the contractor and the owner to keep these costs to a minimum. The type and nature of materials used are important factors affecting the rebound. Two types of aggregate (natural river sand and crushed aggregate) as well as partial replacement of Portland cement with silica fume and fly ash have been investigated. The same amount of steel fibres was added to all mixtures so that the ductility properties of shotcrete could be evaluated. Laboratory trials were undertaken to determine the influence of materials on the rebound and the mechanical properties of shotcrete. This study was expanded to assess the cost implication of using the above materials. Shotcrete manufactured using natural river sand and plain cement was used as reference. Results indicate that substantial reductions in the rebound and cost can be obtained when using crushed aggregate, with greater reductions being experienced when a combination of 8 % silica fume and 15 % fly ash is used as cement replacement. This seems to be a solution to the problem of obtaining sand for shotcrete in regions where natural sand are either not available in sufficient quantities or are of unsuitable quality.

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Keywords: shotcrete, rebound, cement replacement, fly ash, silica fume, aggregate type

INTRODUCTION

Shotcrete (which is mortar or concrete conveyed through a hose and pneumatically projected at high velocity from a nozzle) is fast becoming a material of choice for repair and rehabilitation, low-cost house construction, slope stabilisation, and temporary support in mines and tunnels.

There are two methods of producing shotcrete, namely the dry and the wet processes. The considerable quantity of rebound generated by the dry mix shotcrete process affects the engineering and financial properties by

- causing an overall loss of materials
- changing the mix proportions

The first effect may mean a loss of anything from 10 % to 50 % of the input, depending upon circumstances such as the direction of application, the composition of the starting mix, the substrate surface quality, the pressure, the skill of the nozzle man, the layer thickness, and the nature of the mix. The second effect is not well documented. Owing to the tendency for larger particles to rebound more readily than finer material, this results in a mix in place, which is richer in cement than in the mix proportions (Addis 1994). The final shotcrete product is thus more vulnerable to shrinkage cracking, stresses from moisture gradients, and deterioration when exposed to an aggressive environment. With an inordinately high fibre rebound, the fibre volume fraction on the wall is significantly lower than that in the design mixture, and this translates into loss of fracture toughness, and post crack load-carrying capacity in shotcrete (Bindiganavile *et al* 2000). The in-situ material proportions can have severe implications on both the in-service mechanical performance and the long-term durability of shotcrete products. The reduction of rebound in dry-process shotcrete is therefore recognised as a pressing challenge and the type and nature of materials used are important factors affecting the rebound (Melbye *et al* 1994). Very little information and data have been published on the influence of the South African aggregate types on rebound, cost and the performance characteristics of shotcrete. This study attempts to deal with some of these concerns.

OBJECTIVES OF THE STUDY

Traditionally aggregates (sand and stone) have been thought of as chemically inert and as exercising little influence on the mechanical properties of concrete. More recently it has been appreciated that aggregates may react deleteriously with the products of cement hydration, but also that they may interact beneficially with the cement paste to enhance concrete strength and/or stiffness (Alexander & Davis 1992).

Shotcrete is pneumatically projected and compacted concrete with compaction dynamics that differ significantly from conventional concrete. The mode of interaction between the mixing water, the cementitious and the inert (filler) part of the mixture is different. The input mix proportions are not the same than the in-place mix proportions. The difference in rheology and spatial distribution of the components within the mixture imply that the kinetics of strength gain and paste-

Table 1 The chemical composition of materials

%	Natural river sand	Crushed aggregate	Fly ash	CEM I 42,5 R	Silica fume
SiO_2	73,88	92,74	54,1	21,25	92,9
TiO_2	0,14	0,09	1,6	0,29	–
$Al2O_3$	14,28	2,43	32,37	4,07	0,7
$Fe2O_3$	1,24	0,99	3,13	1,96	1,6
MnO	0,02	0,01	0,03	0,21	–
MgO	0,41	0,15	1,18	1,82	0,5
CaO	1,22	0,41	4,52	65,17	0,1
Na2O	4,39	0,16	0,26	0,27	0,71
K2O	3,81	0,59	0,68	0,42	–
$P2O_5$	0,06	0,03	0,43	0,05	–
$Cr2O_3$	0,02	0,04	0,04	<0,01	–
NiO	<0,01	<0,01	<0,01	<0,01	–
$V2O_5$	<0,01	<0,01	0,03	<0,01	–
ZrO_2	0,02	<0,01	0,06	<0,01	–
LOI	0,36	4,89	0,1	2,57	1,5
TOTAL	100,11	98,03	98,53	98,11	

Table 2 Natural river sand and crushed aggregate grading

SABS sieve (mm)	Total % pass		ACI 506 Grading limits
	Natural river sand	Crushed aggregate	Total % pass
13,2	100,0	100,0	100
9,5	99,9	100,0	90–100
6,7	95,1	100,0	80–95
4,75	87,7	98,0	70–85
2,36	67,0	78,9	50–70
1,18	44,4	56,5	35–55
0,6	26,0	40,2	20–35
0,3	13,1	23,6	10–20
0,15	6,7	12,1	2–10
0,075	2,3	3,3	0–7
<0,075	0,0	0,0	0

aggregate interface development in shotcrete are decidedly different from cast concrete. It is conceivable that the use of aggregate in shotcrete may result in trends that are different from those found with cast concrete (Banthia & Chan 2000).

