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Fiber reinforced dry-mix shotcrete with metakaolin

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Abstract

Both material and fiber rebounds in shotcrete are high, and the use of an appropriate mineral admixture is known to alleviate the problem. However, the exact influence of the particle size gradation and shape on the rebound and the ultimate mechanical properties of shotcrete are poorly understood. In the same context, high reactivity metakaolin (HRM), which has shown a great deal of promise in cast concrete, has not been investigated in shotcrete. This study is divided into two parts: in the first part, the effectiveness of four mineral admixtures – fly ash, silica fume, HRM and carbon black – with varying particle size gradations and shapes was investigated from a rebound reduction point of view. In the second part, HRM and silica fume were compared on the basis of the hardened mechanical properties with special emphasis on flexural toughness in the presence of fiber reinforcement. It was found that so far as rebound reduction is concerned, particle size of the mineral admixture is a more governing factor than its shape. Silica fume, due to its ultra-fine particle size, is superior to HRM in reducing rebound, but a blend of silica fume and HRM achieves better overall properties.

Keywords: Dry-mix shotcrete; Metakaolin; HRM

1. Introduction

The use of various mineral admixtures such as fly ash, slag, silica fume, etc., is now becoming commonplace in concrete. Silica fume, often dubbed as a super-pozzolan, is known to impart concrete with high strengths [1–3], reduced permeability and improved long-term durability [4]. More recently, the use of high reactivity metakaolin (HRM) has shown similar effectiveness as silica fume and, benefits such as reduced sulfate attack [5], increase in compressive strength [6] and improvement in the air-void network [7,8] in concrete have been reported. An advantage often cited in the case of HRM is its lighter color over silica fume, which makes it more suitable for applications related to repair and restoration. It has also been reported that in fiber reinforced concrete, mixes with HRM exhibit a greater post-peak energy dissipation capacity and a better fiber-matrix bond [9,10] over silica fume.

HRM is derived from the calcinations of kaolin in the range of 600–800°C. HRM consists largely of amorphous Al_2O_3 and SiO_2 and, the possible hydration reactions are given as follows [11]:

$$\underset{\text{(HRM)}}{AS_2} + \underset{\text{(Portlandite)}}{6CH} + \underset{\text{(water)}}{9H} \Rightarrow \underset{\text{(tetracalcium aluminate hydrate)}}{C_4AH_{13}} + \underset{\text{(calcium silicate hydrate)}}{2CSH}$$

$$AS_2 + 5CH + 3H \Rightarrow \underset{\text{(hydrogarnet)}}{C_3AH_6} + 2CSH$$

$$AS_2 + 3CH + 6H \Rightarrow \underset{\text{(strätlingite)}}{C_2ASH_8} + CSH$$

In dry-process shotcrete, the choice of a mineral admixtures is not so much driven by the ability of the admixture to reduce the heat of hydration, mitigate shrinkage cracking or improve durability and strength, but from the point of view of reducing rebound. In the dry-process shotcrete, both material and fibers may rebound excessively [12–14] and apart from the economical implications, this may results in excessive shrinkage cracking, reduced durability and a lack of water tightness. The benefit of using a mineral admixture in shotcrete is derived either from its ultra-fine particle size and/or a particle shape which modifies the rheology of the fresh material being sprayed.

Rheology of a fresh shotcrete mix is often characterized by its yield stress (τ_0) and viscosity (η). Replacement

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of cement with fly ash is known to reduce the yield strength (τ_0) while very little change is observed in the viscosity (η) [15]. Fly ash, thus makes the paste more workable and its effect on concrete is similar to that of adding more water. The spherical particles act like ball-bearings and improve both the flowability and placeability of the mix. Cabrera and Wooley [16] observed better compaction and reduction in rebound in shotcrete with 30% fly ash. They also confirmed a reduction in the yield stress through a lower build-up thickness.

Mixes containing silica fume, on the other hand, are cohesive and silica fume may reduce the viscosity of cement paste by up to 50% [17]. However, in the case of silica fume, the yield value is nearly constant until a threshold value is reached and then it increases dramatically [18]. Ivanov and Roshavelov [19] concur with this and report that with an increase in the silica fume content, both the parameters τ_0 and η decrease until a threshold value is attained after which a steep increase in these characteristics occurs. On account of these rheological modifications, silica fume is known to dramatically reduce the rebound and its use in shotcrete has become almost universal [20]. Fig. 1 illustrates the effect of several mix parameters including silica fume on the fresh shotcrete rheology.

Studies of the influence of HRM on the rheology of concrete are limited in number. Bai et al. [21] noted a substantial reduction in workability of cement pastes when HRM was added at 15% by weight of cement. This reduction could, however, be compensated for, by a tertiary blending with fly ash. Calderone et al. [22] reported that concrete mixtures produced using HRM require less high-range water reducer (HRWR) than silica fume, but yielded equally high strengths.

In the study reported here, HRM was investigated as a mineral admixture in plain and fiber reinforced dry-mix shotcrete and compared with other admixtures both on the basis of rebound and hardened properties including flexural toughness.

