HIGH-REACTIVITY METAKAOLIN AND SILICA FUME IN STEEL FIBER REINFORCED DRY-MIX SHOTCRETE

by

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B.Tech., Institute of Technology, Banaras Hindu University, 1996

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
DEPARTMENT OF CIVIL ENGINEERING

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October, 1998

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Abstract

Shotcrete as a construction material has been in use since the early part of this century. It is increasingly being used in new construction and in repair and rehabilitation of older structures. Its use spans a broad array of applications such as in tunnel linings, slope stabilization and in the repair of marine, highway and railway structures. Shotcrete is easy to apply, does not require complicated equipment and if properly applied, it is sufficiently durable.

However, one of the major drawbacks with shotcrete in general and dry mix shotcrete in particular, is the inordinately high amount of rebound that occurs during production. In addition to being an economic liability, rebound results in such adverse conditions as high in-situ cement content and low in-situ fiber volume fraction. The high cement content, apart from being detrimental to shotcrete durability is also of particular concern from the environmental point of view. Cement production is highly energy intensive and therefore, in the last couple of decades, the use of industrial by-products as supplementary cementing admixtures has gained popularity. Considerable research on the use of silica fume, fly ash and blast furnace slag in shotcrete has already been carried out and today, most shotcrete in North America contains one or more of these admixtures. In the case of silica fume, it is seen to impart all of its known benefits in cast concrete to shotcrete, but the main attraction of silica fume for use as an admixture in shotcrete is in the dramatic reduction in rebound through significant increase in cohesiveness.

High strength cementitious composites suffer from an inherent lack of toughness and silica fume dry mix shotcrete is no exception. Silica fume shotcrete beams show
considerable instability under static flexural loading. In addition, all concrete and shotcrete structures having silica fume develop a darker color, which is undesirable from an architectural point of view. In light of above drawbacks witnessed with silica fume addition to dry mix shotcrete, there is a need to search for a substitute to silica fume, which shares all its benefits but none of its demerits.

This search narrowed down to a relatively new development in the field of supplementary cementing admixtures namely, High Reactivity Metakaolin (HRM). It is a refined by-product of the glass manufacturing industry. As it has shown very promising results when used as a cement replacing admixture in cast concrete, it was hoped that the same benefits namely, high strength, better durability, pleasing aesthetics and perhaps most significantly, a higher fracture toughness, would accrue from its use into dry mix shotcrete as well. With this in mind, this research investigates the use of High Reactivity Metakaolin in fiber reinforced dry-mix shotcrete and compares the effects of HRM with those of silica fume.

This research looks into the changes in microstructure, fresh and hardened shotcrete properties resulting due to the presence of HRM and silica fume in the matrix. At the dosage levels in this investigation, the portlandite (CH) consumption of HRM is lower than that of silica fume. This is as a result of the higher SiO₂ content in silica fume. It is found that HRM does not reduce the material and fiber rebound as substantially as does silica fume. It appears that silica fume imparts more cohesiveness to the fresh dry mix shotcrete compared to HRM and this not only means lower rebound but also higher build-up thickness.
Steel fibers bearing two different types of geometry were included in this study to investigate the flexural toughness of HRM-dry mix shotcrete. However, due to the inherent lack of control on water content in the dry process of shotcreting, it was not possible in this study to examine the effect of HRM on shotcrete toughness vis à vis silica fume.

An investigation was carried out on the influence of admixtures, especially of their particle size and shape, on the fresh dry mix shotcrete properties including rebound and build-up. It was found that while the shape of the admixture particles did not significantly affect these properties, size and specific surface area of the admixture particles played a decisive role in affecting rebound and the overhead build-up. Admixtures comprising of finer particles reduced rebound substantially and among the fillers investigated, carbon black, which is finer than silica fume, outperformed all others. In general, it appears that those pozzolans that have spherical particles and higher specific surface area are ideally suited for use as supplementary cementing materials in dry mix shotcrete.
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Chapter – 2 Literature Review

\(a\)  Radius of the contact area formed between the impactor and the substrate

\(c\)  Radius of the elastic-plastic boundary formed around the hydrostatic core

\(h\)  Displacement of the impactor into the substrate

\(p\)  Static contact stress between the impactor and the substrate

\(R\)  Radius of the impactor

\(u\)  Displacement incurred by the substrate in order to accommodate the dislocated volume due to displacement ‘\(h\)’ of the impactor
Acknowledgement

I wish to thank my research advisor Dr. Nemkumar Banthia, for having given me the opportunity to work in a very inspiring environment such as the Civil Engineering Materials laboratory, here at U.B.C. His help in planning, organizing and numerous discussions in the course of this research has been invaluable. I am especially grateful for the freedom I enjoyed working with him which has helped me realize my best potential.

I should also like to thank Dr. Cheng Yan for his constant support and timely advice throughout this research program.

I am grateful to Mr. David Flynn, who helped me prepare all my samples and I thank the technicians who have maintained all the equipment I used. Mr. Hugo Armelin and Mr. Prabhakar Gupta have drawn on their experience in this field to help me avoid major pitfalls and for this I thank them.

I thank my colleagues for making this research an enjoyable experience.
Chapter 1 – Introduction

1.1 Shotcrete
Sprayed concrete may be defined as mortar or concrete pneumatically projected into place [5]. The earliest evidence of shotcrete is widely acknowledged to be due to Carl Akeley, who obtained patents for a ‘cement gun’ to make models of animals [13]. Then known as ‘gunite’, the process involved placing a dry sand/cement mixture in a pressurized chamber whence it was conveyed pneumatically to a nozzle where water was added. It was therefore a ‘dry-mix’ process (Fig. 1.1). The wet-mix process for shotcreting where compressed air is introduced to fresh concrete to propel it into place (Fig. 1.2), was developed only after the Second World War. The popularity of the wet process issues out of the reduced rebound, better control on water and reduced dust levels whereas, the dry process has been found particularly suited for shotcreting areas which are relatively inaccessible for larger equipment like mixers, batching plants and trucks.

1.2 High-reactivity metakaolin (HRM)
One of the most promising developments in supplementary cementing materials in recent times is the advent of high reactivity metakaolin powder. HRM is a white powder, and is highly pozzolanic in character. Though it too is a by-product of an industrial process like other pozzolanic mineral admixtures such as fly ash, slag and silica fume, HRM is better process controlled and hence the batch to batch variations in its physical and chemical characteristics are very small.
Fig. 1.1  Schematic diagram of dry-process shotcreting

Fig. 1.2  Schematic diagram of wet-process shotcreting
HRM powder is white in color, and has significantly smaller particles than cement. The average particle size falls typically between those for cement and silica fume and it therefore lends itself ideally towards triple blending in cast concrete. Being chiefly composed of silica and alumina, both in their amorphous state, and possessing high specific surface area, HRM is highly pozzolanic and conforms to the ASTM C 618, Class N pozzolan specification. It combines with free lime produced as a result of cement hydration and forms further products of hydration such as calcium silicate hydrate (CSH), calcium aluminate hydrates (C-A-H) and calcium alumino-silicate hydrates (C-A-S-H). As is explained in Chapter-2, HRM is seen to impart better workability, higher strengths (strength activity index is equal to 1.14 after 28 days at a dosage rate of less than 10% cement replacement by weight), and improved durability to cast concrete, not to mention the lighter shades that result for the hardened concrete given the whiteness of this powder.

1.3 Silica fume
Silica fume is a by-product from electric arc furnaces used in manufacture of silicon metal or silicon alloys. The material, which contains more than 80% silica in non-crystalline state and in the form of extremely fine, spherical particles (average diameter=0.1μm), is highly pozzolanic. It is a dark gray powder and may be incorporated either as a powder or in the form of slurry. Silica fume reacts pozzolantically with the secondary product of cement hydration namely calcium hydroxide, to produce further reaction products chiefly in the form of calcium silicate hydrate. Malhotra and Carette [69] report that its strength activity index is 1.10 after 28 days at 10% dosage. However,
the ASTM specification C 618 does not at present cover silica fume and would have to be modified to include it [2].

Due to its extreme fineness and high content of amorphous silica, silica fume is the key ingredient in any high-strength concrete. The incorporation of silica fume in portland cement paste contributes to the hydration reactions by providing nucleation sites for Ca(OH)\(_2\) and also by reacting with alkali and Ca\(^{2+}\) ions [57, 71]. In addition to increasing the amount of CSH in the hydrated cement paste (hcp), silica fume changes the chemical composition of this material which leads to a silicate hydrate of different morphology. Further, due to its fineness, it behaves as a filler so that even at early ages, one sees considerable strength with silica fume concrete. The pores are much smaller in size and this results in a far superior durability.

The main drawback with using silica fume in cast concrete has been the loss in toughness for the hardened material. High strength concrete suffers from an inherent tilt towards brittle behavior which is why, in order to make the benefits accruing from silica fume practicable, one has to incorporate significantly higher amounts of steel fibers as reinforcement to impart the necessary ductility. Of a lesser importance, perhaps, another disadvantage with using silica fume is the dark coloration of the finished concrete even at relatively small dosage rates.

1.4 Objectives of the proposed research
Given the numerous advantages of adding HRM to cast concrete as were mentioned before, it appears logical to expect that HRM may be of significant advantage in shotcrete also. Considering the improvements in the fiber-matrix bond-slip characteristics that
occur as a result of the general lack of CH in the system and the denser packing at the interface [47] due to HRM addition, fibers may benefit HRM-shotcrete more than conventional shotcrete. Further, in light of the lower toughness of shotcrete having silica fume, HRM being a highly active pozzolan itself, should result in a new generation high-strength shotcrete without the drawbacks of loss in fracture toughness.

While the studies on using HRM in cast concrete are very promising, no such study has ever been undertaken with shotcrete. With specific reference to dry mix shotcrete, advantages if any, accruing due to incorporation of HRM in the matrix and its interaction with macro steel fibers are unknown. While significant amount of data exists on the use of other supplementary cementitious admixtures in dry mix shotcrete, effects of HRM on the fresh and hardened properties of dry mix shotcrete remain to be investigated.

Silica fume has found a wide acceptance in the shotcreting industry, as it is proven to reduce rebound losses significantly. However, given its negative impact on the structural-aesthetics and also on the flexural toughness, one of the most promising avenues to pursue in the quest for very high performance shotcrete is to combine HRM with silica fume in the same mix. This triple-blending has a logical premise since the particles of HRM are finer than those of cement but are coarser than those of silica fume. Hence combining HRM and silica fume should ensure more perfect packing which may have profound implications on the rheological and strength characteristics of the resulting shotcrete. Even in the case of fiber reinforced shotcrete, silica fume and HRM may together influence the fiber-matrix bond slip and hence improve the overall toughness and deformation capability of the material.

In light of the above observations, the main objectives of this research were:
1. To investigate the fundamental changes in the microstructure of the hardened shotcrete due to incorporation of HRM through studies on HRM-blended cement pastes.

2. To investigate the effects of HRM on the fresh properties of fiber reinforced dry mix shotcrete such as rebound and build-up.

3. To investigate the effects of HRM on hardened properties of fiber reinforced dry mix shotcrete.

4. To compare and contrast the effects of HRM on plain and fiber reinforced dry mix shotcrete with those of silica fume.

5. To compare the effects of several other mineral admixtures with those of HRM on rebound and fresh dry-mix shotcrete properties.
Chapter 2 – Literature Review

2.1 Shotcrete

The ACI Committee 506 [5] defines shotcrete as *mortar or concrete that is pneumatically projected at high velocity onto a surface*. To this definition, the Austrian Concrete Society (1990) adds that in order to be classified as shotcrete, the material should be *compacted by its own momentum*. Due to the ease of application, lack of formwork requirement and its unique hardened properties, shotcrete has become the material of choice for a broad range of applications including new construction, repair and rehabilitation, rock stabilization etc. Of late, it has also gained increasing popularity in underground support for tunnel shaft and station structures.

Depending upon whether all the materials are mixed along with water *before* spraying or whether the dry aggregates and binder mix with water *in the process of* spraying, shotcrete may be classified as wet-mix application and dry-mix application, respectively.

In the wet process, cement, aggregates, water and the admixtures if any, are batched, mixed and fed into the delivery equipment (the gun). Air is then injected to project this mix into place. On the other hand, in the dry process, only cement, aggregates and any dry admixtures are batched, mixed and fed into the delivery equipment. This mix is then conveyed pneumatically along a hose to the nozzle. Water is then injected at the nozzle through a water ring and the entire mixture (now wet) is projected into place. Liquid additives, if any may also be introduced at the nozzle.