As shotcrete is used in various environments (mining, housing, construction etc) with different material and test specifications, it was decided to conduct only comparative tests to determine

- the influence of natural river sand and crushed aggregate on the rebound
- the influence of the interaction between aggregates and cementitious materials such as cement, silica fume and fly ash on the performance characteristics of shotcrete
- the cost implication of using specific materials

Finally this study could provide contractors with information about the handling characteristics, the cost implication, the physical and the mechanical performance of shotcrete products when using specific aggregates and cementitious materials.

MATERIALS

The cement type used in all mixtures is Cement CEM I 42,5 R, from Pretoria Portland Cement. This cement complies with SABS ENV 197-1 and its chemical composition is given in table 1.

In some countries cementitious materials are available only as cement blends where the cement producers blend or inter-grind the ingredients to predetermined proportions and characteristics. In South Africa cement extenders are available on the market as separate products. This may have some advantages as it does keep the options open to the contractor who understands the use of these materials and wishes to take full advantage of the relevant benefits offered by each of them. The fly ash used as cement extender in this project was obtained from Lethabo while the silica fume used was obtained from Middelburg. The chemical compositions of the cement extenders also appear in table 1.

There are about 23 different aggregate types commonly used in South Africa (Alexander 1998). Only two types of aggregate (one a natural river sand and the other a crushed aggregate) that are freely available and frequently used in Gauteng were investigated in this study. The natural river sand used is granite from Rossway quarry in Pretoria. It has a maximum nominal size of 6,7 mm, a fineness modulus of 3,6, a relative density of 2,65, a bulk density of 1 300 kg/m^3 and a moisture content of 6,3 %. The crushed aggregate used is quartzite from Ferro quarry in Pretoria. The aggregate has a maximum nominal size of 4,75 mm, a fineness modulus of 2,9, a relative density of 2,67, a bulk density of 1 285 kg/m^3 and a moisture content of 1,6 %. The chemical composition of both sand sources can be found in table 1 while the particle size distribution (or grading) of the aggregates appear in table 2. Only the natural river sand meets the recommended grading limits for dry shotcrete aggregates (Addis & Owens 2001).

Loose and end-hooked Dramix ZL 30/0,5 fibres, with a length of 30 mm and a diameter of 0,5 mm, were used as steel fibre reinforcing.

The researchers could only estimate the financial consequences of reducing rebound by allocating costs to each material used. The local bulk cost of the materials used is given in table 3.

Table 3 Material cost in bulk

Material	Local cost in bulk (rand per ton)
Cement (Cem 1)	700
Fly ash	100
Silica fume	1 250
Natural river sand	110
Crusher aggregate	60
Steel fibre	12 830
Water	5

MIX PROPORTIONS

Because of the many job-related factors involved, shotcrete mixes cannot be designed in the same way as conventional concrete. The design of the mixture was done following Ryan's recommendations for estimating input mix proportions (Addis 1994). For this project, 30 MPa was taken as the characteristic 28-day compressive strength target for in-place shotcrete. According to Ryan's curve, the input aggregate/cement ratio, cement and aggregate content were obtained as 4,1:1, 435 kg/m^3 and 1 785 kg/m^3 respectively.

One of the drawbacks of dry-mix shotcrete is that the control of water in the mixture is left to the experience and judgement of the nozzle-man. If too much water is added, the mixture becomes too runny and loses its cohesiveness and the capacity to develop a build-up. Keeping the mixture too dry, on the other hand, makes it stiffer and increases the rebound (Bindiganavile & Banthia 2000). It has been demonstrated that the well-known inverse relationship between water-cement ratio and strength (developed for plastic concrete) does not apply to dry-mix shotcrete, for which compaction plays a major role in determining the optimum water content (Armelin & Helene 1995). Experience gained on South African projects has shown however that, for dry-process shotcrete, the water content is typically 200 ℓ/m^3 (Addis 1994). In this investigation the water requirement was presumed to be 200 ℓ/m^3.