2. Experimental procedures

2.1. Materials and mixes

2.1.1. Rebound and build-up studies

It is logical to assume that the fresh properties of shotcrete such as rebound and build-up are affected only by the physical characteristics of the mineral admixture, while its hardened properties are affected both by the physical and the chemical attributes of the admixture. Accordingly, in order to assess the effects of a mineral admixture on the properties of fresh shotcrete, HRM, silica fume, fly ash and carbon black were investigated. These admixtures covered a wide range of particle shapes and mean sizes (Table 1). Scanning electron micrographs of the four admixtures are shown in Fig. 2(a)–(d). The nine mixes chosen to investigate the fresh shotcrete properties are given in Table 2. As seen, for each of the four admixtures, two dosage rates of 5% and 10% by mass of cement were investigated. Flat-ended steel fibers at a dosage rate of 60 kg/m^3 were added to each of the nine mixes. The mixes contained 19% by mass of (CSA Type 10) cement, and 65% and 16%, respectively, of sand and rounded 3/8 in. aggregate. The mixes were shot onto wooden forms placed vertically as well as in an overhead position to simulate the two most common conditions of spraying in practice. Build-up was measured from the overhead shotcreting while rebound of material and fibers was calculated for the panels shot vertically.

2.2. Studies on mature shotcrete

For this study, only HRM and silica fume were studied. Two dosage rates of 5% and 10% by weight of cement were investigated. Two types of steel macro-fibers – one with flat ends and the other with hooked ends – were also studied, which yielded a total of 12 mixes as seen in Table 3. Note that a blend of HRM and silica

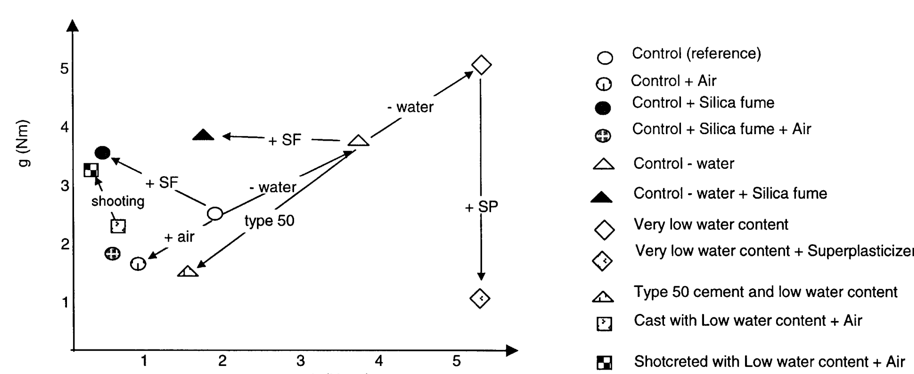


Fig. 1. Effect of mix composition on the yield resistance (g) and viscosity (h) of fresh shotcrete [28].

Table 1
Properties of mineral admixtures investigated

Admixture	Mean particle size (μm)	Specific surface area (m^2/g)	Particle shape
Carbon black	0.05	44	Spherical
Silica fume	0.10	20	Spherical
HRM	<2.5	10	Book structure
Fly ash	10	0.5	Spherical
Cement[a]	50	0.3	Flaky

[a] Listed for reference.