The differences between wet mix and dry mix shotcrete extend beyond their mode of production. Table 2.1 below compares the two processes for shotcreting, as given in Table 1.1 in ACI Committee 506 (1990):
### Table-2.1  
*Comparison of Dry and Wet-mix Processes [5]*

<table>
<thead>
<tr>
<th>Dry-mix Process</th>
<th>Wet-mix Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Instantaneous control over mixing water and consistency of mix at the nozzle to meet variable field conditions.</td>
<td>1. Mixing water is controlled at the delivery equipment and can be accurately measured.</td>
</tr>
<tr>
<td>2. Better suited for placing mixes containing lightweight aggregates, refractory materials and shotcrete requiring early strength properties.</td>
<td>2. Better assurance that the mixing water is thoroughly mixed with other ingredients.</td>
</tr>
<tr>
<td>3. Capable of being transported longer distance.</td>
<td>3. Less dusting and cement loss accompanies the shooting operations.</td>
</tr>
<tr>
<td>4. Start and stop placement characteristics are better with minimal waste and greater placement flexibility.</td>
<td>4. Normally, it has lower rebound resulting in less material waste.</td>
</tr>
<tr>
<td></td>
<td>5. Capable of greater volume of production.</td>
</tr>
</tbody>
</table>

#### 2.1.1 Dry mix shotcrete

Dry mix shotcrete equipment could be either a) single or double chamber guns (Figures 2.1 a & b) or b) continuous feed guns (Fig. 2.2) [5]. The latter forms the most common method of producing shotcrete today and this research involved the use of a rotating barrel containing 8 chambers. The mix is accelerated through the hose (38 to 64mm in diameter and usually more than 20m in length) towards the nozzle, where the remaining water (the dry mix
Fig. 2.1 a  Single chamber gun [5]  
Fig. 2.1 b  Double chamber gun [5]  

Fig. 2.2  Continuous feed gun [5]
Fig. 2.3  Set-up showing water-ring

Fig. 2.4  Dry-process nozzle
may also be pre-damped) and any liquid admixtures are added (Fig. 2.3). The dry mix nozzle (Fig. 2.4) consists of a nozzle-tip, water ring, control valve and water body.

2.1.1.1 Mix design

The design of mix proportion for shotcreting is often based upon a specified compressive strength criterion. The main reasons for variations in the in-place compressive strength are the nature of the shotcrete process, type of delivery equipment and the quality of the workmanship. These factors are pronounced in the case of dry mix shotcrete where water content, a variable which causes fluctuations in strength, depends solely on the discretion and experience of the nozzle-man. Also, factors other than compressive strength may take precedence—for example, permeability and durability are of primary concern in some thin layer applications.

Typically, mix design should look into:

1. Cement type and content;
2. Aggregate gradation, weight or volume;
3. Admixtures and their dosage rate.

However, the specifications may be simplified by stating in terms of cement to aggregate proportion such as 1:4 (which is typically used). Aggregates should be a blend of sizes as required to produce a combined grading. Table 2.1 from ACI-Committee 506 is reproduced below.

Gradation No. 1 is essentially a concrete sand gradation used for fine aggregate shotcrete. It is suited for the dry process but results in high drying shrinkage. Gradation No. 2 is a coarser gradation with about 25% by mass of 10 mm maximum size coarse aggregate and 75% concrete sand. It is commonly used in both dry and wet-process shotcreting.
Gradation No. 3 contains a blend of 20 mm maximum size coarse aggregate and is useful only in large volume wet-process shotcreting with predominantly downward shooting.

Table 2.2  

<table>
<thead>
<tr>
<th>Sieve size, U.S. standard square mesh</th>
<th>Percent by weight passing individual sieves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gradation N° 1</td>
</tr>
<tr>
<td>3/4&quot; (19 mm)</td>
<td>-</td>
</tr>
<tr>
<td>½&quot; (12 mm)</td>
<td>-</td>
</tr>
<tr>
<td>3/8&quot; (10 mm)</td>
<td>100</td>
</tr>
<tr>
<td>No. 4 (4.75 mm)</td>
<td>95-100</td>
</tr>
<tr>
<td>No. 8 (2.4 mm)</td>
<td>80-100</td>
</tr>
<tr>
<td>No. 16 (1.2 mm)</td>
<td>50-85</td>
</tr>
<tr>
<td>No. 30 (600 μm)</td>
<td>25-60</td>
</tr>
<tr>
<td>No. 50 (300 μm)</td>
<td>10-30</td>
</tr>
<tr>
<td>No. 100 (150 μm)</td>
<td>2-10</td>
</tr>
</tbody>
</table>

The water content is at best estimated in the dry process. If one expects a water to cementitious ratio of 0.40, the aggregate to cement composition is such that the cement content is usually around 400 to 450 kg/m³. The maximum size of the coarse aggregate is limited to 9.5 mm (3/8") with a 35% to 65% coarse to fine aggregate composition. This results in what is commonly termed as ACI N° 2 recommended gradation [5].

The water injected into the nozzle is controlled by the nozzle-man who uses his experience to judge the consistency of the in-place material. If required, liquid
admixtures (including silica fume slurry) may also be added at the nozzle. With rebound of material (especially coarse aggregates and macro fibers) being the chief concern with both forms of shotcrete, addition of pozzolans (mainly silica fume) is now widely practised. [10, 74, 78, 75].

2.1.2 Fiber reinforced shotcrete

In mining, tunneling and rock stabilization, the criterion for load capacity is replaced with a deformability criterion. Shotcrete in such cases must possess toughness characteristics to render adequate ductility.

As plain shotcrete is no better than plain cast concrete with respect to flexural performance, traditionally ductility in shotcrete linings has been obtained by the use of wire mesh. The mesh is now being increasingly replaced with random distribution of steel fibers. Studies have shown that the load bearing capacity and post-cracking behavior of steel fiber-reinforced shotcrete (FRS) are comparable to those with wire mesh reinforcement. The main effect of fiber reinforcement is to give some load bearing capacity at large deformations after cracking, to control restrained shrinkage cracking and to improve impact resistance [58, 108]. The post-cracking behavior of FRS can be evaluated by a flexural toughness test. A variety of fibers such as steel fibers, polypropylene fibers, glass and carbon fibers have been investigated [58]. However, the most common fiber by far is steel fiber.

2.1.2.1 Steel fiber reinforced dry mix shotcrete

The placement of shotcrete tends to orient the fibers in a plane parallel to the surface being sprayed [109], and this is beneficial to the flexural properties of shotcrete, particularly for thin layers. When used in dry mix shotcrete, steel fibers are simply mixed
and sprayed along with aggregates and cement and therefore do not present any further placing difficulties. The main advantages of steel fiber over mesh reinforcement may be enumerated as [10]:

- Doing away with installing mesh along dangerous rock slopes;
- Increase protection against rock bursts in deep mines;
- Less rebound as the mesh tends to behave as an obstacle to placement;
- Elimination of voids and sand pockets behind the mesh;
- Decreasing the material used since the fibers allow shotcrete to follow the contours of the substrate as opposed to the need for creating a smooth finish with mesh reinforcement [99].

2.2 High-reactivity metakaolin

Kaolin \([\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4]\), is an important constituent of soils and is used widely in ceramics and related industries. High-Reactivity Metakaolin (HRM) is produced by controlled thermal activation of purified kaolin, to a reactive, amorphous state. After calcination at 650-850°C, kaolinitic clays show high pozzolanic property. It is classified under ASTM C618 as a Class N pozzolan.

2.2.1 Production

Purified kaolin clay –raw feed for producing HRM– is a by-product of the glass manufacturing industry. The following five steps are involved in the production of HRM:

- Kaolin is separated from sand and other impurities and pumped into a thickener where the water content is reduced from 90-93 percent to 65-68 percent;
• Thickened kaolin is then pumped into rotary vacuum filters where it is transformed into a plastic cake;

• From the filters, kaolin is conveyed to a rotary dryer where the moisture content is further reduced to about 10 percent;

• After drying, kaolin is blended in a pug mill with filter cake and extruded in the form of pellets;

• Pellets are calcined in a rotary kiln, ground to a fine powder and bagged.

HRM, in effect is a poorly crystallized transition phase with a very high reactivity with lime.

2.2.2 Physical properties and chemical composition

The average particle size of HRM is around 2 μm. This gives it a specific surface area of around 10,000 m²/kg. It is thus much finer than cement but still coarser than silica fume. HRM particles have a book structure (flakes stacked one on top of another as seen in Slide-5.2) which makes it quite difficult to specify a mean particle size, in a strict sense. The material is mostly amorphous with only a trace of crystalline phases. The main crystalline phases identified are anatase (TiO₂), cristobalite (SiO₂) and quartz (SiO₂) [104]. HRM is a white powder, with a Hunter L whiteness value of 90 (on a scale of zero to 100, with zero denoting jet-black). Depending upon the mineralogical composition of the source-clay, metakaolin may have varied chemical composition:
Table-2.3  *Chemical composition of HRM derived from different clays* [3]

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Kaolinitic Clays</th>
<th>Illitic Clays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>SiO₂</td>
<td>43.34</td>
<td>47.07</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>34.93</td>
<td>36.42</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.15</td>
<td>0.52</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.72</td>
<td>1.33</td>
</tr>
<tr>
<td>CaO</td>
<td>0.29</td>
<td>–</td>
</tr>
<tr>
<td>MgO</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.08</td>
<td>–</td>
</tr>
<tr>
<td>LOI</td>
<td>16.00</td>
<td>14.43</td>
</tr>
</tbody>
</table>

In particular, while silica fume consists of mostly SiO₂ (~97%), HRM consists of about 50% SiO₂ and about 40% Al₂O₃ [104]. It also contains traces of SO₃ (<0.5%), alcalis (<0.5%), and moisture (<1%).

2.2.3 Hydration of HRM-cement pastes

Upon calcination in the range of 650-850°C, kaolin [Al₂Si₂O₅(OH)₄] loses its water of crystallization. The change occurs with considerable disorganization of its structure, corresponding to the formation of a poorly crystallized transition phase, designated as metakaolin (or HRM). Eventually upon continued heating, metakaolin will yield mullite and cristoballite (corresponding to Alumina and Silica respectively).

Owing to its unstable atomic arrangement, particularly of its Al-O portions, HRM is much more reactive towards alkaline solutions than is raw kaolin [42]. In addition, in the
process of calcination, the original book structure of particles stacked together is considerably broken down thereby increasing the surface area of metakaolin. These effects make HRM a very reactive pozzolan. The effect of HRM on hcp microstructure has been dealt with in detail in Chapter-4.

*Products of HRM-CH hydration*

Strätling [67] was the first to report the coexistence of $\text{C}_2\text{ASH}_8$ (*gehlenite hydrate* or *strätlingite*) with CSH in hydration of metakaolin-lime mixtures at 20°C. The phase relations of HRM/CH mixtures with different amounts of CH has been reported by Serry *et al.* [94]. Gehlenite hydrate was the main crystalline product obtained. Investigators have also reported the occurrence of $\text{C}_4\text{AH}_{13}$ with $\text{C}_2\text{ASH}_8$ and CSH at 20°C: it appears that minor carbonation is unavoidable. In a study by de Silva and Glasser [43], 5 mixes with varying metakaolin/calcium hydroxide ratios were investigated. They reported that the principal hydrates found amongst the reaction products of HRM-CH mixtures at 20-55°C are $\text{C}_2\text{ASH}_8$, $\text{C}_4\text{AH}_{13}$, CSH and hydrogarnet.

The pozzolanic reactions of interest are:

\[
\begin{align*}
\text{AS}_2 & + 6\text{CH} + 9\text{H} \rightarrow \text{C}_4\text{AH}_{13} + 2 \text{CSH} \\
\text{(HRM)} & \quad \text{(Portlandite)} \quad \text{(water)} \quad \text{(tetracalcium aluminan hydrate)} \\
\text{AS}_2 & + 5\text{CH} + 3\text{H} \rightarrow \text{C}_3\text{AH}_6 + 2 \text{CSH} \\
\text{AS}_2 & + 3\text{CH} + 6\text{H} \rightarrow \text{C}_2\text{ASH}_8 + \text{CSH} \\
\end{align*}
\]

\(\text{(hydrogarnet)}\)

\(\text{(strätlingite)}\)
<table>
<thead>
<tr>
<th>Mixture</th>
<th>Curing Time (days) @ 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>A (HRM/CH=1/6)</td>
<td>( \text{GH,} \text{C} \text{4AH}_{13}, \text{CH,C} \text{SH} )</td>
</tr>
<tr>
<td>B (HRM/CH=1/3)</td>
<td>( \text{GH,} \text{C} \text{4AH}_{13}, \text{CH,C} \text{SH} )</td>
</tr>
<tr>
<td>C (HRM/CH=1/1.50)</td>
<td>( \text{GH,} \text{C} \text{4AH}_{13} \text{(tr.),CH,CSH} )</td>
</tr>
<tr>
<td>D (HRM/CH=1/1.75)</td>
<td>( \text{GH,} \text{C} \text{4AH}_{13} \text{(tr.),CH,CSH} )</td>
</tr>
<tr>
<td>E (HRM/CH=1/0.40)</td>
<td>( \text{C} \text{4AH}_{13}, \text{CH,C} \text{SH} )</td>
</tr>
</tbody>
</table>

Abbreviations:

(tr.) - Traces
GH - Gehlenite hydrate
\( \text{C} \text{4AH}_{13} \) - Tetra calcium amuminumhydrate
CH - Calcium hydroxide
CSH - Calcium silicate hydrate gel

The table above describes the sequence of hydrate development in different metakaoline-
calcium hydroxide mixtures as reported in reference [43]. Accordingly, the appearance of
\( \text{C} \text{4AH}_{13} \) in the initial stage of hydration is attributed to metastable phenomenon caused by
supersaturation of the aqueous phase with respect to CH. High concentration of \( \text{Ca}^{2+} \) and
\( \text{OH}^- \) in the pore solution, created by CH dissolution, maintain pore fluid composition
which enables \( \text{C} \text{4AH}_{13} \) to precipitate. Strätlingite has a distinctive X-ray pattern and
forms a weakly birefringent plate structure, with a refractive index of 1.500 to 1.505 [67].

It has been ascertained that strätlingite exists in all hydrated HRM-OPC pastes for HRM contents beyond 30% of the binder [4].