A fibre content of 30 kg/m^3 was used

Table 4 Designed mix proportions

Before shooting: mix constituents (kg)										
Mixtures	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix10
Constituents	NRS	CrA	NRS	CrA	NRS	CrA	NRS	CrA	NRS	CrA
Cement	435	435	370	370	305	305	335	335	305	305
Silica fume	0	0	65	65	0	0	35	35	65	65
Fly ash	0	0	0	0	131	131	65	65	65	65
Natural river sand	1 785	0	1 785	0	1 785	0	1 785	0	1 785	0
Crushed aggregate	0	1 785	0	1 785	0	1 785	0	1 785	0	1 785
Steel fibre	30	30	30	30	30	30	30	30	30	30
Water content*	200	200	200	200	200	200	200	200	200	200
Aggr/(C+fa+sf)	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1	4,1:1

NRS = Natural river sand
CrA = Crushed aggregate
* The theoretical water content (Addis 1994)

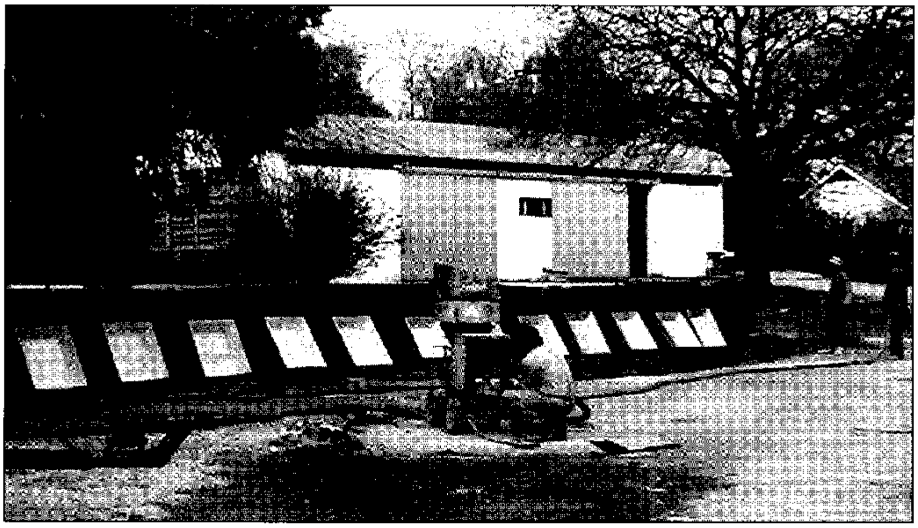

Figure 1 Experimental shotcrete setup

in all mixes so that the ductility properties of the shotcrete made with the material above could be evaluated. Shotcrete mixes (aggregates, cement, cement extenders, steel fibres) were weight-batched and bagged in bulk bags on site. One plain 'control' and four different shotcretes cement blended mixes were prepared for each type of aggregate. All mixes have the same design mass of aggregates (1 785 kg), fibre content (30 kg) and aggregate/cementitious ratio (4,1:1=A:(C+sf+fa)) as indicated in table 4. Within the constraints of batching accuracy, it was only the type and quantity of cement and cement extender in the blended cement, which varied. Considering the relative densities of cement, silica fume, fly ash, natural river sand and crusher sand, the volume of material indicated for mix 1 in table 4 is 1 m^3 while the volumes indicated for the other mixes are slightly more (or less for mix 2) than 1 m^3.

EXPERIMENTAL SETUP

The basic layout of the test programme was to shoot shotcrete mixes onto previously prepared wooden panels (EFNARC panel size: small base 600 x 600, big base 840 x 840 and deep 150). A local contractor performed the shotcreting of all the panels in one day. The shooting was carried out from 8 am to 4 pm on 11 September 2001, on the experimental farm of the University of Pretoria. The temperature and relative humidity of the day were between 14 °C and 22 °C and 70 % RH respectively. A rotor dry-mix spraying machine and 17 m^3/min (600 cfm) compressor were used, with a 30 m conveying hose, which had an internal diameter of 45 mm leading to a nozzle. The diameter of the hose satisfied the requirement that 'the length of the steel fibres shall not exceed 0,7 of the internal diameter of the pipes or hoses used unless a test has proven that longer fibres can be sprayed without blockage' (EFNARC 1996).

Panels were aligned parallel to each other, inclined almost vertically, with identical lighting conditions during the shoots. To study the relative effects of the different aggregates the shooting technique was assumed to be constant and variation was limited by using the same nozzle-man for shooting the thirty panels (three panels for each mixture) in one day. The experimental set-up appears in figure 1.

The rebound was collected from the plastic sheet placed on the floor, at the bottom of panels, and weighed, kept and collected for further testing. After shooting, the test panels remained in their original position for 24 hours, covered with black plastic sheets to keep them damp and shield them from the sun and wind, thus preventing evaporation and providing normal curing conditions. After 24 hours a curing compound was sprayed onto all panels, which were re-covered with the same plastic sheet and left in their initial position.

The European Federation of National Associations of Specialist Contractors and Material Suppliers for the construction Industry (EFNARC) specification for sprayed concrete states that the compressive strength of sprayed concrete can be determined from drilled cores with a minimum diameter of 50 mm and a height/diameter ratio in the range of 1 to 2 (EFNARC 1996). Based on the EFNARC specification it was decided to use 68 mm cores for compressive strength tests.