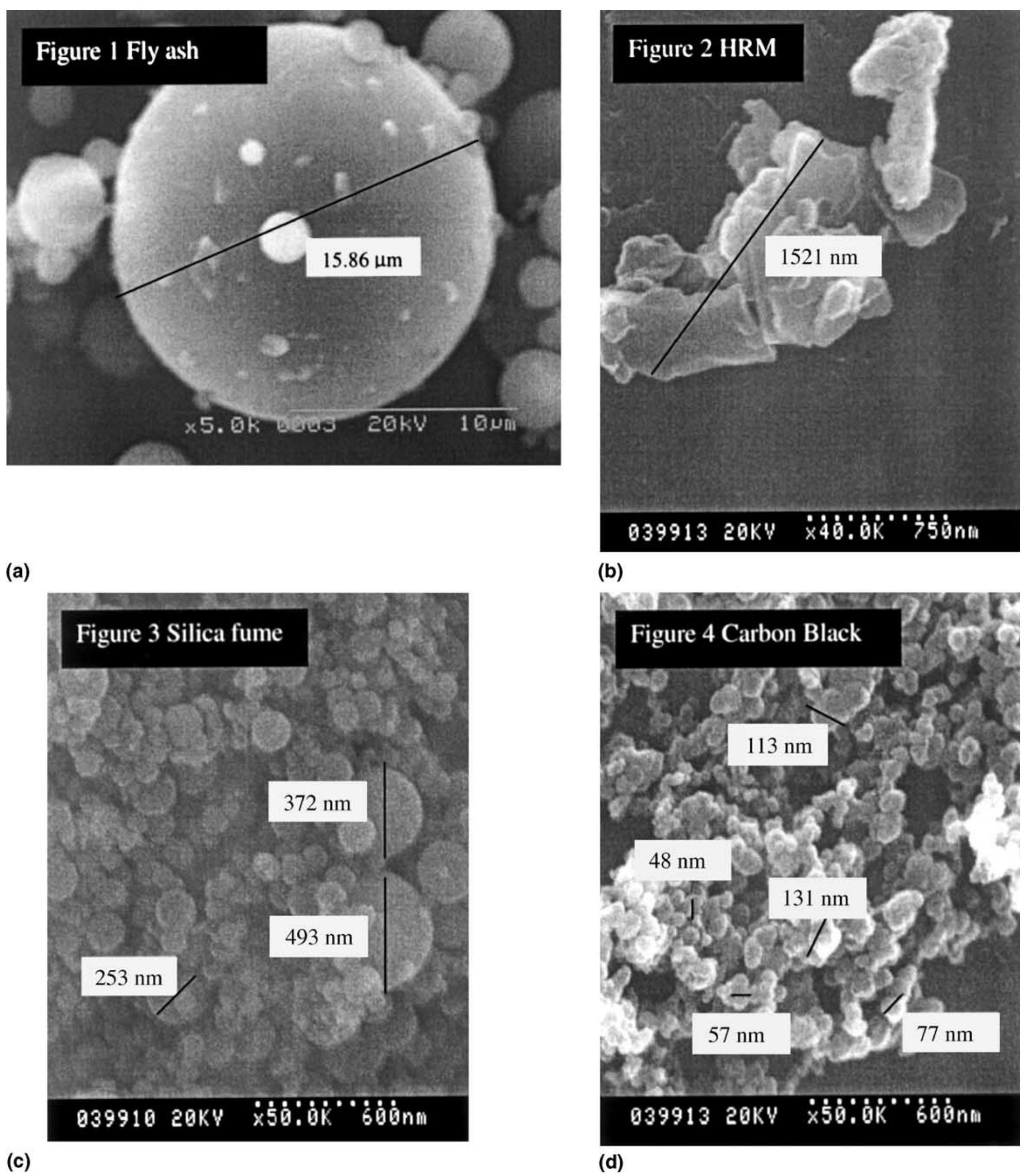


Fig. 2. Scanning electron micrographs of the four admixtures.

Table 2
Mixes investigated for fresh shotcrete properties

Mixture designation	Water content (kg/m^3)[a]	Cement (kg/m^3)	Fiber flattened end (kg/m^3)	Admixture			
				Fly ash (kg/m^3)	Carbon black (kg/m^3)	Silica fume (kg/m^3)	HRM (kg/m^3)
Control-FE	193	437	60	0	0	0	0
FA-5-FE	230	415	60	22	0	0	0
FA-10-FE	272	393	60	44	0	0	0
CB-5-FE	245	415	60	0	22	0	0
CB-10-FE	228	393	60	0	44	0	0
SF-5-FE	218	415	60	0	0	22	0
SF-10-FE	232	393	60	0	0	44	0
HRM-5-FE	260	415	60	0	0	0	22
HRM-10-FE	213	393	60	0	0	0	44

[a] Determined from heat drying fresh shotcrete.

fume was also investigated at a dosage rate of 5% each. All mixes were prepared with pre-bagged dry-mix materials similar to those described before.

3. Shotcreting and specimen preparation

All mixes were shot using an ALIVA 246 dry-mix machine. The machine has a rotating barrel with a 3.6 l eight pocket drum. With a 50 mm internal diameter hose, the machine can place up to 4 m^3/h of shotcrete. Mixes were shot on prepared wooden forms with tapered edges (600 mm × 500 mm × 100 mm) mounted on the wall of a chamber (Fig. 3) designed specifically for shotcrete research. Right after shooting, about 2 kg of in situ material was taken from the panels to determine its in situ water content through heat drying (see Table 2).

In the dry-mix shotcreting process, the control of water rests solely with the nozzleman who falls back upon his experience and judgement. The approximate water content is assessed only after the mix has been placed. If too much water is added, the mix loses its consistency and becomes too runny and sloughs off. Too little water on the other hand, makes the mix very stiff and increases the rebound. Clearly, in order to compare different mixes, they must be standardized on the basis of their consistency. This was done with a digital penetrometer [23], which had a 9 mm ϕ needle. Consistency is indicated by the yield plateau that begins at a penetration of half the needle diameter. Shotcrete panels were tested for penetration resistance immediately after each shoot (Fig. 4) and only those specimens that registered a penetration resistance in the range 2 ± 0.5 MPa were considered for further study. This value of yield resistance is considered ideal for both fresh and mature

Table 3
Mixes investigated for toughness response

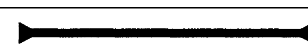
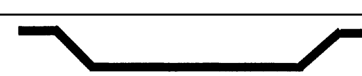
Mix mix composition (as batched)	Fiber (kg/m^3)	Silica fume (kg/m^3)	HRM (kg/m^3)
Flat-end fiber (30 mm long, 0.85 mm wide and 0.50 mm thick)			
Control-FE	60	–	–
SF-5-FE	60	21.85	–
HRM-5-FE	60	–	21.85
SF-10-FE	60	43.70	–
HRM-10-FE	60	–	43.70
SF-5-HRM-5-FE	60	21.85	21.85
Hooked-end fiber (30 mm long and 0.50 mm ϕ)			
Control-HE	60	–	–
SF-5-HE	60	21.85	–
HRM-5-HE	60	–	21.85
SF-10-HE	60	43.70	–
HRM-10-HE	60	–	43.70
SF-5-HRM-5-HE	60	21.85	21.85

Fig. 3. Shotcreting in progress.

Fig. 4. Measurement of penetration resistance of shotcrete soon after placement.

shotcrete performances. Specimens that did not meet this criterion were rejected.