Consumption of portlandite has been studied by Wild and Khatib [101]. The CH contents of both pastes and mortar showed a minimum at about 14 days. This coincided also with a maximum in relative strength vis-à-vis OPC pastes and mortars. Apparently the pozzolanic reaction is at its peak after 14 days of curing. There was evidence of a sharp decline in reactivity from 14 to 28 days after which the reaction resumed again. This is attributed to formation of an inhibiting layer of reaction product around the HRM particles.

**Effect of HRM on C₃S**

For plain C₃S, study of dissolution kinetics reveals a rapid dissolution and the conductivity quickly increases to reach its maximum value after 320 minutes. When HRM is added the initial dissolution is slowed down during a period ranging from 60 to 220 minutes. The higher the HRM content, longer is this period [4]. The maximum conductivity has been reported at 260 minutes for low HRM contents (C₃S:HRM = 2.40), with this period increasing to 350 minutes for high HRM contents (C₃S:HRM = 0.60). This shows that at low contents HRM accelerates C₃S hydration while at higher contents, it has a retarding effect. At higher contents, a large proportion of HRM possibly acts as a filler.
Effect of HRM on C₃A

At a C₃A:HRM ratio of 0.10, such a paste does not seem to hydrate at all [4]. This paste is as inert as plain HRM paste. DTA and XRD performed by the investigators showed that C₃A is not an activator for HRM hydration.

Chemistry of the pore fluid

Incorporation of HRM, as a partial cement replacement into OPC pastes causes substantial changes in chemical composition of the pore solution phase of the hydrated material [40]. Significant reductions in the pH value of the pore solution have been observed when 10 to 20% of HRM is blended with OPC of moderate alkali content (0.63% equivalent Na₂O). This consequence of the pozzolanic reactivity of HRM is considered to be relevant to the ability of HRM-blended cements to reduce the risk of expansive alkali-aggregate reaction in concrete, but to have very little effect on the stability of the passive layer of film that provides corrosion protection to embedded steel. Blended cement pastes having 10 to 20% HRM were also found to exhibit higher capacities than plain OPC pastes to bind chloride ions which are introduced by contamination of the mix water with sodium chloride. This effect counteracts the reduction in pH and results in [Cl⁻]/[OH⁺] ratios in the pore solution phase, which are similar for both OPC and HRM blended cement pastes at the same dosages of sodium chloride. Thus the risk of chloride-induced corrosion of embedded steel is expected to stay more or less unaffected by replacement of cement by up to 20% HRM.

2.2.4 HRM in cast concrete

Calderone and Gruber [36] compared the effects of HRM with those of silica fume on fresh and hardened properties of concrete. It was found that induction of HRM increased
the compressive strength and decreased the permeability without affecting freeze-thaw durability. HRM-mixes consistently required about 40-50% less High Range Water Reducing Admixtures (HRWRA) [38, 15] than the silica fume ones. Dubey and Banthia [47] investigated the flexural toughness response of HRM-fiber reinforced concrete. Marginal increases were reported in the 7 and 28-day compressive strengths, over control specimen without HRM. Although the hardened air content (ASTM C457) of concrete with HRM was higher than that of concrete with an equal substitution of silica fume, the strength and performance of the former were similar to those of the latter. Toughness indices (ASTM C 1018) for beams with HRM were superior to those with silica fume. At the fiber volume fraction used in their study (1%), a near elasto-plastic response was indicated for HRM-concrete to a mid-span 15.5 times the first crack deflection. Toughness analysis based on JSCE [62] revealed that to a deflection of span/150, high-reactivity metakaolin concrete specimens dissipated the largest amount of energy. The flexural toughness factor with HRM was about 9% greater than control and 21% more than with silica fume. This is perhaps due to change in matrix brittleness brought about through chemical reaction of this pozzolan.

**Durability and drying shrinkage**

The drying shrinkage of HRM concrete is similar to concrete with silica fume but significantly less than for conventional Portland cement concrete [104]. The rapid chloride ion permeability (ASTM C 1202) of HRM concrete is also much lower (almost 1/6th in coulombs rating) than conventional concrete and as low as silica fume concrete [38]. Given its high reactivity with calcium hydroxide (portlandite) in concrete [83], there
is less lime left in the system and the potential for alkali-silica reaction and efflorescence is low.

HRM additions do not interfere with the air-void network needed for proper freeze-thaw durability and the reduced bleeding indicates a better quality concrete thus improving the abrasion and scaling resistance. Improvements in the durability of concrete in a tropical marine environment have also been reported [30]. Durability tests carried out on mortars immersed in seawater at 20° C have shown the beneficial effect of the combination of HRM and melamine superplasticizer. The setting is not delayed and there is no evaporation of water during the early hours of curing. Compressive strength increased by 40% and length variation fell by 60% compared to control. The pore size distribution reduced and the quantity of micropores increased thereby lowering the permeability of blended mortars.

*Mechanism of sulfate resistance in HRM-blended cement paste*

Khatib and Wild [64] investigated the resistance of blended cement (with both high and intermediate contents of C₃A) mortar having HRM, to sulfate solution. They found an increase in resistance to sulfate expansion with HRM up to 25% replacement. Mortars exposed to Na₂SO₄ solution and containing HRM up to 10% exhibited a loss of strength and those containing 15% or greater exhibited a gain in strength. Reduction in CH content is considered to be the principal factor by which HRM improves sulfate resistance and it is suggested that the nature of sulfate containing reaction product formed at high HRM levels (and low CH contents) is different from that formed at low HRM values (i.e. higher CH values). Hence at least 15% HRM is believed to be required for good sulfate resistance. It is suggested that at low HRM contents (0-10%), there is excess
CH available, therefore, the onset and magnitude of expansion is controlled by the amount of C\textsubscript{3}A available to react to form an expansive product. Hence, mortars having higher C\textsubscript{3}A content showed early and rapid expansion, whereas those with intermediate C\textsubscript{3}A contents showed much later expansion and slower rates. At higher HRM contents (15-25%), CH content is much reduced and the magnitude and rate of expansion is lower and far less sensitive to C\textsubscript{3}A content. In this case expansion is controlled by CH content and hence the reduction in expansion.

2.3 Silica fume

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the production of silicon metal and ferro-silicon alloys. Interest in the use of silica fume as an admixture in the concrete industry stemmed out of the strict enforcement of pollution control measures in various countries. The fume, which has a high content of amorphous silicon dioxide and consists of very fine spherical particles, is collected from the gases escaping from the furnaces. It may be collected as a condensed byproduct from related industries such as ferrochromium, ferromanganese, ferromagnesium and calcium silicon. According to ACI Committee 226 [2], the silica content of the by-product collected is related to the manufacture of silicon alloys as follows:
Table-2.5  Variation in silica content with source [2]

<table>
<thead>
<tr>
<th>Ferrosilicon alloy/metal*</th>
<th>SiO$_2$ content of Silica fume</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 percent ferrosilicon</td>
<td>72 to 77 percent</td>
</tr>
<tr>
<td>75 percent ferrosilicon</td>
<td>84 to 88 percent</td>
</tr>
<tr>
<td>Silicon metal (98 percent)</td>
<td>93 to 98 percent</td>
</tr>
</tbody>
</table>

* Ferrosilicon alloys are produced with nominal silicon contents of 50, 75 and 90 percent. When the silicon content reaches 98 percent, the product is called silicon metal rather than ferrosilicon. As the silicon content increases in the alloy, the SiO$_2$ content will increase in the silica fume.

2.3.1 Physical properties and chemical composition

Silica fume consists of very fine spherical particles with a specific surface area of the order of 20,000 m$^2$/kg when measured by nitrogen adsorption techniques. X-ray diffraction analysis of different silica fumes reveals that the material is essentially vitreous silica, mainly of the cristobalite form. Particle size distribution for a typical silica fume together with cement and fly ashes for comparison is shown in Fig. 2.5. As is evident, silica fume is two orders of magnitude smaller than cement.

According to Aïtcin et al. [1], silica fume from silicon metal manufacture is very fine because of high furnace temperatures. With ferrosilicon alloy-furnaces, as the amount of iron increases in the alloy, the temperature of the furnace decreases and the grain size distribution of the fume shifts towards coarser particles. Table 2.6 reproduces composition of some silica fumes as reported by various authors.
Fig. 2.5  Particle size distribution for condensed silica fume, fly ash and Portland cement
Table-2.6  *Chemical composition of silica fume* [46]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>93.6</td>
<td>92.1</td>
<td>91.2</td>
<td>93.2</td>
<td>92.5</td>
<td>97.8</td>
<td>95.6</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>1.2</td>
<td>0.4</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.5</td>
<td>1.4</td>
<td>0.6</td>
<td>1.6</td>
<td>0.4</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>CaO</td>
<td>0.3</td>
<td>0.5</td>
<td>1.1</td>
<td>0.9</td>
<td>0.5</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>MgO</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
<td>0.9</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.3</td>
<td>0.7</td>
<td>0.8</td>
<td>1.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>1.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>L.O.I</td>
<td>2.8</td>
<td>2.8</td>
<td>2.1</td>
<td>-</td>
<td>2.6</td>
<td>-</td>
<td>1.4</td>
</tr>
</tbody>
</table>

2.3.1.1 Availability

Silica fume for use in concrete is available in four major forms: the as-produced silica fume, densified (compacted) silica fume, slurry containing 50% water by mass and pelletized silica fume. In sharp contrast to the experience with fly ash, field and laboratory tests indicate that there is no difference in hardened concrete properties when using any of the forms above [93].

2.3.2 Use in cast concrete

According to Detwiler and Mehta [45], there was little pozzolanic effect accruing from silica fume at ages up to 7 days. Hence any improvement seen in the performance of such
concrete is mainly the physical effect of the fineness of the particles. Apparently, grain refinement and reduction in the size of pores compensates for reduction in cement. At later ages, the high pozzolanicity of silica fume (due to its fineness as well as its high amorphous silica content) ensures higher strength and better durability. A basic law in concrete technology is that there exists, for given materials, a unique relationship between the w/c ratio and compressive strength. This relationship is changed quantitatively, but not qualitatively, with the addition of silica fume \[114\]. Using a fixed percentage of silica fume results in a shift of the strength vs. w/c curve to a higher level, but the shape of this curve remains the same. As silica fume addition is accompanied with water reducing admixtures, this further indicates that such admixtures do not affect the strength of hardened concrete.

The hydration of C\(_3\)S, C\(_3\)A, and C\(_4\)AF are accelerated in the presence of silica fume \[57, 65, 98\]. Silica fume experiences rapid dissolution in the presence of CH. The silica in solution reaches supersaturation with respect to a new phase in a matter of minutes. This unstable silica-rich phase forms a layer on the surface of the silica fume particle. This layer is then partly dissolved and the remainder acts as a substrate on which conventional CSH forms. Due to the combination of the ‘filler’ effect and its pozzolanicity, there results a strengthened interface as well as a finer pore structure. This causes a vastly strengthened matrix, so much so that the aggregate becomes the weak link. It should be noted however, that the benefits from silica fume might be realized only with a reduced water/solids ratio and use of superplasticizer.
2.3.2.1 Effect on the transition zone

Studies have shown that the primary effect of silica fume is the improvement of the aggregate-matrix interface [53, 54, 55]. Using carbon black as a comparative inert filler, they found that it was just as effective in filling the spaces in the transition zone as silica fume. The Scanning Electron Microscopic observations show two types of interparticle linkages [55]:

- Direct, possibly chemical or physical in origin;
- Indirect, created through the hydration products, formed on the particle surface between adjacent particles.

Thus, silica fume particles act as nucleation sites for further hydration and also bridge gaps by filling spaces. This causes reduced ‘free’ water available for CH crystallization which in turn results in an improved transition zone.

2.3.2.2 Effect on mechanical properties

Investigation by Cong et al. [41] has shown that when accompanied with a superplasticizer, silica fume increases the strength of the paste, and in turn the compressive strength of the resulting concrete. While they believe that change in the paste-aggregate interface due to presence of silica fume does not affect the compressive strength, Goldman and Bentur [53], found that the improvement in the paste-aggregate interface due to silica fume leads to the higher compressive strength of concrete. Xie et al. [103] concluded that although both tensile strength and fracture energy increased with silica fume content, such concrete is less ductile in both tension and compression.
2.3.3 Use of silica fume in shotcrete

Silica fume is now almost an inseparable part of the shotcrete industry. Its use began in Norway in the 1970's in wet-mix shotcrete. It was first used in Canada around 1980 almost simultaneously with fibers. Silica fume in wet-mix shotcrete improves the properties of both fresh and hardened shotcrete. In dry-mix shotcrete, it ensures a much-reduced rebound as well as faster setting (precluding the use of accelerators).

2.3.3.1 Silica fume wet-mix shotcrete

Effect on fresh shotcrete

Silica fume, when replacing a part of cement, reduces the workability of fresh concrete and, for this reason, is often used with a superplasticizer. By changing the cohesion of the mix, it reduces bleeding and segregation and increases pumpability by reducing the risk of pump blocking [27]. However, if the curing is not appropriate, reduced bleeding increases susceptibility to early plastic shrinkage cracking.

As it improves the cohesiveness of fresh shotcrete, silica fume reduces rebound and the build-up thickness [102]. The addition of silica fume allows a two fold (sometimes even three fold) increase in the overhead build up, which is one of the main reasons for its popularity in shotcrete technology.