Three days after shooting, one panel for each mixture was cored with a diamond-tipped bit to recover three cylinders of 68 mm diameter. These cylinders were trimmed about 60 mm from the rough side and 25 mm from the contact side of shotcrete and milled to a core length of 68 mm. All specimens were moist cured until they were tested for compressive strength seven days after shooting. The drilled panels were re-covered with the plastic sheet and kept outside. After 10 and 25 days three cores of each mix were taken as above and moist cured for a minimum of three days until they were tested for 14- and 28-day compressive strength respectively.

From 21 days after shooting samples were cut with a diamond saw to create three test prisms of 75 x 125 x 600 mm for each mix. All specimens were moist cured until they were tested for flexural strength and toughness index parameters at 28 days. For 56-day compressive strengths core samples were taken from the ends of beam specimens (after testing) and stored in the water.

The properties evaluated included the following:

- rebound characteristics according to ACI 506R-90
- dry density of the in-situ shotcrete in accordance with ASTM C642:90
- compressive strength at 7, 14, 28 and 56 days in accordance with ISO 4012-1978

Table 5 In-situ mix proportions

After shooting: in-situ mix constituents in %										
	Mix 1	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**	**Mix 7**	**Mix 8**	**Mix 9**	**Mix 10**
Cement	21,3	18,2	15,7	12,2	13,3	12,1	13,6	14,8	14,4	11,5
Natural river sand	73,9		71,9		78,2		72,3		70,7	
Crushed aggregate		77,6		80,2		77,6		77,8		72,1
Silica fume			8,8	4,8			5,1	1,0	5,4	10,5
Fly ash					5,5	7,6	6,0	3,0	5,6	3,3
Water	4,9	4,2	3,6	2,8	3,1	2,8	3,1	3,4	3,3	2,6
After shooting: In-situ mix constituents in kg/m³ and A/C ratio										
	Mix 1	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**	**Mix 7**	**Mix 8**	**Mix 9**	**Mix 10**
Cement	467	414	357	284	302	272	313	327	320	268
Natural river sand	1 621		1 641		1 775		1 670		1 576	
Crushed aggregate		1 763		1 868		1 750		1 725		1 679
Silica fume			201	112			117	23	121	245
Fly ash					124	170	138	66	125	77
Steel fibre	16	17	21	19	26	23	21	22	18	22
A/(C+sf+fa)	3,3 :1	4,3:1	3,0:1	5,3:1	3,3:1	3,8:1	3,0:1	4,3:1	2,8:1	2,8:1

Table 6 Density and flexural strength

Mix no	Density (*kg/m³*)	Flexural strength $f_{ct,fl}$ (*MPa*)
Mix 1	2 210	5,1
Mix 2	2 289	4,8
Mix 3	2 302	5,7
Mix 4	2 348	6,5
Mix 5	2 296	2,2
Mix 6	2 278	3,3
Mix 7	2 331	3,3
Mix 8	2 239	5,0
Mix 9	2 247	5,5
Mix 10	2 352	4,7

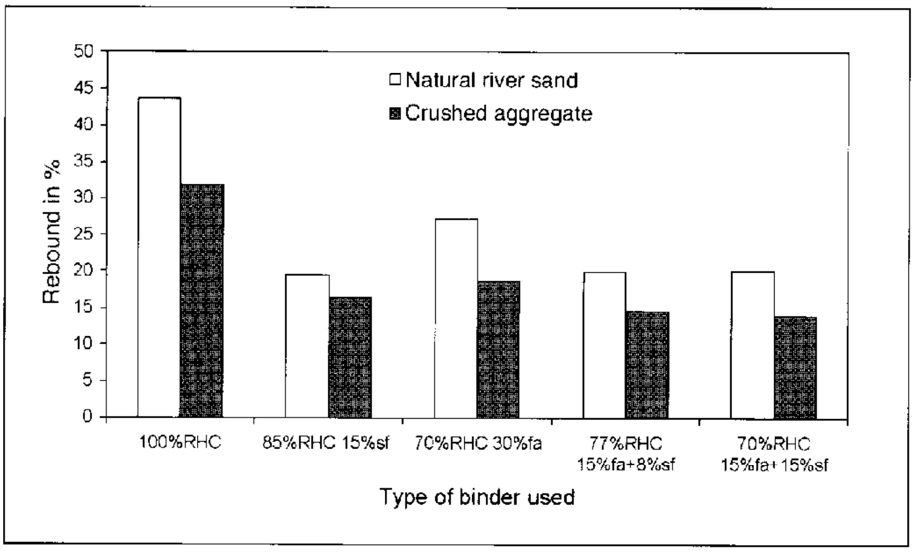

Figure 2 Rebound as a percentage of the weight of dry material

- flexural strength, equivalent flexural strength (according to EFNARC 1996)