Rebound was measured after each shoot by collecting material on plastic sheets which were later weighed. This weight (W_m) was assessed as a percentage of the total material shot (W_s) and expressed as material rebound ($R_m = 100 \times W_m/W_s$). The fibers were separated using a magnet and weighed (W_{fr}). The total weight of fibers shot (W_{fs}) was evaluated based on the volume fraction of the fibers in the mix design (V_f) as

$$W_{fs} = V_f W_s \rho_s/\rho_c,$$

where ρ_s and ρ_c are, respectively, the unit weight of steel and concrete. Once again, fiber rebound was calculated as the percentage of total material shot that was collected on the plastic sheet. Thus, fiber rebound, R_f, is given by

$$R_f = 100 W_{fr}/W_{fs}.$$

4. Tests on matured shotcrete

For the 12 mixes in Table 3, after 10 days of moist curing, beams were sawn and cores were drilled out of the panels which were then left to be cured for an additional 18 days. The beams were tested under four-point bending as per ASTM C1018 [24] as seen in Fig. 5. The

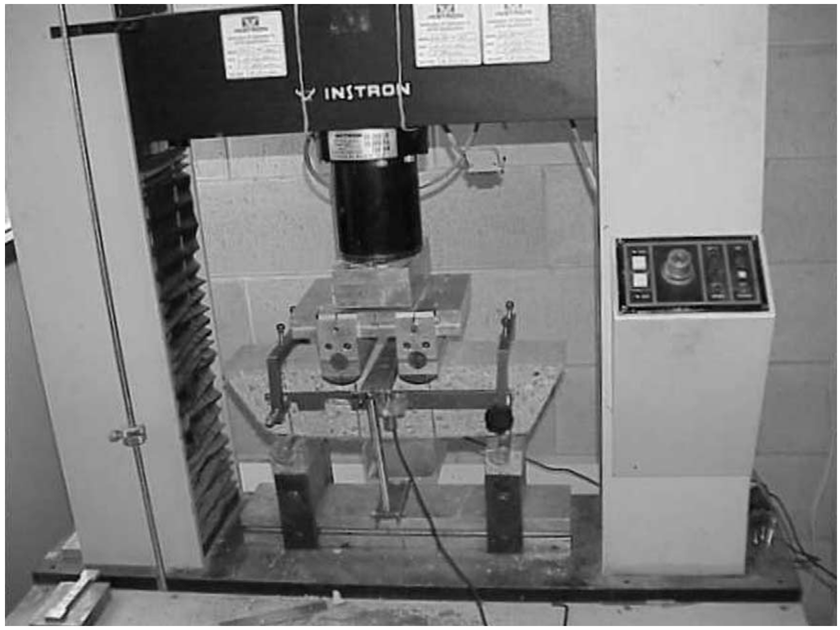


Fig. 5. Flexural toughness test on fiber reinforced shotcrete beams.

resulting load deflection curve was analyzed using the ASTM C1018 as well as the JSCE-SF4 [25] procedures. The reason for this was the general lack of confidence in the ASTM C1018 analysis procedure where toughness parameters are calculated based on energy absorption to 'first crack' point on the curve, and locating this point on the curve is arbitrary and highly subjective [26].

The cylinders were tested according to ASTM C42 and subsequently corrected for size as per ASTM C39. Selected mixes were also analyzed for boiled absorption and permeable voids according to ASTM C642.

5. Results

5.1. Fresh shotcrete properties

5.1.1. Consistency

Fig. 6 shows some penetration plots obtained from shoots that were deemed acceptable; notice that all mixes met the criterion for standard consistency, i.e., a plateau resistance in the range of 2 ± 0.50 MPa. As mentioned before, shoots that did not meet this criterion were rejected.

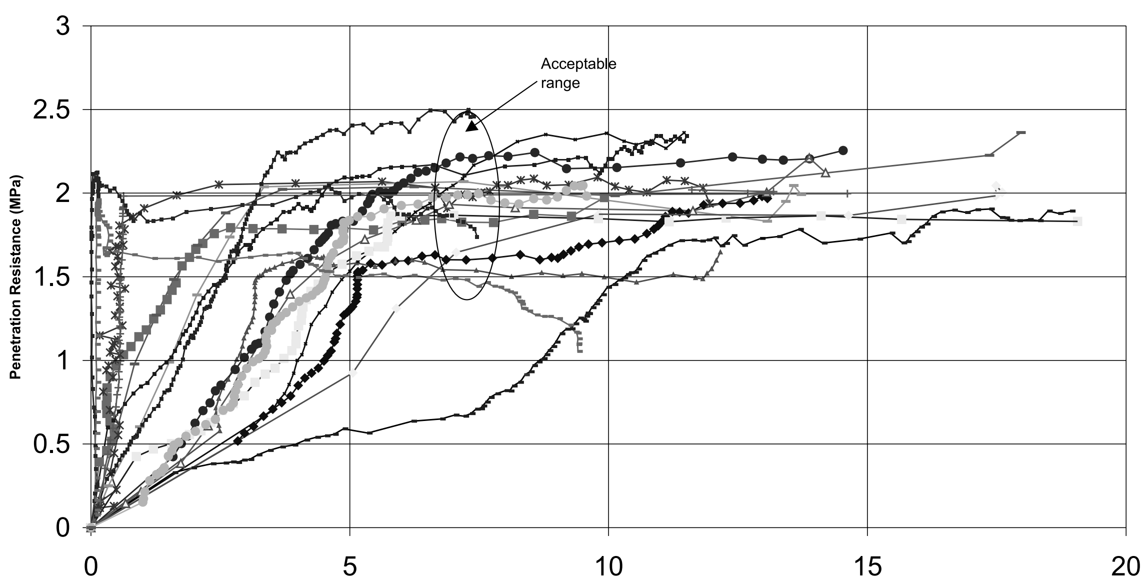


Fig. 6. Penetration resistance plots.