Effect on hardened properties

There is no difference in the hardened properties of shotcrete and those of cast concrete, when incorporating silica fume. Reduced porosity and the pozzolanic reaction impart better durability and mechanical strength. However, a loss of ductility is observed.
2.3.3.2 Silica fume dry-mix shotcrete

Silica fume is used in dry-mix shotcrete primarily to reduce rebound, especially of fibers. Also, in marine construction, it improves the resistance of the freshly placed shotcrete to washout by tidal waves [74]. As with wet-mix shotcrete, here too the build up is vastly enhanced and this has very attractive implications for construction of triangulated lattice girders in the New Austrian Tunneling Method (NATM).

Another attribute of the plastic dry-mix shotcrete is its substantially improved adhesion, particularly in wet-areas such as locks, dry-docks, tunnels and leaking structures. Normally, adhesion in such areas is achieved only through addition of high concentration of shotcrete accelerators to create a flash-setting condition—a process which is detrimental to long term performance. Silica fume promotes excellent adhesion in such cases.

Silica fume is helpful in reducing leaching of shotcrete lining in tunnels [32]. The introduction of 5 to 10% silica fume was found to increase the microstructure density and reduce the contents of both soluble and precipitatable CH. The content of other easily soluble alkalis is also reduced.

2.4 Rebound in dry-mix shotcrete

When spraying concrete, losses arise in a number of ways and can be defined as any material that is not part of the finished insitu material. The three chief sources are:

a) Overspray: -material missing the target surface;

b) Rebound: -material which strikes the target surface but does not adhere;

c) Cutback: -material which sticks to the surface but is subsequently removed before setting to bring the surface to the correct profile.
A skilled nozzle-man can reduce and almost eliminate the losses due to overspray and cutback. The biggest concern facing the shotcrete industry is rebound which may be 10-15% in the wet process [13] and as high as 40% in dry process shotcrete [13, 26, 102].

It is observed that coarser aggregates, stiffer mixes, macro fibers—all lead to a higher rebound. As a consequence, the inplace material tends to have a composition rather different from the batched mix. Table 6.1 ACI 506 '90 is reproduced below to indicate this change between cement to aggregate proportions.

<table>
<thead>
<tr>
<th>Nominal mix entering gun</th>
<th>Mix in Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 : 3.0</td>
<td>1 : 2.00</td>
</tr>
<tr>
<td>1 : 3.5</td>
<td>1 : 2.80</td>
</tr>
<tr>
<td>1 : 4.0</td>
<td>1 : 3.25</td>
</tr>
<tr>
<td>1 : 4.5</td>
<td>1 : 3.60</td>
</tr>
<tr>
<td>1 : 5.0</td>
<td>1 : 3.80</td>
</tr>
<tr>
<td>1 : 6.0</td>
<td>1 : 4.10</td>
</tr>
</tbody>
</table>

It is clear therefore that the mix in place is richer in cement. This is accompanied by high shrinkage cracking, an increased tendency for alkali-aggregate reactions and fall in durability. Further, since fiber rebound is observed to be higher than matrix rebound, the desired toughness is not achieved. Hence, rebound is of both economic and engineering concern.
2.4.1 Factors affecting material rebound

In the dry process, material rebound is influenced by many factors including direction of spraying, spraying distance, aggregate grading, moisture content, water pressure, nozzle design, additives and admixtures, layer thickness and rheology of the mix [10, 13]. While some of these are mix design factors, others are based on the shooting technique. According to Parker et al. [86], an examination of material rebound revealed that:-

- Rebound during the production of the first layer of thickness equal to the size of maximum coarse aggregate, was 60% compared to 10% for the subsequent layers;
- Rebound contains four times more aggregate than cement.

It is advisable to achieve the desired thickness in a single pass application rather than in multiple passes as this effectively reduces rebound [27]. Because coarser aggregates tend to rebound more, ACI recognizes 3 distinct gradation curves namely, Nos. 1, 2 and 3. As No. 3 is the coarsest, gradations 1 and 2 are commonly used with No. 2 being the most common in N. America [79, 10]. Also, while spraying, rotating the nozzle and keeping the nozzle perpendicular to the target surface minimizes the rebound. The effect of fiber addition on material rebound is not clearly understood. Henager [60] reported that a plain dry mix that rebounded 31%, reduced to 10% with addition of 4.4% by weight of 13 x 0.25mm steel fibers. A similar claim is made by Ryan [92] who states that the presence of fibers reduced material rebound by nearly 45%. This is countered by Ruffert (in [13]), Maher et al. [68] and Austin and Robins [13] who see no effect of fibers on material rebound. As discussed in later chapters, this study also found no evidence to suggest any influence of fibers on material rebound.
An important characteristic of dry mix shotcrete is the shooting consistency as defined by the yield resistance to penetration (dealt with in detail in section 3.5). It has a profound bearing on rebound and build-up thickness. Although the yield strength of fresh dry mix shotcrete is related to the in-situ water/cementitious ratio by an exponential curve [10] just as cement paste is known to be [89], the origin and nature of the yield strength of dry mix shotcrete differs significantly from cast concrete. It was found that when the same material from the in-place dry mix shotcrete was agitated in a mixer for four minutes and then vibrated back into the panel, the resistance offered to penetration dropped by almost 75% [10]. There was a corresponding drop in overhead build-up also. Powers suggested that the reason behind such a phenomenon was a breakage of the initial hydration products or a redispersion of particles. It is evident from these observations that dry mix shotcrete is unique in that water comes in contact with cement and the two are placed in the final position within a fraction of a second, thereafter. This provides workability features, that are distinct from the cast concrete mixes.

2.4.2 Fiber rebound in dry-mix steel fiber reinforced shotcrete

It is unanimously agreed that steel fibers rebound more than the surrounding material with values as high as 70% [26, 10, 58,].

There is however no universally accepted method to calculate rebound. While some consider the reduction in fiber volume fraction to represent rebound [25], others have included parameters ranging from overall rebound [9] to in-situ water content and insitu aggregate to cement ratios [13]. The following is a list of methods encountered in literature:
Define:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{fr} )</td>
<td>Mass of fiber in rebound</td>
</tr>
<tr>
<td>( W_{is} )</td>
<td>Mass of insitu shotcrete</td>
</tr>
<tr>
<td>( W_{rs} )</td>
<td>Mass of total rebound</td>
</tr>
<tr>
<td>( M_f )</td>
<td>Mass per unit volume of fibers in shotcrete as batched</td>
</tr>
<tr>
<td>( V_f )</td>
<td>Volume fraction of fibers as batched</td>
</tr>
<tr>
<td>( V_{fs} )</td>
<td>Volume fraction of fibers insitu</td>
</tr>
<tr>
<td>( T )</td>
<td>Ratio of insitu fiber volume fraction to that as batched</td>
</tr>
<tr>
<td>( R )</td>
<td>Total rebound of material in percentage</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Fiber rebound expressed in percentage</td>
</tr>
<tr>
<td>( D_f )</td>
<td>Density of fiber material.</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Density of shotcrete (=2300 kg/m(^3))</td>
</tr>
<tr>
<td>( FC_i )</td>
<td>In-situ fiber content, as a percentage by weight of dry material</td>
</tr>
<tr>
<td>( WFC )</td>
<td>In-situ fiber content as a percentage by weight of wet material</td>
</tr>
<tr>
<td>( WCR )</td>
<td>Water/cement ratio</td>
</tr>
<tr>
<td>( ACR_i )</td>
<td>In-situ aggregate/cement ratio</td>
</tr>
<tr>
<td>( FCR_{dm} )</td>
<td>Dry mix fiber/cement ratio</td>
</tr>
</tbody>
</table>

- **Method-1** describes rebound as obtained by direct measurement of fibers in rebound, recording the amount of material shot and knowing the design fiber content.

\[
\% \text{ Rebound} = \frac{W_{fr}}{W_f}
\]
Where $W_{fr}$ refers to mass of fiber in rebound and $W_{ft}$ refers to mass of fibers shot as obtained by

$$W_{ft} = \left(\frac{W_{st}}{2300}\right) \times M_f;$$

$W_{st}$ = Weight of total material sprayed given by

$$W_{st} = W_{rs} + W_{is}.$$

- **Method-2** describes rebound as a percentage of change in volume fraction of fibers upon shooting.

$$\% \text{ Rebound} = 100.(V_f - V_{fs}) / V_f$$

where $V_{fs}$ refers to fiber-volume fraction in-situ as obtained by

$$V_{fs} = \left\{ \left[ (W_{is} + W_{rs})/\rho_s \right] \times V_f \times D_f \right\} - W_{fr} / D_f \times (\rho_s / W_{is})$$

- **Method-3** describes rebound as given by Armelin and Helene [9] and is equal to

$$R_f = 100 \times (1-T) + T \times R$$

where $T = V_{fs}/V_f$ and $R$ = overall rebound expressed as percentage given by

$$R = W_{rs} \times 100 / (W_{rs} + W_{is}).$$

- **Method-4** for calculation of rebound is due to Robins and Austin [90] where the in-situ fiber content $FC_i$, as a percentage by weight of the dry material and fiber rebound, $R_f$ are obtained by the following expressions:

$$FC_i = W_{FC_i} \left[ \frac{(1 + WCR + ACR_i)}{(1 + ACR_i)} \right] \%$$
and

\[ R_f = 100 - \frac{WFC_i(1 + WCR + ACR_i)}{FCR_{dm}} \%
\]

where, \( WFC_i \) = the in-situ fiber content (% by weight of wet material)

Perhaps the most straightforward approach (method-1) would be to collect all the rebound and separate the fibers using magnets. Whereupon, rebound could be calculated as the ratio of the mass of fibers collected to the mass of fibers shot. This would however, be good only for laboratory studies for in real applications, collecting the rebound (leave alone separating the fibers) would be an impossible task.

There is little data on rebound of fibers other than steel fibers. Gupta [58] lists rebound values for polypropylene, carbon and glass fibers in wet mix shotcrete.

2.4.3 Factors influencing fiber rebound

It is quite clear that fiber geometry influences rebound. However, the specific parameters have not been identified so far. Banthia et al. [25] hypothesized that fiber rebound could be related to fiber accelerations experienced during shooting. This was in turn proportional to the fiber projected surface area and inversely proportional to fiber mass. Thus, relative fiber rebound (among 5 different steel fiber geometries in the trial) was found to be proportional to what was termed as the specific projected area i.e. the projected area/fiber mass. However, this was not confirmed by Peaston [87] and Armelin and Helene [9]. Although, as Parker et al. [86] observed, particles tend to spin in the air stream with elongated particles having higher velocities (up to 250 rpm). This is substantiated by Armelin and Helene [9], who said that only those fibers which upon striking the substrate, rotate to within 11° of the plane of the substrate, adhere to it. It is
therefore apparent that a combination of fiber geometry and mass in so far as it influences its rotational kinematics, plays an important role in fiber rebound.

2.4.4 Mechanism of rebound

Rebound is a dynamic process which occurs when rapidly moving particles in the shotcrete stream are brought into sudden contact with the target surface resulting in an immediate deceleration and transfer of momentum. The duration of the entire event (from the time a particle leaves the nozzle, travels towards the target surface and then either embeds itself or rebounds from the surface) may be only a fraction of a second.

High-speed photography was used in an extensive investigation towards developing a model explaining the nature and causes of rebound [7,8]. This allowed for a determination not only of the variation in aggregate velocity as a function of aggregate size and shooting characteristics, but also provided the basis for a conceptual modeling of rebound. Based on their study Armelin and Banthia [7] found that aggregate velocity (V) is inversely proportional to its size (\( \phi \)) and air volume and may be given by a general expression,

\[
v = A \left( \frac{1}{\phi} \right)^B
\]

where A and B are constants.

Fiber velocities also follow a pattern similar to aggregates such that the longer and thicker fibers developed smaller velocities. In modeling rebound in shotcrete, the usual assumption of fresh concrete being a Bingham fluid is of limited usefulness since it fails to account for the elastically stored energy in fresh shotcrete substrate, which when transferred back to the impinging particles may cause it to 'pop' out of the bed.
Fig. 2.6  Spherical impactor striking the elasto-plastic substrate with the formation of the hydrostatic cavity ($r<a$) and the elasto-plastic region ($r<c$) [10]
In actual modeling of rebound, the process may be seen to compose of two phases, the penetration phase and the reaction phase. During the penetration phase one could invoke theories of plasticity [63] to develop the parameters of the hydrostatic stress-field that developed around the impinging aggregate as shown in Fig. 2.6.

The final depth of penetration is determined simply by balancing the work done in creating the indentation \( (p_d V_a) \) and the kinetic energy available in the fast moving particle \( (W_1) \). In other words,

\[
W_1 = p_d V_a
\]

In the reaction phase, the rebound energy \( (W_2) \) is given by

\[
W_2 = \frac{3\pi^2}{10} p^2 a^3 \left[ \frac{1 - \frac{1}{E_c}}{E} + \frac{1 - v_1^2}{E_1} \right]
\]

The tendency of sprayed material to rebound is expressed in terms of the coefficient of rebound given by

\[
e = K \psi,
\]

where

\[
K = \left[ \frac{3\pi^2}{10} \left( \frac{4r_1}{\pi} \right)^{3/4} \left( 2.25 \epsilon_{pc} \left( \frac{1}{2} m \right) \right)^{1/4} \right]
\]

and

\[
\psi = p^{1/2} p_d^{-3/8} V^{-1/4}
\]

where,

\[
r_1 = \text{radius of impactor},
\]

\[
\epsilon_{pc} = \text{Limit elastic strain of fresh concrete}
\]

\[
m = \text{mass of the impactor}
\]

\[
p \text{ and } p_d = \text{Static and dynamic contact stresses}
\]

\[
V = \text{Velocity of impact.}
\]
The above expression takes into account both the material properties of the substrate and the intensity of the impact. With a known value of the coefficient of restitution \( e \), the available energy for rebound \( W_2 \) can be calculated. This can then be compared with the energy necessary for debonding \( (W_D) \) given by,

\[
W = \delta^* [\sigma_0 (\pi a^2)]
\]

The condition of rebound is given by

\[
\frac{W_2}{W_D} \geq 1 \Rightarrow REBOUND
\]

The other specific conclusions from Armelin [10] were:

1. An aggregate particle faces a constant dynamic contact stress \( (p_d) \) that is approximately one order of magnitude greater than its static equivalent \( (p) \).