RESULTS

Rebound

The material rebound (R_m) as a percentage of the weight of dry material sprayed for all mixes are given in figure 2. These results indicate that up to 45 % of material sprayed with the dry shotcrete method can be lost through rebound. Natural river sand mixtures tend to have higher rebound than crusher aggregate mixtures. This may be the result of a higher proportion of coarse particles in this sand (FM = 3,6), which rebound more easily. This confirms the result of Bindiganavile and Banthia (2000) showing that while both the shape and size of the particles have an effect on rebound, the size of the particles has a much greater influence on the rebound than their shape. The high water demands of the crusher aggregate improve the adhesion and cohesion of the binder (Austine & Robins 1998). When compared to the plain control mixture, 15 % silica fume reduces the rebound by about 50 %. Fly ash does not impart the same cohesive properties than silica fume. The rebound of 30 % fly ash mixture is slightly higher than silica fume. However, the combination of fly ash and silica fume results in a low rebound (less than 15 % if used with crushed aggregate).

Mix composition

From the chemical composition (different oxides) obtained by XRF analysis of shotcrete the in-situ cement, silica fume, fly ash and aggregate contents were determined according to BS 1881: PART 124: 1988. The in-situ mix proportions can be seen in table 5 and these results clearly indicate that the mix composition is significantly altered during the placing process. The aggregate/cement ratio of the majority of the mixes is reduced resulting in an increase in cement content which could increase the strength of the material but would more likely result in more shrinkage cracks forming. The in-situ aggregate/cement ratios for the natural river sand correlates well with the published in-place value of 3,3 that was expected (Addis 1994). The aggregate/cement ratios seems to be higher for the crushed aggregate than for the natural aggregate indicating that crushed aggregate can be used to limit the changes in mix composition that takes place during placing of shotcrete.

The fibre content was determined by washing the fibres out of the rebound and weighing it, thus determining the pro rata in-situ content. Although the fibre content of all mixtures is reduced (which could result in reduced ductility), the reduction is significantly more in the mixes containing no cement extenders (nearly 50 %) than in the mixes with high ash contents (less than 15%). Lower cement contents in the in-situ proportions seems to result in higher fibre contents.

Density

The mean density values of three cores for each mixture are given in table 6. These densities vary between 2 210 kg/m³ and 2 352 kg/m³ but no trends between mix composition and density could be found.

Table 7 Compressive strength for different mixtures

Mix no	Compressive strength (MPa)			
	7days	14 days	28 days	56 days
Mix 1	18	26	36	37
Mix 2	13	17	24	28
Mix 3	17	20	37	32
Mix 4	9	17	20	32
Mix 5	10	10	12	16
Mix 6	9	11	18	17
Mix 7	11	15	20	20
Mix 8	10	19	28	29
Mix 9	14	21	26	29
Mix 10	9	14	19	24

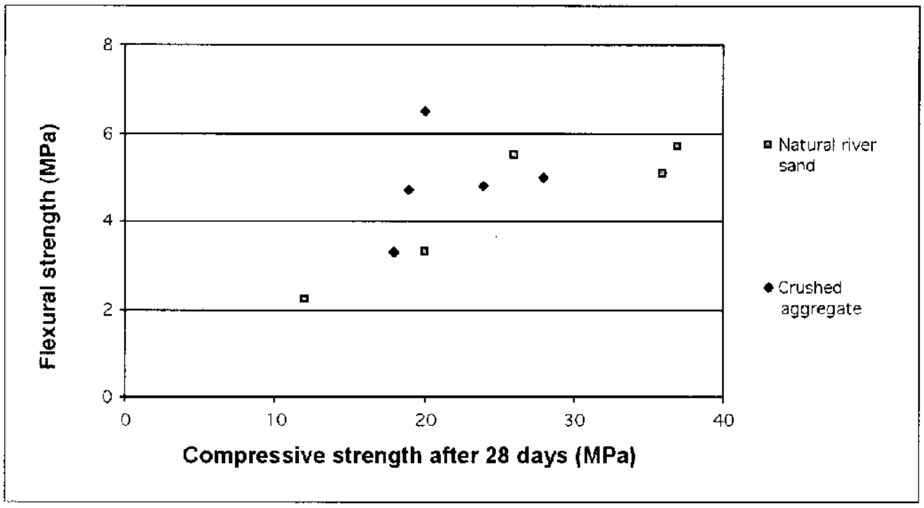

Figure 3 Flexural strength versus compressive strength

Compressive strength

Compressive strength tests were conducted 7 days, 14 days, 28 days and 56 days after casting and the results are listed in table 7. Each result reported in table 7 is an average of three cores (68 mm diameter and 68 mm height). While comparing these results one should keep in mind that different to normal test cubes that are kept in a controlled environment, these samples were left outside under a plastic sheet and only placed in water three days before testing. As a result of the low ambient temperature in the days following the shooting of the panels, the in-situ strengths should be significantly lower than what one would expect from standard cubes cured under water at 25 °C. No correlation could be found between the density and compressive strength of the samples tested.