5.2. Rebound

The rebound data for mixes listed in Table 2 are plotted in Fig. 7. It may be noted that fiber rebound was always greater than the material rebound and also increased proportionally with it. HRM, silica fume and carbon black reduced the rebound of material and fibers, and their effectiveness increased with an increase in their dosage rate. Of all the mixes, the most efficient was the one with carbon black at 10% cement replacement rate. Incorporating HRM reduced rebound over that of the control mix, but the results were not as promising as those were for silica fume or carbon black. This suggests that the finer the admixture, the lower the rebound. Fly ash was an exception in this regard; 5% fly ash addition rates produced a reasonably low rebound, but the mix with 10% replacement rate showed an anomalous adverse effect. Rebound values are further plotted as functions of mean admixture particle size in Figs. 8 and 9 for the 5% and 10% dosage rates, respectively.

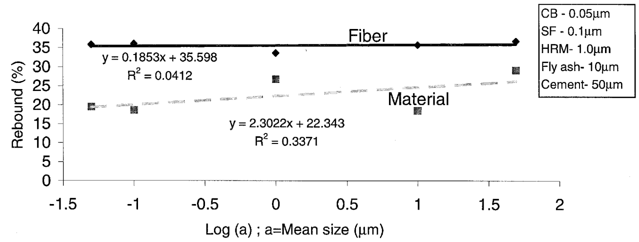


Fig. 8. Variation of rebound with admixture particle size for 5% replacement rate.

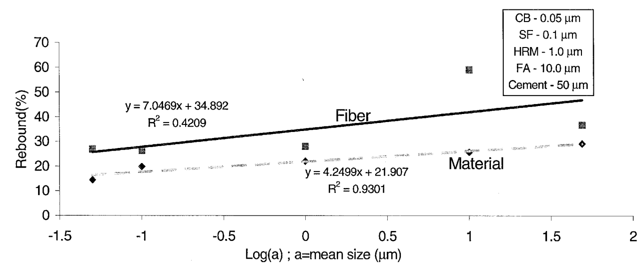


Fig. 9. Variation of rebound with admixture particle size for 10% replacement rate.

5.3. Overhead build-up

Build-up thickness is defined as the maximum thickness to which a material may be placed in a stable manner during shotcreting without a drop or collapse. It is important from both practical and economical points of view, because lower the build-up, greater will be the number of passes required to achieve a given placement thickness. A single pass application is clearly the most preferred. Fig. 10 presents the build-up obtained from overhead shooting for the mixes listed in Table 2. Once again, silica fume and carbon black (at 10% cement replacement) produced greater build-up thicknesses than the other admixtures, and carbon black performed marginally better than silica fume. Overhead build-up also increased with an increase in the admixture dosage rate.

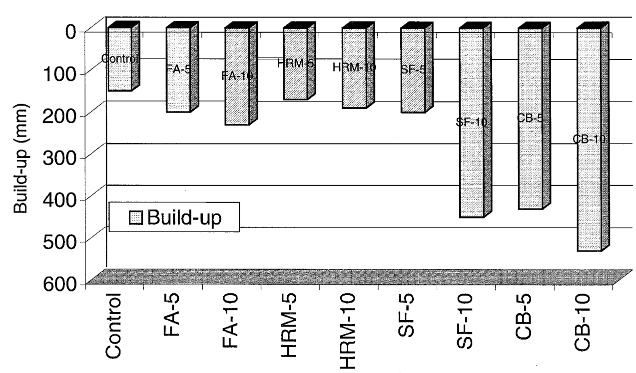


Fig. 10. Overhead build-up with different admixtures.

5.4. Hardened shotcrete properties

5.4.1. Compressive strength and permeable voids

Table 4 presents the compressive strength at 28 days and total permeable voids for the mixes described in Table 3. Note that the water/binder ratio is not constant and is adjusted by the nozzleman through a visual assessment of consistency. Note also that the presence of both 'superpozzolans' silica fume and HRM did not enhance the compressive strength in any significant way. The compressive strengths are plotted as a function of the water/binder ratio and also, the volume of permeable voids in Fig. 11. Notice that a far better correlation is achieved with permeable voids (Fig. 11(b)) rather than with water/binder ratio (Fig. 11(a)). This trend has previously been reported for dry-mix shotcrete over a wide range of mix composition [27].

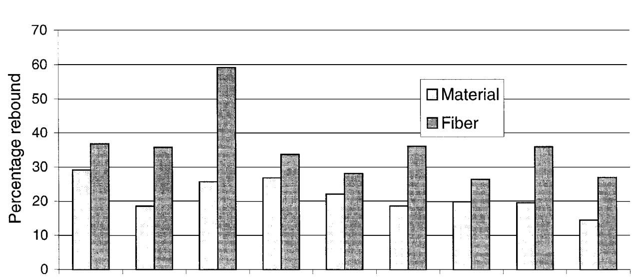


Fig. 7. Material and fiber rebound for various admixtures.

The compressive strengths from the mixes in Table 2 are given in Table 5. These results (and those in Table 4) indicate that the pozzolanic nature of a mineral

Table 4
Compressive strength, boiled absorption and permeable voids

Mix description	w/b ratio[a]	Permeable voids	Boiled absorption (%)	f'_c (MPa)	Fiber rebound (%)
With flattened-end steel fiber					
Control	0.40	13.93	6.13	51.30	36.73
5% silica fume	0.50	15.75	7.14	53.90	30.06
5% HRM	0.41	13.45	5.91	46.30	33.64
10% silica fume	0.45	15.37	6.92	50.70	26.41
10% HRM	0.54	16.20	7.25	55.20	28.06
5% SF + 5% HRM	0.40	15.95	7.22	50.80	30.03
With hooked-end steel fiber					
Control	0.41	14.30	6.35	66.00	38.50
5% silica fume	0.50	15.28	6.95	49.30	36.97
5% HRM	0.46	15.65	7.01	48.80	39.80
10% silica fume	0.46	14.63	6.57	56.10	26.05
10% HRM	0.56	17.35	8.00	51.10	30.39
5% SF + 5% HRM	0.46	18.38	8.41	49.50	34.73

[a] Water/binder ratio.