2. For a fixed workability (determined by consistency) and impactor speed, a higher cement content or presence of silica fume were found to significantly reduce the dynamic contact stress \( (p_d) \). Though this increases the rebound energy, the fall in debonding energy is greater and hence the ratio of the two which determines tendency to rebound is reduced. This explains the reduced rebound with higher cement content and/or silica fume.

3. Lower velocities of impact lead to higher coefficients of restitution. (Hence coarser aggregates rebound more)

4. There is an optimum value of airflow for minimum rebound.

5. Lower water contents increase debonding energy.

6. The mechanisms and forces involved in aggregate rebound are the same for both vertical and overhead modes of shooting.
2.4.5 Mechanism of fiber rebound

The essential difference between fiber rebound and aggregate rebound lies in the aspect ratio of fibers. With aggregates, it was possible to assume a particle to be spherical and model accordingly. Consequently, there was no rotational component of motion to take into account [8]. However, with a fiber, the mass is distributed along the entire fiber length and one can no longer ignore the rotational component of motion. This is especially so after impact with the shotcrete substrate, when the fiber's translational kinetic energy is transformed into its rotational kinetic energy.

It has been found that fibers in shotcrete tend to align themselves to the shotcrete surface. Armelin and Helene [9] quantified the fiber alignment as being within 22° to the plane of shooting and being on average within 11°. The condition of rebound is set by asserting that, in order to adhere to the shooting surface and become part of the in-place shotcrete, a steel fiber must attain a contact angle lower than or equal to a maximum value. Thus, for a fiber geometry, and shotcrete substrate, the main variable determining rebound is its tendency to align itself with the contact surface.

Some of the conclusions drawn from studying the influence of fiber geometry, mix design and shooting techniques by Armelin [10] are:

1. A close correlation exists between material and fiber rebound with fiber rebound being consistently higher;

2. The shooting consistency has a direct effect on fiber rebound with stiffer consistencies leading to higher rebound;

3. Higher cement content and presence of silica fume effectively reduced fiber rebound;
4. Presence of an accelerating admixture and high air flow increased fiber rebound;

5. Fiber rebound is directly proportional to fiber length while being inversely proportional to fiber diameter. For circular cross-sections, rebound was found to be linearly dependent on an aspect ratio defined by fiber length upon square root of its diameter.

The model proposed by Armelin and Banthia [110] suggested that steel fiber rebound in dry mix shotcrete was determined by the ability of the fiber to align itself with the substrate. This is in turn dependent upon the following factors:

1. With increase in fiber length, the fiber mass moment of inertia (I) increases exponentially thereby causing the fiber to rotate at a lower angular velocity towards the shooting surface during impact and thus lose contact before alignment. This leads to higher rebound.

2. An increase in fiber diameter results in an exponential growth in fiber mass, (m) while the ratio between mass moment of inertia and its mass (I/m) is not affected. As a result, while the angular velocity is only slightly affected, the fiber tends to penetrate further into the shotcrete substrate and remain in contact for a longer period of time. This favors alignment and reduces rebound.

3. With a decrease in the dynamic yield strength of shotcrete, steel fibers tend to rotate at greater angular speed towards the target surface and penetrate deeper into the substrate, remaining in contact for a greater period of time. This results in a greater tendency for alignment with a corresponding fall in rebound. Such a condition is achieved upon adding silica fume.
An important role in the rebound of shotcrete is played by rheology of the fresh shotcrete and this issue is addressed in the following section.

2.5 Rheology of fresh concrete and its implication in shotcrete

Rheology is defined as the science of deformation and flow of matter [33]. In terms of fresh concrete, the field of rheology is related to the flow properties of concrete or with its mobility before setting takes place. Since pumpability, shootability and rebound are all factors which determine the hardened properties of the in-place shotcrete [27], one is therefore required to understand the rheology of fresh shotcrete and the factors affecting it. For a fluid, the stress-strain relationship is replaced by a stress-strain rate relationship. When the strain rate (under shear) is proportional to the applied stress (shear stress), the fluid is called *newtonian*. The above relationship is idealized for a liquid confined between two parallel planes, one of which is moved slowly relative to the other, so that a laminar flow results. A newtonian fluid may be represented mathematically as $\tau = \eta \dot{\gamma}$, where $\tau$ is the shear stress, $\dot{\gamma}$ is the strain rate and $\eta$ is the coefficient of viscosity given by the reciprocal slope of the linear relationship shown in Fig. 2.7. Thus, a newtonian fluid is completely described by just one parameter, namely the coefficient of viscosity.

![Fig. 2.7 Behavior of a Newtonian fluid](image-url)
Newtonian behavior is the simplest possible behavior for a fluid and very few fluids conform to it. As shown in Fig. 2.8, non-newtonian behavior may be exhibited in the form of non-linear curves and others where more than one constant is required to completely define the nature of the fluid. A more detailed list of models that attempt to describe rheology of cement paste is given in [81].

Fig. 2.8  Non-Linear flow curves and the Bingham model

Fig. 2.8 represents the simplest of the complicated non-newtonian fluids. Here, two constants (unlike just the one for newtonian fluids) are required to describe the nature of the fluid. Fluids which conform to this behavior are termed as Bingham fluids and are represented mathematically as $\tau = \tau_0 + \eta \dot{\gamma}$, where $\tau_0$ is the yield value of shear and $\eta$ is the coefficient of viscosity. The flow curve is a straight line but does not pass through the origin. In order to measure these two constants, Tattersal [95] devised the Mk I apparatus wherein a standard quantity of concrete (25kg) is subjected to low shear rates. The difference between the power required for giving a certain torque with and without the concrete is first evaluated. This is then divided by the speed of the rotor 'N' to give the
torque ‘T’. A plot of torque ‘T’ vs. speed ‘N’ is found to be linear at low shear rates. The linear curve may be represented as $T = g + hN$, where, ‘g’ is the intercept on the T axis while ‘h’ is the reciprocal of the slope of the line. Fresh concrete, when subjected to low shear rates, as is common in practice, is idealized by the Bingham model. However, fresh shotcrete differs from fresh concrete as it involves the application of medium to high shear rates [50]. A penetration test results in a rapidly increasing curve followed by a plateau, which indicates that, under dynamic conditions of impact, fresh shotcrete is an elasto-plastic material, behaving according to Tresca’s yield criterion of maximum shear stress [7]. Nevertheless, the Bingham model provides a starting point towards understanding the rheology of shotcrete.

2.5.1 Rheology of fresh cement paste

An indirect understanding of fresh concrete rheology is possible through the understanding of its constituents. As the cement paste lubricates the aggregates in a concrete mix, therefore for concrete mixes with the same aggregate gradation and content, the rheological parameters for the mix ought to be close to those for the cement paste. It is necessary therefore to understand the structure of fresh cement paste.

Cement paste may be modeled as a suspension of solid, reactive particles in water [59]. The rheological behavior of cement paste is very different from that of a suspension of solid, inert particles in water of similar grading. Because of the electric charges on the surface of dry cement particles, they do not disperse easily in pure water, rather they tend to form flocs [85]. Since a good number of particles are in the range of 1μm in size, interparticle forces and gravity forces are of the same order of magnitude and hence both should be considered [39].
The interparticle forces may be van der Waals forces or the electrical double layer interactions [105]. Van der Waals forces generate attraction between neutral, chemically saturated molecules. Three types of such intermolecular attraction are recognized [50]:

- Two molecules with permanent dipoles mutually orient each other in such a way that, on average, attraction results;
- Dipolar molecules induce dipoles in the other molecules so that attraction results;
- Dispersion forces (also called London dispersion forces), are operative between non-polar particles. They arise due to polarization of one molecule due to fluctuations in the charge distributions in a second molecule and vice-versa.

London dispersion forces account for nearly all the van der Waals interactive forces operative in cement suspension. Van der Waals interactive attraction is, to a first approximation, inversely proportional to the square of the separating distance between two particles.

The electrical double layer appears for most substances in contact with an aqueous medium. It consists of the particle surface charge and an accumulation of counterions (opposite charge) in the liquid near the surface of the particle. The particles may obtain a charge either due to imperfections in the crystal structure near the surface or through preferential adsorption of specific ions on the surface. In the case of cement grains coated in a CSH gel membrane, the former is highly probable as the conditions of high supersaturation under which the membrane forms, produce a highly disordered amorphous structure. On the other hand, the second scenario is equally plausible for, this
membrane is postulated to form as a result of a re-adsorption of Ca\(^{2+}\) onto a partially hydrolyzed anhydrous cement grain and therefore would be susceptible to adsorption of excess ions from solution.

It has been shown that suspensions are stable when repulsive double layer interactions are larger than van der Waals forces and that there is flocculation in the opposite case [44, 100]. Which means that suspensions have good flowing capacity when repulsive forces dominate. On the other hand if the repulsive double layer forces are smaller than attractive van der Waals forces, the solid particles form a structure inside the liquid and the suspension is very cohesive.

2.5.2 Rheology of fresh shotcrete

It has been shown by Tattersal [96] that for a given concrete placement requirement, it is possible to identify a region, known as the workability box (Fig. 2.9) or “the suitability diamond” [95]. This would enclose all such values of \(\tau\) and \(\eta\) which are suitable for a particular application. Cast concrete requires lower yield values of resistance and plastic viscosity for application that encounter lower shear rates.

The rheological requirements for the shotcrete process are: [27, 49]

- Low viscosity at high shear rates (aid the ease of pumping and spraying);
- High viscosity at low shear rates (achieve higher build-up);
- High yield value after spraying (achieve higher build-up);
- Low viscosity for the in-place shotcrete (to minimize rebound).

2.5.3 Effect of admixtures and additives on concrete rheology.

*Fly ash:* Replacement of cement with fly ash based on mass, results in a reduction in the yield stress (\(\tau_0\)) while very little change is observed in the plastic viscosity (\(\eta\)) [48].
Fig. 2.9 Relationship between 'g' and 'h' and the workability box [95]

Correlation coefficient = 0.19
It makes concrete more flowable and the effect of fly ash is similar to adding water. According to Mehta [70], fly ash effects dispersion of the cement flocs while increasing the particle packing. Due to its spherical shape, it results in a ball bearing effect, all of which lead to ease in placeability and pumpability. However, the loss in yield value means lower build-up, which was also confirmed in this research.

*Ground-granulated blast furnace slag:* There is generally a decreasing trend for both $\tau$ and $\eta$ with the addition of slag [95]. It must be borne in mind that the tests were carried out about 20 minutes after mixing with water. This may therefore not be representative of conditions encountered in dry mix shotcrete.

*Silica fume:* Mixes containing silica fume are cohesive. Small additions of silica fume (in the order of 2-3% will act as a pumping aid for normal concrete [39]. According to Tattersal [97], substitutions of cement with silica fume up to a threshold value (which depends upon the cement content), reduces viscosity by up to 50%. The threshold value decreases with decreasing water content. Yield value is nearly constant until the threshold value is reached and then it increases dramatically [50]. Ivanov and Roshavelov concur with this and report that with increase in silica fume content, both the parameters, $\tau$ and $\eta$ decrease till the threshold value which is followed by a rigid increase in their values [61].

*Limestone filler:* Using Limestone fillers with mean particle size 3-5$\mu$m, has been found to complement the deficiency of fine particle sizes in cement. It results in higher cohesion and better plasticity. Yield stress reduces with increase in replacement and viscosity drops after a certain threshold value. Nehdi [81] also reports a reduction in both these parameters.
As the limestone fillers used in the references above are of the same particle characteristics as HRM, one should expect a similar effect for HRM upon the rheological characteristics of cement paste, especially as with respect to dry mix shotcreting, no chemical interactions need be considered. If one expects therefore with HRM too, a reduction in $\tau$ and $\eta$, one may predict a reduction in rebound but no improvement in build-up for the HRM blended shotcrete. The results in the present study do indeed agree with the above predictions.

In general, the effect of microfillers on fresh concrete rheology is to reduce viscosity [81]. Yield stress was found to increase as is confirmed with the increase in superplasticizer requirement for equal workability. The filler effect on the rheology of an additive will depend on its fineness, its particle size distribution and its particle shape. A continuously graded admixture will have a higher maximum particle packing because the finer particles will fit into the gaps between the coarser particles. The viscosity of suspensions usually increases as the admixture becomes increasingly gap-graded. Also, any deviation from a spherical shape implies an increase in viscosity for the same phase volume. Thus, the finer and more spherical the particle, the better are the rheological properties. This statement holds good for shotcrete as well.