After seven days the compressive strength varies between 9 MPa and 18 MPa with the majority of the mixes is in the region of 10 MPa. Mix 1 and mix 3, containing natural river sand and either only cement or cement and silica fume, yield significantly higher early strengths than the other mixes.

The strength of all mixes increases with time. The mixes where 30 % of the cement was replaced with fly ash (mix 5 and mix 6) shows very little increase in strength and the mature strengths (as measured after 56 days) of 16 MPa and 17 MPa respectively are less than half that of mix 1. Only three of the mixes (mix 1, mix 3 and mix 4) yielded mature strengths in excess of 30 MPa.

Flexural strength

For each mixture third-point loading tests were conducted at 28 days on three beams (125 x 75 x 600). The mean flexural strengths (modulus of rupture) are given in table 6. The flexural strength of the mixes varied between 2,2 MPa and 6,5 MPa and yet again the mixes with the high ash contents results in low strengths. As indicated in figure 3, there is a weak correlation between the compressive and flexural strength of samples. Although the mixes with low compressive strengths also had low flexural strengths, the mixes with the highest compressive strengths did not have the highest flexural strengths. The fibre content used was too low to have any effect on the flexural strength of the samples.

COST IMPLICATION

Cost estimation

The estimating and costing of the various components relating to the final in-place

Table 8 Cost of 1 m^3 in-situ shotcrete

Material	Unit cost/ton (R)	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
		M_{st1} (kg)	Cost (R)	M_{st2} (kg)	Cost (R)	M_{st3} (kg)	Cost (R)	M_{st4} (kg)	Cost (R)	M_{st5} (kg)	Cost (R)
Cement	700	791	554	651	456	479	335	460	322	438	307
Silica fume	1 250	0		0		84	105	81	101	0	0
Fly ash	100	0		0		0	0	0	0	188	19
NRS	110	3 247	357	0		2 312	254	0	0	2 564	282
CrA	60	0		2 671	160	0	0	2 218	133	0	0
Steel fibre	12 830	55	700	45	576	39	498	37	478	43	553
Water	5	364	2	299	1	259	1	248	1	287	1
Labour	13*	0,264**	3,4	0,226**	2,9	0,190**	2,5	0,189**	2,5	0,213**	2,8
Total cost			**1 616**		**1 196**		**1 196**		**1 038**		**1 165**

Material	Unit cost/ton(R)	Mix 6		Mix 7		Mix 8		Mix 9		Mix 10	
		M_{st1} (kg)	Cost (R)	M_{st2} (kg)	Cost (R)	M_{st3} (kg)	Cost (R)	M_{st4} (kg)	Cost (R)	M_{st5} (kg)	Cost (R)
Cement	700	376	263	445	311	388	271	391	273	354	248
Silica fume	1 250	0	0	46	58	40	51	83	104	75	94
Fly ash	100	162	16	86	9	75	8	83	8	75	8
NRS	110	0	0	2 371	261	0	0	2 285	251	0	0
CrA	60	2 203	132	0	0	2 065	124	0	0	2 073	124
Steel fibre	12 830	37	475	40	511	35	445	38	493	35	447
Water	5	247	1,2	266	1,3	231	1,2	256	1,3	232	1,2
Labour	13*	0,190**	2,5	0,196**	2,5	0,177**	2,3	0,189**	2,5	0,178**	2,3
Total cost			**890**		**1 154**		**903**		**1 133**		**926**

* Unit in rand/hour
** Time in hours

cost of sprayed concrete is a difficult and complex task. The components may be summarised as follows:

- the material cost of the sprayed concrete mix per m^3
- the in-place applied sprayed concrete cost, allowing rebound and overspray
- the cost of collecting, loading, carting away and dumping rebound from a project to a suitable approved site
- the cost of sprayed concrete waste that has to be washed out of pumps and hoses when either breakdowns and delays cause interruption to spraying operations, or at the end of spraying shifts
- the cost of downtime in equipment and personnel when deliveries of sprayed concrete are delayed, or interrupted
- the cost and maintenance of sprayed concrete pumps and equipment, etc (Melbye *et al* 2000)
- the cost of labour.

For the purpose of this study, only the cost of in-place applied shotcrete per m^3 (allowing for rebound) was estimated. The price was calculated as follows:

Let,

D_m
the density of shotcrete given in table 5

$M_{is} = 1m^3 * D_m$
mass of in-place shotcrete

M_{rs}
mass of total rebound

$R_m = M_{rs}*100/(M_{rs}+M_{is})$
the material rebound expressed as percentage

$M_{st} = M_{rs} + M_{is}$
$= 100*M_{is}/(100-R_m(\%))$
mass of total material sprayed

Given that the composition of sprayed material for each mixture is in table 4, the cost of the total material sprayed is calculated as shown in table 8.