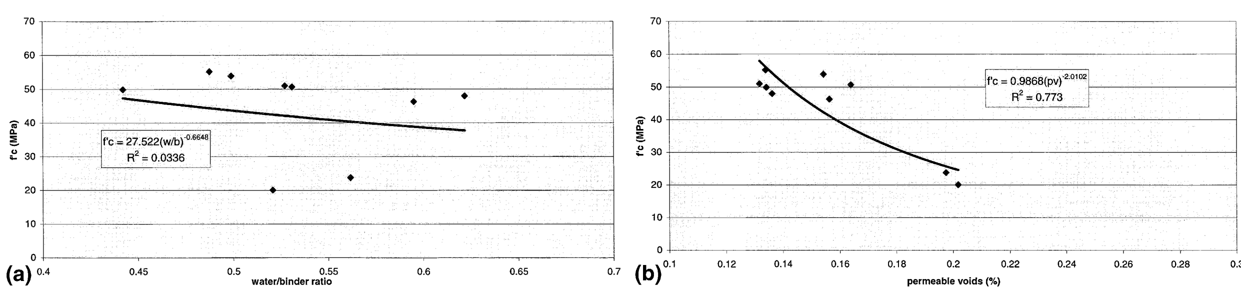


Fig. 11. Correlation between compressive strength and (a) water/cement ratio or (b) volume of permeable voids.

Table 5
Compressive strength, boiled absorption and permeable voids for mixes containing various mineral admixtures (described in Table 2)

Mix	Compressive strength (MPa)		Mix porosity	
	7 day	28 day	Boiled absorption (%)	Permeable voids (%)
Control-FE	37.30	51.30	5.86	13.42
FA-5-FE	43.40	51.00	5.84	13.18
FA-10-FE	34.80	48.00	6.10	13.62
CB-5-FE	19.20	23.80	9.33	19.75
CB-10-FE	20.00	20.10	9.61	20.18
SF-5-FE	46.30	53.90	6.96	15.42
SF-10-FE	29.90	50.70	7.40	16.39
HRM-5-FE	37.15	46.30	6.95	15.63
HRM-10-FE	37.58	55.20	5.86	13.39

admixture plays only a secondary role in dry-process shotcrete and its primary function is to modify the rheology. These aspects are further discussed later.

5.4.2. Flexural response

Representative load–displacement curves for shotcrete beams reinforced with flat-end and hooked-end steel fibers (Table 3) are shown in Figs. 12 and 13, respectively. Toughness indices and residual strength factors calculated as per ASTM C1018 are plotted in Figs. 14 and 15, respectively, for the flat-end steel fiber and the hooked-end steel fiber. Flexural toughness factors calculated as per JSCE SF4 procedure are given in Table 6.

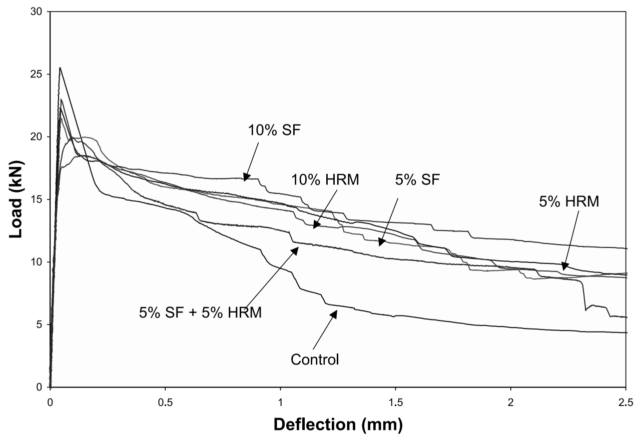


Fig. 12. Representative load displacement curves for shotcrete with the flat-end fiber.

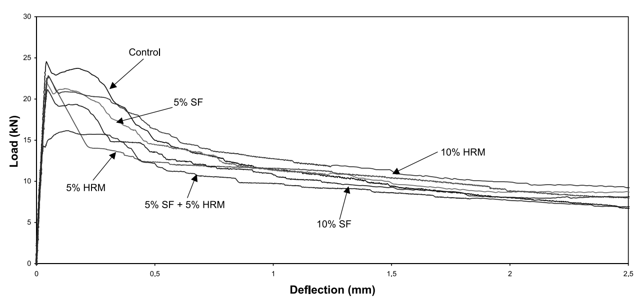


Fig. 13. Representative load displacement curves for shotcrete with the hooked-end fiber.

6. Discussion

6.1. Fresh properties and rebound

Rebound in dry-mix shotcrete is expected to increase with an increase in the viscosity of the freshly applied substrate. On the other hand, build-up increases proportionately with the yield value of shear flow [28]. The need for admixtures arises because such simplistic measures as increasing water content to lower the viscosity also reduces the shear resistance. An ideal admixture, therefore, is one that reduces the viscosity while maintaining or increasing the yield strength (cohesiveness). This concept has been schematically illustrated in Fig. 1.

The mechanisms of aggregate rebound have been described in detail in [29,30]. As seen in Fig. 7, of the four mineral admixtures tested, carbon black was the most effective in reducing rebound as well as achieving the maximum build-up in a single pass application. This indicates the benefits of increasing the fineness of the admixture added, and indeed, such a trend is noticed in Fig. 9 for 10% replacement levels.