**Polysaccharide gum additives (PSG):** Ghio and Monteiro [49] report that the rheological properties of fresh concrete can be suitably modified with PSG. The viscosity of concrete under low shear rates tends to be very high whereas under high shear rates it is no different from concrete without the additive. These conditions are ideal for wet-mix shotcreting as it enables pumping and shooting while, once placed, the quick viscosity recovery ensures a higher build up.
2.6 Fracture mechanics

Most steel fiber reinforced concrete or shotcrete (SFRC and SFRS) used in practice contain low volume fractions (<1%) of fibers. At such low volume fractions, improvements in compressive or flexural strengths are not expected. The real advantage with fibers is apparent after matrix cracking, when fibers bridge these cracks and undergo pullout processes, such that deformation can continue only with a further input of energy from the loading source. This property of steel fiber reinforced concrete—which manifests itself as the long descending branch in the load-deformation curve—is often referred to as toughness.

In a cement-based composite under tension or flexure, the brittle matrix is almost always the first to fail by cracking. Fibers, if well bonded to the matrix, transmit stresses across these matrix cracks and preserve the load carrying capacity of these sections. The resistance of the section to further cracking depends largely on the bond-slip characteristics of the bridging fibers and a number of possibilities, including complete fiber pullout to a fiber fracture across a crack. Thus, fiber reinforced composites exhibit better performance not only under static and quasi-static loading conditions but also under fatigue, impact and impulsive loading regimes [24].

Banthia and Trottier [19] concluded that for deformed fibers, peak load supported by those fibers that are aligned in the direction of loading are higher than those supported by fibers inclined with respect to loading direction. Also, the peak loads occurred at smaller slips for aligned fibers. Which means that an aligned fiber absorbs a greater amount of energy at a certain slip than one that is inclined. High strength concrete features
premature matrix failure conditions in the form of matrix splitting or fiber fracture and thus incites a brittle response.

In a subsequent paper, Banthia and Trottier [16] reported that deformations in a fiber enhance its energy-absorbing capacity. Moreover, deformations at the ends were more effective than those over the entire fiber length. Further, they note an influence of matrix strength over toughness, which in turn, is dependent on fiber-geometry. Hooked-end fibers, were generally found to be more efficient than other fiber-geometries [25]. Pullout resistance of the individual fibers is the most important factor governing composite toughness. This, in turn, is affected, among other things by fiber geometry and matrix properties [17], fiber inclination [80], fiber grouping [51], curing conditions [21], rate of load application [20, 52], test temperature and the existence of sustained strains [18].

2.6.1 Flexural toughness characterization

ASTM C1018 and JSCE SF-4 [12, 62] are two methods most widely employed to determine flexural-toughness in fiber reinforced composites. Banthia and Trottier [22] discussed the difficulties encountered in predicting toughness with these methods. The most widely expressed concern with ASTM C1018 is the location of the “first crack”, a vital prerequisite for this test method. The ambiguity on this point in the code can lead to toughness indices for plain concrete being as high as for FRC/FRS whereas all the while, visual observations and common sense suggest otherwise!

While the JSCE method does away with the concerns related to location of first crack and the instability in the descending part of the load-deflection plot, it too is however, not without limitations. The flexural toughness factors are specimen geometry-dependent.
This makes an exact correlation with the field performance of FRC/FRS rather difficult. Moreover, the end-point chosen on the curve for determination of toughness (deflection=span/150), is often criticized for being far greater than allowable serviceability limits. The behavior immediately following the first crack, which may be of importance in many applications, is not indicated in the flexural toughness factor in any way. Further, this method fails to distinguish between the pre-peak and post-peak behaviors by adopting a smeared approach of using the combined area under the curve to calculate flexural toughness factors.
Chapter 3 – Experimental Program

3.1 Introduction and objectives

As described in previous chapters, the dry-mix shotcrete produced with conventional concrete materials was found to have very high rebound losses, which also resulted in the requirement of multiple passes of the nozzle to achieve the desired build up. One way to resolve this problem is to incorporate silica fume in the dry mix, usually as a 5-15% replacement by weight of cement. However, this led to increased brittle behavior (the bane of high strength concrete), which somehow denies the advantages achieved through reduced rebound.

It was decided therefore to incorporate a different mineral admixture, in this case High Reactivity Metakaolin (HRM) which has been reported to introduce considerable ductility and also high compressive strength in cast concrete. This chapter illustrates the materials used in this study, the equipment utilized and the methods employed to compare and contrast the various parameters which were investigated.

3.2 Materials

The raw materials in the dry mix used for the main body of this research program were a) the shotcrete dry-mix b) HRM c) silica fume, and d) steel macro fibers (used as reinforcement).

*Shotcrete dry mix:* Throughout this research program pre-bagged shotcrete bone-dry mixes were used. They comprised of 19% by mass of ordinary Portland cement (CSA-Type 10), 16% coarse aggregate and 65% fine aggregate. The coarse aggregate used was
3/8" (9.5mm) rounded type aggregate while the fine aggregate consisted of about 37% forestry sand, 44% screened sand and the remaining (19%) superfine sand, thereby conforming to ACI Gradation No. 2.

**HRM:** High Reactivity Metakaolin was supplied by Advanced Cement Technologies under the trade name *Powerpozz.* The physical and chemical properties of the HRM used in this study are listed in Table 3.1 & 3.2 below.

**Table-3.1 HRM-Physical Properties**

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specific gravity</strong></td>
<td>2.50</td>
</tr>
<tr>
<td><strong>Color</strong></td>
<td>White (Hunter L value=90)</td>
</tr>
<tr>
<td><strong>Physical form</strong></td>
<td>Dry powder</td>
</tr>
<tr>
<td>+ 325 Mesh (45 μm) residue</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td><strong>Average particle size</strong></td>
<td>&lt; 2.50μm</td>
</tr>
<tr>
<td><strong>Shape of Particles</strong></td>
<td>Book Structure*</td>
</tr>
<tr>
<td><strong>Specific Surface Area</strong></td>
<td>10,000 m$^{2}$/g</td>
</tr>
</tbody>
</table>

* Refer Slide 5.2, Chapter-5

**Table-3.2 HRM-Chemical Composition (Wt %)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$</strong></td>
<td>&gt; 97</td>
</tr>
<tr>
<td><strong>Sulfur Trioxide (SO$_3$)</strong></td>
<td>&lt; 0.50</td>
</tr>
<tr>
<td><strong>Alkalis (Na$_2$O, K$_2$O etc.)</strong></td>
<td>&lt; 0.50</td>
</tr>
<tr>
<td><strong>Loss on Ignition</strong></td>
<td>&lt; 1.00</td>
</tr>
<tr>
<td><strong>Moisture Content</strong></td>
<td>&lt; 1.00</td>
</tr>
</tbody>
</table>
**Silica fume:** Silica fume used in the present study came from the flue gases of a ferrosilicon plant. It is a ready-to-use dry densified powder. The physical and chemical properties are given in Tables 3.3 and 3.4 below.

**Table-3.3  **Silica fume-Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.2</td>
</tr>
<tr>
<td>Color</td>
<td>Dark gray</td>
</tr>
<tr>
<td>Physical form</td>
<td>Dry powder</td>
</tr>
<tr>
<td>Specific Surface Area</td>
<td>20,000 m²/g</td>
</tr>
<tr>
<td>Average particle size</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>Shape of Particles</td>
<td>Spherical*</td>
</tr>
</tbody>
</table>

- Refer Slide 5.3, Chapter-5

**Table-3.4  **Silica fume-Chemical Composition (Wt %)

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ + Al₂O₃ + Fe₂O₃</td>
<td>97</td>
</tr>
<tr>
<td>Quartz</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Alkalies (Na₂O, K₂O etc.)</td>
<td>Trace</td>
</tr>
</tbody>
</table>

**Fibers:** Two steel fiber types, geometrically differentiated as Flattened-End and Hooked-End, were used in this study. They were added at a dosage rate of 60 kg/m³ which resulted in a fiber volume fraction of 0.76 % in the batched dry-mix. The steel macro fibers used in this study had the characteristics given in Table 3.5.
Table-3.5  *Fibers: Technical Information*

<table>
<thead>
<tr>
<th>Trade name</th>
<th>Novotex</th>
<th>Dramix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Novocon</td>
<td>Bekaert</td>
</tr>
<tr>
<td>Material</td>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>Fiber length</td>
<td>30 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td>0.70 mm</td>
<td>0.50 mm</td>
</tr>
<tr>
<td>Average aspect ratio</td>
<td>43</td>
<td>60</td>
</tr>
<tr>
<td>Deformation</td>
<td>Flattened Ends</td>
<td>Hooked Ends</td>
</tr>
<tr>
<td>Density</td>
<td>7850 kg/m³</td>
<td>7850 kg/m³</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>1150 MPa</td>
<td>1115 MPa</td>
</tr>
<tr>
<td>Schematic</td>
<td><img src="image" alt="Schematic" /></td>
<td><img src="image" alt="Schematic" /></td>
</tr>
</tbody>
</table>

3.3  **Mix design**

Silica fume has been used in shotcreting in North America at cement replacement levels of 5-15 %. Hence, to compare and contrast the effects it has on dry mix fiber reinforced shotcrete, levels of replacement for HRM had to be in the same range. From a materials cost point of view however, it was decided to study the effects of the two admixtures only at 5 and 10% cement replacement rates. A triple blended shotcrete mix, having 5% each of silica fume and HRM was also investigated to study the effect of a combination of both mineral admixtures in the same mix. All mixes were investigated with and without fibers. This led to a total of eighteen mixes as shown in Table-3.6.
<table>
<thead>
<tr>
<th>MIX N°</th>
<th>Fiber content (kg/m³)</th>
<th>Silica fume</th>
<th>HRM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flattened End</td>
<td>Hooked End</td>
<td>% replacement</td>
</tr>
<tr>
<td>1. Plain-control (PC)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2. Plain-5% HRM (PM5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3. Plain-10% HRM (PM10)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4. Plain-5% SF (PS5)</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>5. Plain-10 SF (PS10)</td>
<td>-</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>6. Plain-5%HRM+5%SF (PMS55)</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>7. Fiber(FE)-control (FC)</td>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8. Fiber(FE)-5%HRM (FM5)</td>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9. Fiber(FE)-10%HRM (FM10)</td>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10. Fiber(FE)-5%SF (FS5)</td>
<td>60</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>11. Fiber(FE)-10%SF (FS10)</td>
<td>60</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>12. Fiber(FE)-5%HRM+5%SF (FMS55)</td>
<td>60</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>13. Fiber(HE)-control (HC)</td>
<td>-</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>14. Fiber(HE)-5%HRM (HM5)</td>
<td>-</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>15. Fiber(HE)-10%HRM (HM10)</td>
<td>-</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>16. Fiber(HE)-5%SF (HS5)</td>
<td>-</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>17. Fiber(HE)-10%SF (HS10)</td>
<td>-</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>18. Fiber(HE)-5%HRM+5%SF (HMS%%)</td>
<td>-</td>
<td>60</td>
<td>5</td>
</tr>
</tbody>
</table>
3.4 Shotcrete: spraying and equipment

Throughout this research program, shotcrete was produced using a dry-mix rotating barrel equipment (model ALIVA 246 with a 3.6 litre, eight pocket drum) instrumented with a spring-loaded, in-line, air flowmeter (model OMEGA FL8945). This machine (Fig.3.1-a), operates at two rotor speeds such that speed-1 allows for a discharge of 1.5 m$^3$/h while speed-2 allows for a discharge of 4 m$^3$/h. Water was introduced in the hose 2 m before the nozzle at a high pressure (between 1 and 5.2 MPa), controlled and read on a manometer by the operator at the nozzle. The high pressure water system enables a better water dispersion in the mix as well as a reduction in the variation in the water feed caused by fluctuations in the air pressure (between 0.5 and 0.8 MPa). Additionally, a 20 m long hose with 50 mm internal diameter, and a maximum rotor speed were used throughout in order to minimise any fluctuations in the feed of the material to the nozzle.

Mixes were shot on prepared wooden forms with tapered edges (500 mm x 300 mm x 100 mm), that were mounted on the wall of a chamber (2.4 m x 2.4 m x 2.4 m) designed specifically for shotcrete research (Fig.3.1-b).

3.5 Shooting consistency and penetration resistance

When dealing with rebound in dry mix shotcrete, one of the most important parameters to be considered is the shooting consistency (or shooting stiffness), with rebound increasing for stiffer (or drier) shooting consistencies. It is generally recognised that although some degree of variation in the amount of water may be allowed, depending upon the position of shooting (overhead or wall), in general, dry mix shotcrete is a workability controlled material. Thus, if too much water is added, the mix tends to have low cohesiveness and
Fig. 3.1 a) Dry-mix shotcreting equipment  
b) Shotcreting in progress
will slough off whereas, if too little water is added, the mix is extremely stiff and the rebound tends to increase rapidly.

In practice, the control of water addition is left to the judgement of the nozzleman, who relies solely on his experience and discretion during shooting. As one can imagine, this leads to a fair amount of scatter on rebound measurements between successive shootings by the same operator which is compounded when different operators are employed for a project. This subjectivity in controlling the shooting consistency is one of the first problems encountered when analysing rebound data from different sources or carrying any kind of research involving dry mix shotcrete.

However, there are tools available to assess the shooting consistency: ASTM C 1117 (1989) recommends and some investigators have used (Schultz, [111]; Prudencio et al. [112], and Jolin, [113]) penetration tests to measure the consistency of fresh shotcrete.

For this research program, a more sophisticated, instrumented version of the penetration test (developed at UBC as part of an earlier research program [10]) was utilised. The device is equipped with one load cell and two Linear Variable Displacement Transducers (LVDTs) and, when using a cylindrical needle, the penetration test results are characterised by an increasing resistance to penetration for the first few millimetres followed by a plateau, which tends to be reached at a penetration depth approximately equal to half the needle diameter (Figs. 3.2 a & b).