Effect of rebound on cost

The effect of rebound on the cost of shotcrete can be seen in figure 4. The following has been found:

- An increase in the rebound resulted in a polynomial increase in shotcrete cost.
- Cost savings in rebound reduction alone can offset the additional costs of the cement extenders.
- The use of cement extenders in shotcrete can significantly reduce the material cost. By utilising cement extenders cost savings of 30 % to 25 % or 26 % to 13 % can be made for natural river sand or crusher aggregate respectively.

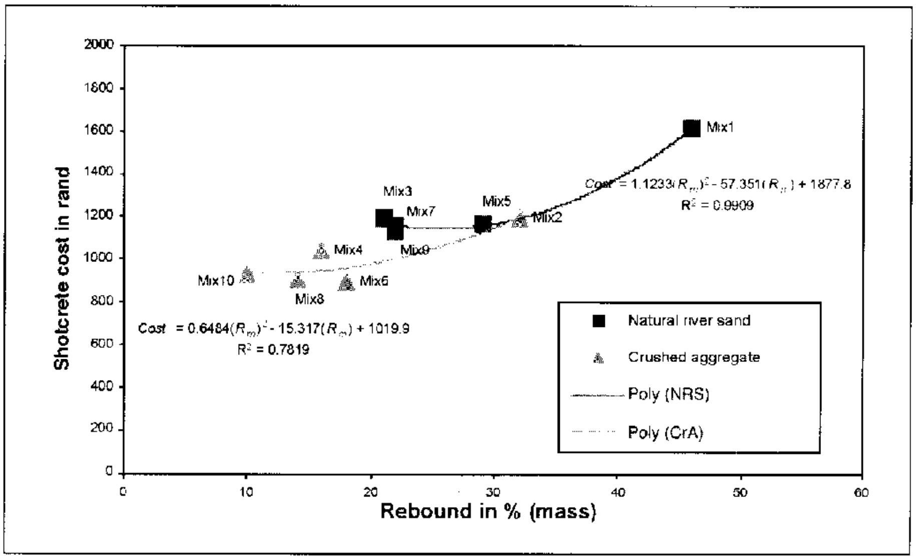

Figure 4 Rebound and shotcrete cost relationship

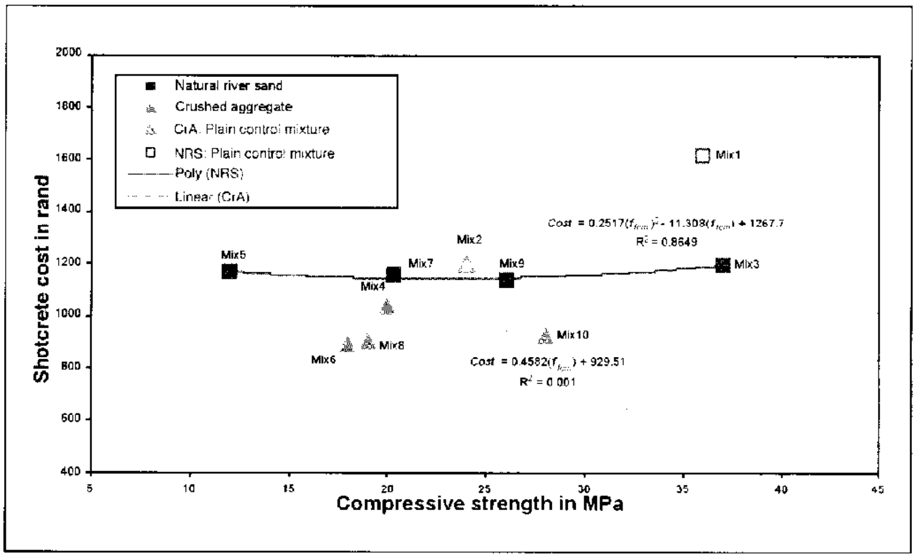

Figure 5 Relationship between compressive strength and shotcrete cost

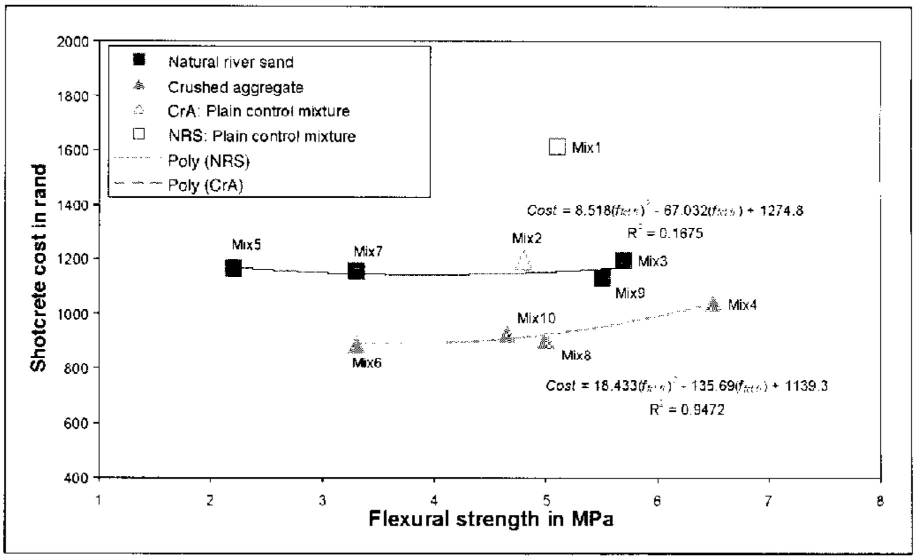

Figure 6 Relationship between flexural strength and shotcrete cost

- The type of aggregate used significantly affects shotcrete cost. When using plain shotcrete (without any cement extenders), a cost saving of 26 % can be obtained by using crusher aggregate in stead of natural river sand.

Effect of compressive strength on cost

The effect of 28 day compressive strength on cost can be seen in figure 5. This graph clearly indicates that the cost (per cubic metre placed) of the natural river sand mixture without cement extenders (mix 1) is significantly higher than any other mixtures. Although the 28-day compressive strength of the reference mixture is higher than the majority of mixes it was found that by replacing 15 % of the cement with silica fume (mix 3) the cost can be reduced significantly without any reduction in compressive strength. Changing the sand to crushed aggregate can further reduce the cost but this could result in a reduction in compressive strength.

Effect of flexural strength on cost

The effect of flexural strength on cost appears in figure 6. These results indicate that using crushed aggregate and cement extenders can increase the flexural strength of the mix while reducing the cost of the mix.

CONCLUSIONS

Based on the test results obtained in this project, the following conclusions can be drawn:

- Although the material cost of aggregates does not have a significant effect on the cost of shotcrete, the type of aggregate used can have a significant effect on the rebound and thus significantly affect the shotcrete cost. When using plain shotcrete (without any cement extenders) a cost reduction of 26 % can be obtained by using crushed aggregate instead of natural river sand.