The four admixtures varied also in their particle shapes. One notes that in spite of its flaky structure, HRM performed better than fly ash; the latter was not seen to alter the rebound and build-up over the control mix. Given that fly ash and cement have similar fineness, it appears that the mean particle size has a far greater influence on modifying fresh shotcrete rheology than the particle shape. Nehdi [31] studied the effect of limestone microfiller and silica fume on rheology of cement pastes and concluded that their presence increased the yield strength and reduced its viscosity with silica fume having a greater overall effect. Further, Nehdi et al. [32] reported that limestone microfilller increases yield and decreases viscosity in tertiary blends having silica fume. Bearing in mind that limestone microfillers (mean size = 3 μm) are similar to HRM, it corroborates the observations in this study where in both HRM and silica fume were seen to reduce rebound and increase build-up with silica fume being more efficient of the two.

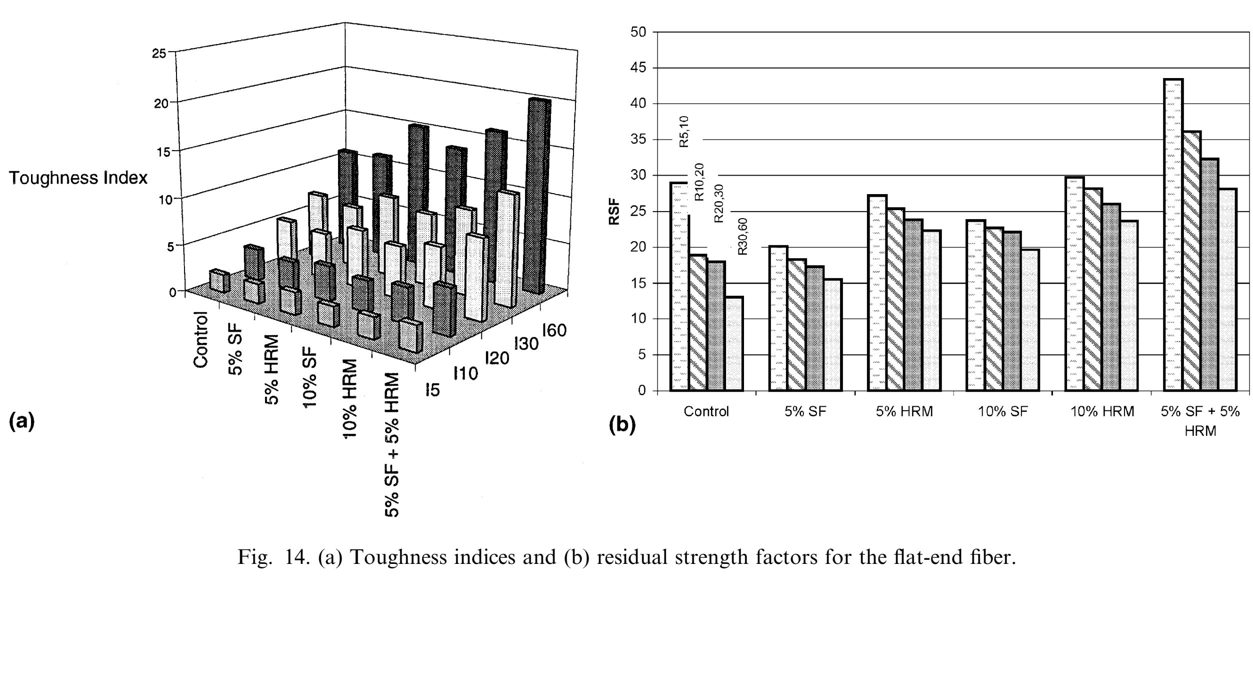
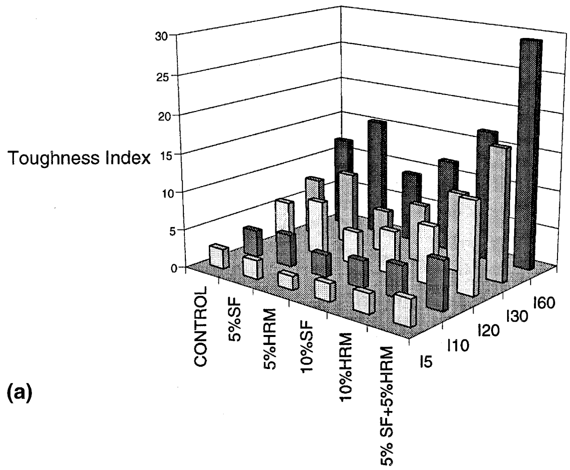


Fig. 14. (a) Toughness indices and (b) residual strength factors for the flat-end fiber.



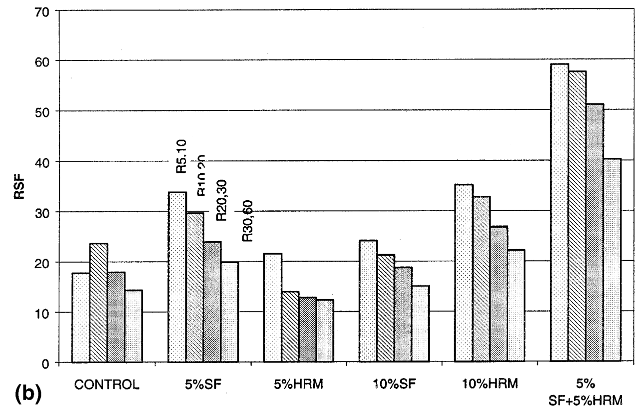


Fig. 15. (a) Toughness indices and (b) residual strength factors for the hooked-end fiber.