Because the plateau value in the penetration test is actually a measure of the yield strength of fresh shotcrete [10], it correlates well with the maximum overhead build up thickness and thus may be treated as a general test for dry mix shotcrete workability.
Fig. 3.2  a) Penetration test  b) Load-displacement plot on the data acquisition system
When carrying out a research program in concrete technology, it is important to set certain criteria that guarantee comparability among mixtures of widely different compositions. In the case of dry mix shotcrete, there are basically two possibilities: either "equal shooting water" or "equal consistency" should be maintained. The former would require monitoring of the water-flow by the nozzle-man at the time of shooting, regardless of consistency, while in the latter, the nozzle-man is allowed to exercise his judgement and maintain minimum variation in consistency by varying the water-flow during shotcreting.

The former criterion leads to erratic water demands depending upon the quantity of fines in the mix, augmented by further loss of control over rebound. Hence, throughout this research program, the "equal workability" criterion was adopted by maintaining a certain predetermined consistency. In this regard, mixes were shot to conform to equal consistency obtained by a penetration resistance of 2±0.5 MPa using a 9 mm diameter needle; those which did not conform were rejected.

3.6 Collection and calculation of rebound

During the vertical shoot on the wall, rebound was collected on plastic sheets placed on the floor of the chamber. The rebound was weighed, and for those mixes with fibers, the fibers were separated magnetically and weighed. Rebound of material as well as fibers was calculated as that amount of each which fell onto the plastic sheets, as a percentage of the total (for each) that was sprayed in making a panel full of shotcrete. The calculation of rebound may be in one of the various ways mentioned in section 2.4.2.
In a laboratory environment such as the one available here, it is possible to accurately measure all of the losses involved in the process of shotcreting. Moreover, since the in-situ material is a panel of shotcrete, weighing the material in-place is also not a problem. Therefore, it makes sense to employ Method-1 as mentioned in section 2.4.2 in order to accurately determine the material and fiber rebound value. In the field, however, more practical methods such as Method-3 may be employed.

3.7 Overhead build-up

An important characteristic of fresh shotcrete is its build-up thickness. This is defined as the maximum thickness to which material may be built-up in a stable manner [27]. It is very important from a practical and economic point of view, to minimise the number of layers required to achieve a certain build-up or thickness. A single pass application is by far the most desirable option.

There is no standard test to measure this characteristic of placement and the maximum build-up thickness is generally obtained by trial and error. Depending upon the application (vertical wall, overhead ceiling, presence of reinforcement, etc.), this property may vary for the same mix [27], and it is thus very difficult to provide a numerical value. Nevertheless, it is useful in order to make a comparison between mixes, and since the same mechanisms are presumably at work during both overhead and vertical rebound, this forms a good test to determine cohesiveness of a given mix.

Morgan [76] observes two mechanisms for failure which may cause the freshly applied shotcrete to behave in an unstable manner namely, adhesion failure and cohesion failure. Adhesion is defined as the ability of shotcrete to stick to the substrate while, cohesion is
the inherent capacity of shotcrete to stick to itself. Adhesion failure involves sloughing off due to self-weight whereas, cohesion failure occurs when the fresh shotcrete ruptures within itself.

Figure below shows the set-up used by Morgan to measure the thickness to sloughing parameter. Depending on the shape of the applied shotcrete, the measured thickness is very variable. In case (a) of Fig 3.3, due to a bigger base and a better shape, the shotcrete would probably exhibit adhesion failure, while in case (b), it is more likely to exhibit cohesion failure.

![Failure modes of built shotcrete](image)

Fig (3.3) Failure modes of built shotcrete

Shotcrete was directed towards a panel fixed to the ceiling of the rebound chamber. Overhead shotcreting produced a honey-comb like placement suspended from this panel and the maximum thickness of the placement was measured just prior to its sloughing off. It must be mentioned that, unlike wall-shotcreting, a test to measure penetration resistance was not possible in this case. Hence, the various mixes and build-up results are not subject to a controlling criterion. It is safe to assume nevertheless, that if the water gauge at the nozzle be set to the same values as during the wall shotcreting (for the corresponding mix), one can expect the penetration plateau to be maintained within the desired limits for the built-up material overhead.
From this kind of test, some general observations are [10, 27]:

- The build-up thickness is generally increased when the slump of the fresh concrete before pumping is reduced;
- The use of accelerators increases the thickness, proportional to the accelerator addition rate;
- Use of fine microfillers (silica fume and carbon black), increases the build up thickness;
- Presence of fibers and use of a high initial air-content results in a greater compaction and can in turn increase the build-up thickness;
- Overhead build up increases with increasing shooting consistency;

3.7.1 Effect of microfillers on rebound and build-up

A related study devoted exclusively to the effect of fillers on build-up and rebound in dry mix shotcrete was carried out as part of this research. In addition to HRM and silica fume, two other admixtures-fly ash and carbon black-were also incorporated such that the four fillers represented a broad range of particle sizes (from 0.05 μm to 10 μm) and a variety of shapes (perfectly spherical to plate-like). The objective was to investigate the individual effects of geometrical parameters of mineral admixtures, namely their mean particle size and particle shape on rebound and build-up in dry mix shotcrete. This was a reasonable expectation, given that microfillers have varying effects on fresh concrete rheology depending upon their particle geometry [81].

The properties of the four fillers is listed in Table-3.7 below:
Table 3.7  Properties of Mineral Admixtures Investigated

<table>
<thead>
<tr>
<th>Admixture</th>
<th>Mean Particle size (µm)</th>
<th>Specific surface area (m²/g)</th>
<th>Particle Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Black</td>
<td>0.05</td>
<td>44</td>
<td>Spherical</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0.10</td>
<td>20</td>
<td>Spherical</td>
</tr>
<tr>
<td>HRM</td>
<td>&lt;2.5</td>
<td>10</td>
<td>Book Structure</td>
</tr>
<tr>
<td>Fly ash</td>
<td>10</td>
<td>0.5</td>
<td>Spherical</td>
</tr>
<tr>
<td>Cement*</td>
<td>50</td>
<td>0.3</td>
<td>Flaky</td>
</tr>
</tbody>
</table>

*Listed for reference.

Carbon Black pigment was obtained from Harcros Pigments Inc. marketed under the trade name ‘Harcros LB-1011’. It is a black amorphous carbon pigment produced by the thermal decomposition of natural hydrocarbons. Its physical and chemical properties are listed below:

Table 3.8  Properties of Carbon Black

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>98.5% Amorphous carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle shape</strong></td>
<td>Spherical*</td>
</tr>
<tr>
<td><strong>Average Particle size</strong></td>
<td>0.05 µm</td>
</tr>
<tr>
<td><strong>Specific surface area</strong></td>
<td>44 m²/g</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>9</td>
</tr>
<tr>
<td><strong>Specific gravity</strong></td>
<td>1.79</td>
</tr>
</tbody>
</table>

*Refer Slide 5.4, Chapter-5
Nine fiber reinforced dry mix shotcrete mixes were designed for this study. The four admixtures were incorporated individually as cement replacement at two dosage rate of 5 and 10 %. Flattened End steel fibers were added @ 60 kg/m$^3$ thus giving a desired fiber volume fraction of 0.76 % in the batched mix. Pre-bagged shotcrete dry-mix was used which had a cement content of 19 % of total weight. Together with the control mix, which had no cement substitutes, the nine mixes given in Table-3.9 emerged.

### Table-3.9 Mix Designs

<table>
<thead>
<tr>
<th>Mix Number and Designation</th>
<th>Water* Content (kg/m$^3$)</th>
<th>Cement (kg/m$^3$)</th>
<th>Admixture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fly Ash (kg/m$^3$)</td>
</tr>
<tr>
<td>1. Control</td>
<td>193.20</td>
<td>437.00</td>
<td>0</td>
</tr>
<tr>
<td>2. FA-5</td>
<td>230.38</td>
<td>415.15</td>
<td>21.85</td>
</tr>
<tr>
<td>3. FA-10</td>
<td>271.73</td>
<td>393.30</td>
<td>43.70</td>
</tr>
<tr>
<td>4. CB-5</td>
<td>245.39</td>
<td>415.15</td>
<td>0</td>
</tr>
<tr>
<td>5. CB-10</td>
<td>227.58</td>
<td>393.30</td>
<td>0</td>
</tr>
<tr>
<td>6. SF-5</td>
<td>218.00</td>
<td>415.15</td>
<td>0</td>
</tr>
<tr>
<td>7. SF-10</td>
<td>232.00</td>
<td>393.30</td>
<td>0</td>
</tr>
<tr>
<td>8. HRM-5</td>
<td>260.00</td>
<td>415.15</td>
<td>0</td>
</tr>
<tr>
<td>9. HRM-10</td>
<td>213.00</td>
<td>393.30</td>
<td>0</td>
</tr>
</tbody>
</table>

* Determined from heat drying fresh shotcrete

### 3.8 Water content

Unlike cast concrete or even wet mix shotcrete, in dry mix shotcrete, there is no way of accurately determining the water content of the batched mix prior to shotcreting. Hence, water content is found indirectly by taking a sample from the in-place shotcrete and
evaporating the water away. In each case, about 2 kg in-situ material was taken and a
difference in weight before and after heating yielded the water content.

Another 2-3 kg of the in-situ material was subjected to a wash-out with water in order to
retain only the aggregates and fibers (if any). This was then oven-dried for 24 hours. The
difference in weight of this sample before wash-out and after oven-drying allowed us to
determine the cementitious content of the in-situ material. It was then possible to
determine the water/cementitious ratio of the in-place shotcrete.

3.9 Compression tests

Compression tests were conducted on cylindrical cores, 85 mm in diameter and 100 mm
in height, drilled out from the shotcrete panels. This was done with a 220,000 lb. (981
kN) hydraulically controlled testing machine in accordance with ASTM C42.
Appropriate corrections for the non-standardised length/diameter ratio were made in
accordance with ASTM C39.

3.10 Flexural tests on beams

Beam specimens were obtained from the shotcrete panels, each measuring 100 mm x 100
mm x 350 mm. Three beams were tested for each mix under four-point flexure on a span
of 300 mm in accordance with ASTM C 1018-96. A 150 kN floor mounted Instron
materials test system (Fig. 3.3) was used. As is well known, during a flexural toughness
test, there is crushing at the load point and settlement of the specimen supports with the
result that the measured beam deflections are often far greater than the true deflections at
the specimen neutral axis. In order to correct for deflections arising from support
Set-up showing the 'Japanese yoke'.
settlements, a yoke, as suggested in the Japanese standard (JSCE-SF4 [62]), was installed around the specimens as shown in Fig. 3.4. It has been previously shown that it is only with the help of a yoke [22] or equivalent deflection measuring system that true beam deflections (conforming to the theoretical deflections) can be measured. The applied load and deflection data were electronically acquired at an acquisition frequency of 1 Hz. JSCE toughness parameters are based on the total amount of energy that is required to cause a specific deflection in the beam specimen. The absolute toughness \( \tau_{JCI} \) is defined as the area under the load deflection curve to a deflection of span/150. Another parameter, called the flexural toughness factor, \( \sigma_b \), a measure of the equivalent flexural strength, is defined as,

\[
\sigma_b = \frac{\tau_{JCI} \times S}{\delta_{150} \times w \times d^2}
\]

where,

\[
\begin{align*}
S & = \text{beam span} \\
W & = \text{beam width}, \\
D & = \text{beam depth}, \text{ and} \\
\delta_{150} & = \frac{S}{150}
\end{align*}
\]

3.11 Microscopic analysis

In order to study the changes induced by incorporating HRM at the microscopic level, it was decided to carry out X-ray diffraction analyses and observations under the Scanning Electron Microscope (SEM).

For the SEM observation, two cylinders were prepared; each had a water/binder ratio of 0.35 and HRM at 10 % replacement by weight of cement. SEM and XRD analysis were carried out on each after 7 and 28 days of curing. Two other cylinders were cast, one with
pure cement and the other with 10% silica fume as cement replacement. The water/binder ratio was maintained at 0.35. These two specimens were observed after one day of curing to study the effect of silica fume in the system, both physical and chemical. The fractured specimens were oven dried for 24 hours at 105°C after which they were gold coated and mounted in the microscope. A small amount of each cylinder was ground to fine powder and analysed under X-ray diffraction for its chemical and crystalline content. Results are reported in chapter-4.

Similarly, the various admixtures investigated in this research program were carefully observed under the SEM to understand their physical characteristics such as particle shape and size.

A pinch of each admixture (Fly ash, HRM, Silica fume and Carbon black) was added to about 3-4 ml of alcohol and the mix was agitated thoroughly to ensure complete dispersion and deflocculation. A drop of this suspension was then placed on the graphite mount which was later placed under the microscope. The alcohol being volatile, evaporated soon and allowed one to observe the individual particles. The SEM micrographs are included in chapter-5.
Chapter 4 – Effect of HRM and Silica fume on Microstructure

4.1 Introduction

Due to its high pozzolanic reactivity, HRM has considerable effects on the hydrated cement paste matrix such as changes in the chemical composition and content of hydrated products, formation of new products, changes in morphology of the gel and related changes in pore size and porosity. Together, these changes are grouped as a) Grain size refinement and b) Pore size refinement. Consequently, as part of this research program, microstructure investigation was conducted upon blended cement pastes containing HRM or silica fume to study the effect of the admixtures on hcp microstructure. Scanning Electron Micrographs showed the various features that may be expected from incorporation of HRM while, X-ray diffraction provided a qualitative measure of the changes in hcp composition. This chapter illustrates the results from these studies accompanied with reviewed material on the subject from literature. The effects of HRM and silica fume are compared in order to explain some of the macroscopic properties seen in later Chapters.