- The use of cement extenders in shotcrete can reduce the in-situ cost significantly by drastically reducing the rebound. By utilising appropriate cement extenders a cost reduction of 30 % to 25 % and 26 % to 13 % can be achieved with natural river sand and crushed aggregate respectively.

The cost of dry shotcrete can be significantly reduced with the selection and use of appropriate aggregate types and binder combinations. Based on the results obtained in this project crushed aggregate shotcrete incorporating 8 % silica fume and 15 % fly ash (mix 8) is the best mixture to be used in dry shotcrete (taking into account mechanical performance and cost).

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References

Addis, B and Owens G 2001. *Fulton's concrete technology*. 8th ed. Midrand: C & CI.

Addis, B 1994. *Fulton's concrete technology*. 7th ed. Midrand: PCI.

Alexander, M G and Davis, D E 1992. The influence of aggregates on the compressive strength and elastic modulus of concrete. *The Civil Engineer in South Africa*, 34(5):161–170.

Alexander, M G 1998. *Materials science of concrete*, vol VI, edited by J P Skalny. American Ceramics Society.

Armelin, H S and Helene, P 1995. Physical and mechanical properties of steel fibre reinforced dry-mix shotcrete. *ACI Materials Journal*, May–June, pp 258–267.

Austin, S A, Robins, P J and Peaston, C H 1998. Effects of silica fume on dry-process sprayed concrete. *Magazine of Concrete Research*, 50(1):25–36.

Banthia, N and Chan, C 2000. Use of recycled aggregate in plain and fiber-reinforced shotcrete. *Concrete Journal*, June, pp 41–45.

Bindiganavile, V and Banthia, N 2000. Rebound in dry-mix shotcrete: influence of type of mineral admixture. *ACI Materials Journal*, March–April, pp 115–119.

Chan, C and Banhia, N 2000. Use of recycled aggregate in shotcrete. In *Concrete technology for a sustainable development in the 21st century*, edited by O E Gjorv and K Sakai. London and New York: E & FN Spon.

Chi-Tso Chang and Hong-Shiang Liu 1999. Sinotech Engineering Consultants, Ltd. In the *Third International Symposium on Sprayed Concrete*, edited by N Barton *et al*, September, pp 129 149.

Lushiku, M D 2002. *The effect of material composition on dry shotcrete*, ACT Project Report, Midrand.

Melbye, T and Garshol, K F 2000. *Sprayed concrete for rock support*. 8th ed. Edited by MBT International Underground Construction Group, Switzerland.

Ryan, T F 1973. *Gunite: a handbook for engineers*. London: Cement and Concrete Association, pp 18 19.

Ryan, W G 1988. *Concrete 88 workshops*. Sydney: CIA.

The European Federation of National Associations of Specialist Contractors and Material Suppliers for the Construction 1996. *Specification for sprayed concrete*. Final draft by EFNARC, Aldershot.