Table 6
JSCE flexural toughness (FT) factors

Mix	C	5% SF	5% HRM	10% SF	10% HRM	5% SF + 5% HRM
Flat-end fiber						
FT (Mpa)	3.26	4.56	4.56	4.79	4.33	3.99
Hooked-end fiber						
FT (Mpa)	4.13	3.97	3.90	3.75	4.32	3.22

Similarly, reduction in rebound was noted in triple-blended shotcrete mixes having both HRM and silica fume (refer Table 4).

Fiber rebound in dry-mix shotcrete is considerably more than the overall material rebound (Fig. 7). The influence of fiber geometry on its rebound, unfortunately, is not clear. Armelin [23] showed that for straight fibers, rebound is proportional to the modified fiber aspect ratio $l/\sqrt{d}$). This was verified in the present study, where hooked-end fibers ($l/\sqrt{d} = 42.42\ \mathrm{mm}^{0.5}$) were seen to rebound more than the flat-end fibers ($l/\sqrt{d} = 34.97\ \mathrm{mm}^{0.5}$). However, the fiber geometry plays a critical role in influencing its rebound and hence its suitability as reinforcement in dry-mix shotcrete as has been reported by Banthia et al. [13].

6.2. Strength

It appears from the strength values that in dry-mix shotcrete, the pozzolanic nature of a mineral admixture plays only a secondary role and its primary function is to modify the rheology (Tables 4 and 5). With the exception of mixes having an inert filler, i.e., carbon black, all mixes regardless of the admixture type exhibited strengths similar to the control mix. This is because of the varying amounts of water needed at the nozzle for various admixtures (refer to Table 2) to meet the penetration requirement of 2 ± 0.50 MPa. This diversity in the water demand negates any benefits accruing from the pozzolanic reaction, and follows clearly from our understanding of cast concrete where silica fume is known to yield high strengths only when low water/cement ratios are combined with the presence of a superplasticizer. For carbon black, although Detwiler and Mehta [33] reported no loss in compressive strength due to its inert nature, the low values of strength seen in the present study may be explained through the presence of higher volumes of permeable voids. Being electrically active in nature, it is possible that in the process of spraying, carbon black attracts and traps a higher volume of air bubbles leading to an eventual loss in strength.

6.3. Fiber shotcrete and toughness

The toughness response of steel fiber reinforced dry-mix shotcrete is intimately related to the rebound issue. The in situ fiber volume fraction decreases with an increase in fiber rebound, and therefore, in spite of equal volume fractions in the design mix, wide variations in toughness indices and flexural toughness factors were noted.

As is clear from Table 4, silica fume is more efficient in reducing fiber rebound than HRM, and this applies to both fiber types. For the flat-end fiber, that has in relative terms, a somewhat lesser tendency to rebound than the hooked-end fiber, the benefit of HRM towards achieving a superior set of toughness indices and residual strength factors is evident even at lower dosage of 5%. For the hooked-end fiber, on the other hand, which has a greater tendency to rebound, at 5% HRM replacement, the adverse effects of a higher rebound overshadow the beneficial effects of reduced matrix brittleness. At 5% replacement rate, therefore, HRM does not result in an improvement in toughness indices or the residual strength factors for the hooked-end fiber. At a higher dosage rate of 10% HRM, a reasonably low rebound combined with a sharp decrease in the matrix brittleness produces higher toughness indices and residual strength factors for both fibers.

It emerges from the argument presented above, that the need to reduce rebound conflicts with the need to produce matrices with minimal brittleness. For example, silica fume, which is the most efficient in reducing rebound, is also the one that significantly increases the matrix brittleness [9]. The solution therefore exists in properly blending admixtures and producing tailor-made shotcrete mixes. Indeed, when the blends (5% SF and 5% HRM) are considered, a much better performance is evident (Figs. 14 and 15). In a blend, SF provides a much needed rebound reduction, and the presence of HRM provides a reduction in matrix brittleness. Together, therefore, for both fibers types they produce composites that have toughness characteristics that surpass all others. This reasoning is further supported indirectly by data from Dubey and Banthia [9] who showed that in cast concrete a blend of 5% HRM and 5% SF is not as effective as 10% HRM alone. In the case of cast concrete, the beneficial effects of SF in rebound reduction remain obscured since there is no shooting involved, and hence the blends are not as efficient.

Interestingly, the flexural toughness factors as per JSCE SF-4 (Table 6) do not capture the above trends. This is so because the JSCE toughness factors are calculated at a large displacement of 2 mm (span/150), and all the effects that occur at small to medium displacements due to instability and matrix brittleness, therefore, remain obscured. Clearly, an analysis with a wider range of specimen displacements is needed in order to capture trends in post-peak instability, and this is provided by the ASTM method.

7. Conclusion

1. Mineral admixtures are highly efficient in controlling rebound in dry-mix shotcrete. Particle size of the admixture is of a greater importance than its shape, and finer the particles, greater is the effectiveness of the admixture in controlling material and fiber rebound.

2. A mere reduction in rebound does not ensure high performance in matured fiber reinforced dry-mix shotcrete. While silica fume is very successful in reducing fiber rebound and ensuring a high in situ fiber volume fraction, the brittleness introduced into the matrix due to silica fume, adversely affects the toughness characteristics. The solution, therefore, is in blending SF with another admixture, such as HRM, whereby a significant reduction in fiber rebound is achieved without a compromise in the toughness and deformability.

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