4.2 Effect of HRM on hcp microstructure

On complete hydration, up to 28 % by weight of OPC is expected to be converted to portlandite (CH) although complete hydration is only a theoretical concept; typically CH content at extended ages of curing is in the range of 16-20 % [106]. Pozzolanic materials when partially replacing cement and mortar react with the portlandite to produce
Fig. 4.1 Change in CH content vs. time for a) HRM mortar and b) HRM paste [101]
additional cementitious gel, the formation of which apart from increasing strength, has the added benefits of pore blocking and reduced permeability [107].

Wild And Khatib [101] report that with HRM the CH content (expressed as percent by weight of cement) is significantly below that of control pastes at shorter curing periods whereas, at longer curing periods the differences are less pronounced (Fig. 4.1).

The conclusions drawn from their study were:

1. The amount of CH detected in young mortar pastes (both with and without metakaolin) is less than those detected in the equivalent aggregate free pastes. This is explained in terms of a reduced initial hydration in the mortar pastes due to the formation of a denser bulk cement paste matrix of lower w/c ratio than the cement pastes in the equivalent aggregate free pastes. It is suggested that this may have been caused by better compaction of the paste matrix in the mortar and greater loss of water due to bleeding, relative to the neat paste.

2. The CH contents of both HRM mortars and their equivalent pastes show a minimum at about 14 days, which coincides well with observed maximum relative strength. This is attributed to a peak in pozzolanic activity for which more CH is being removed from the paste than is being generated by cement hydration.

3. Reaction between HRM and lime is severely retarded. This is accompanied by a corresponding increase in the CH content. This retardation is due to the formation of an inhibiting layer of reaction product on the HRM particles.
4. Due to its relatively low SiO₂ content, even at 15 % HRM there still is 50 % CH present relative to that in control paste. This indicates that higher replacement levels would be required to completely consume CH.

Bredy et al. [31] investigated five compositions with cement substitutions of 10 % to 50 %. Microstructure studies (XRD) showed that blended pastes were less crystallized than the plain ones. Mercury intrusion porosimetry showed that the porosity in the blended mixes was higher than with cement alone, beyond 20 % substitution. SEM studies of pore sizes showed that HRM enhances smaller diameters. Differential thermal analysis (DTA) carried out by them showed that HRM considerably reduces portlandite (CH) and results in appearance of new products, hydrated gehlenite (or strätlingite) \(-\text{C}_2\text{ASH}_8\) - which is not found in pure OPC pastes. Ambroise et al. [4] found from SEM analysis that the matrix is poorly crystallized and the CSH gel is typically rich in Si with a molar Ca/Si ratio varying from 1 (for 50 % HRM) to 1.6 (for 15 % HRM). Bredy et al. also found that XRD analysis confirms that portlandite content falls considerably with increasing HRM content. However, for higher HRM contents (40-50 %) the peaks are all of \(\text{C}_2\text{ASH}_8\) which is increasingly well crystallized for higher contents of HRM and at later ages of curing. In blended cement pastes, hydrated gehlenite crystallizes in pores and reduces their diameters; the matrix is less crystalline and at higher replacement contents, some HRM particles remain unreacted.

4.3 **Effect of silica fume on hcp microstructure**

When using silica fume, there is substantial change in the microstructure of the cement paste. The structure is denser and more amorphous and the interface within the CSH is
indistinct as though the particles have partly fused [73]. The apparent improvement in bonding within the CSH does not seem to improve the overall mechanical strength. The strength of cement pastes made with and without silica fume is the same at similar water/cementitious ratios. Detwiler and Mehta [45] have shown that addition of silica fume reduces the pore sizes. This vastly improves durability. Portlandite consumption of silica fume blended pastes is very high and therefore, one may expect increase in compressive strength. The Ca/Si ratio of CSH gel in vastly reduced in presence of silica fume and the paste is poor in aluminum hydrates [81]. The paste aggregate interface in mortar and concrete shows a strong bonding and large silica fume particle surrounded by CH crystals exist at the transition zone [14]. The appearance of silica fume particles at the transition zone suggests the agglomeration phenomenon at the interface [28]. The affixation of CH to silica fume particles is due to the affinity of silica fume to Ca$$^{++}$$ ions [34]. As was confirmed in this research, the residual CH crystals (remaining after the SiO$_2$-Ca(OH)$_2$ reaction) were not easily discerned through SEM observations. Their presence is manifested in the XRD analysis. This is perhaps due to the change in morphology of the compound—from massive tubular crystals to those much smaller in dimension. This transformation is due to the increase in nucleation sites for cement hydration and portlandite consumption by silica fume. The low heat of hydration results in a dense and amorphous CSH gel.

In particular, silica fume has been successfully used to check leaching of shotcrete tunnel linings by effectively reducing the content of CH as well as other soluble alkalis and by densifying the microstructure of the matrix [32]. On the other hand, Lagerblad and Utkin [66] express concerns with undispersed grains of silica fume turning rapidly into alkali-
silica gel nodules. Though the gel rim may transform into CSH with time, if further exposed to alkalis, the gels show a tendency to react, which in turn would lead to expansion and cracking. Studies [82] on the influence of several mineral admixtures on the transition zone of concrete has shown that the substitution of cement by silica fume, to some extent changes the thickness of the transition zone. The concentration of CH is vastly reduced but the introduction of admixtures does not change the degree of preferred orientation of these CH crystals in the transition zone. Study of the fracture surfaces in a paste cast against a fractured rock indicates that the failure crack starts at the notch and either propagates along the original interface, or else enters the paste at an angle before turning and running parallel to the interface but several millimetres from it [72]. Silica fume pastes tend to generate a sufficiently strong bond to favour the second mode, especially when cast against the andesite rock.

4.4 Results of SEM

Pure cement paste and silica fume blended cement paste were observed after one day of curing. This was in order to study the effect that silica fume had even at early ages on the microstructure of hcp. Specimens with HRM were observed after 7 and 28 days of curing in order to study the progress of hydration in HRM-blended cements. This was not repeated with silica fume for its effects on the microstructure are well documented.


The ordinary cement paste showed different morphologies of C-S-H. Both plate-like and honeycombed structures are visible. Some unhydrated cement cores are present at this early age. One-day old hcp must definitely have a lot of ettringite and CH. However, we were not
able to identify any ettringite rods. Perhaps at this level of magnification (x 800), ettringite could not be easily distinguished. Likewise it was not possible to identify any CH crystals through these micrographs either. Powder-XRD analyses were definitive in indicating the presence of both CH and ettringite, both of which are crystalline.

Slide 1: - We see an unhydrated cement particle which is cuboidal in shape. After only one day of hydration, most of the ‘alite’ phases and all of the ‘belite’ phase are still unreacted and hence appearance of these cement grains is not surprising.

Slide 2: - We can distinguish different forms of CSH from plate-like at the right hand corner, to honeycombed morphology in the surrounding region.

Slide 3: - One observes the honeycombed structure once again, though at this magnification (x 1000), it is still not possible to be certain.

Slide 4: - The plate structure in the centre of this slide is clearly darker than its surroundings. Moreover, it is not a hexagonal shaped growth. This leads us to conclude that it is C-S-H gel of a plate-like morphology. The surrounding areas are probably also C-S-H but of a different form—honeycomb or fibrilar.

B). Silica fume cement composite.

This paste had 10 % silica fume as replacement by weight of cement. The water/cementitious ratio was equal to 0.35 and hence a few drops of superplasticizer was added to achieve the desired workability.
Slide 4.5: - One can see smaller but greater number of pores. It is perhaps due to poor compaction and more time spent in mixing. This would have led to larger volume of air to be entrapped. (The flakes are due our omission to use an air jet prior to mounting into the SEM!)

Slide 4.6: - The large plate like structure of a lighter hue, is most certainly a CH crystal on its edge. This surmise is based on the fact that it is lighter than its surroundings, and is much too large to be an ettringite crystal. (It certainly does not possess the correct aspect ratio.) Moreover, CH tends to grow near and around pores as this is where maximum water is likely to be available. The apparent voids in the vicinity of this crystal make it more likely that we are seeing a CH crystal here.

Slide 4.7: - We can see ettringite crystals to the bottom left. Surrounding these plates is CSH gel of honeycomb morphology.

Slide 4.8: - The plates (needles?) seen in this slide are most likely ettringite crystals. Fibrous CSH gel can be seen as spikes jutting out in the surrounding area.

Slide 4.9: - We took this slide to see the numerous tiny needle-like formations. They are ettringite crystals.

Slide 4.10: - This slide was taken to magnify the 'needles' seen in the previous slide. One can clearly see interlocking needles (crystals?) growing normal to their parent surface. The level of magnification makes it very clear that it is indeed ettringite since we expect it to possess columnar structure and high aspect ratio (10 μm x 0.5 μm), both evident from this slide. The surrounding honeycomb like structure is certainly C-S-H as it is growing as an outgrowth onto the parent surface.
C). HRM-blended cement composite [88]

The specimens had 10 % HRM as cement replacement. Water/cementitious ratio was maintained at 0.35.

Slide 4.11: - This slide was taken after 7 days of curing. It shows 2 CH crystals both of which are hexagonal and have very thin plate-like structures. Such features were found throughout the specimen usually in pores and voids.

The following slides are from pastes which were cured for 28 days.

Slide 4.12&4.13: - As with the 7-day paste microstructure, the 28-day cured specimen also showed extensive presence of CH crystals. Portlandite crystals are visible here in these two slides. Hexagonal mesh such as visible here were common at fracture surfaces and protruded from the walls of pores and voids.

Slides 4.14-4.16: - These three slides depict the CH 'rosettes' that were found scattered throughout the specimen.

Slide 4.17&4.18: - Small portlandite crystals surrounded by larger ones are visible in these slides.

Slide 4.19: - An isolated CH crystal is visible in this slide. One can discern that the portlandite is being slowly consumed by the pozzolanic reaction, which explains the gradual rounding of sharp corners/edges for the hexagonal crystal.

Slide 4.20-4.22: - These slides are also of CH crystals in various stages of further reactivity wherefore, not all are truly hexagonal in shape.
The number of pores seen in the specimens with silica fume is larger than with any other. This is due to poor compaction and also a longer mixing duration which must have allowed more air to be entrapped.

One did not observe any ettringite needles in those specimens which had HRM. Indeed one did not see any feature other than the lighter-hued thin hexagonal plates as shown here.

4.5 Powder-XRD analysis.

We could not make out any significant decrease in content of CH from microscopic observations; this was primarily due to our being unable to locate any CH crystals in the 'control' cement paste. Hence, a clear picture of the chemistry at 1-day hydration was obtained through the XRD.

In an XRD analysis, one expects to observe presence of only the crystalline components of the paste. This will mean absence of a number of hydrated products because of their amorphous nature. So, important constituents such as C-S-H gel do not show up. However, the main purpose of this analysis is to distinguish the content of CH crystals in the two specimens because the most telling effect of the pozzolanic reaction is the conversion of crystalline CH into amorphous C-S-H gel upon reaction with reactive silica. Silica fume is a highly pozzolanic admixture and so, a definite reduction in CH is expected. However, since this was a 1-day-old specimen, pozzolanic reaction being slower than the usual hydration reactions of the silicate phases, one will still expect to see some amounts of CH in the paste. This was indeed the case. HRM contains less reactive silica compared to silica fume and therefore does not consume lime as efficiently as the latter. This fact was verified through the XRD plots.

The characteristics of the four XRD plots were as follows.
• The peaks of CH were clearly visible in all the plots. However, in the cement paste (Fig. 4.2), the peaks were higher. This can be correlated with the higher content of CH in ordinary cement paste.

• Peaks of CH at lower intensities were visible more clearly in the ordinary cement paste. Corresponding peaks in the silica fume mix (Fig. 4.3) were of a far lower intensity, so that they were not quite distinguishable from the 'background'.

• The AFt phases are mostly crystalline. Of these, the most significant for cement chemistry is ettringite or high-sulphate. At one day, gypsum (i.e. sulphate ions) is still in sufficient supply to permit formation of ettringite at the end of the C-A-S-H phase equilibrium. Accordingly, we note ettringite peaks, in both the specimens. Interestingly, we observed considerable evidence of ettringite in the composite specimen. The peaks of ettringite are of a lesser intensity than, for instance the CH crystals. This is probably because ettringite, as formed in cement hydration, is less crystalline than CH.

It must be mentioned that the highest intensity peak for ettringite is formed at $2\theta = 9^\circ$. However, we began the analysis at $2\theta = 10^\circ$. This means that we missed the highest peak for ettringite, in our specimens.

C-S-H gel is mostly in the range of cryptocrystalline to amorphous but it is likened to the natural mineral tobermorite, which shows peaks during XRD. Accordingly, weak peaks were obtained in the ordinary cement paste. However, we could not distinguish them from the background, in the silica fume-cement paste. Hence, it is just possible that C-S-H formed as a result of pozzolanic reaction is more amorphous than in the usual hydration reaction. Still one cannot be certain on this since the peaks were too faint to distinguish, in the first place.
It must be pointed out that, we were interested in peaks of relatively high intensity only. Thus, we have reported only those peaks which had higher than 50% intensity.

In pure systems, AFm phase will show clear peaks, as they are highly crystalline, but in Portland cement and its composites, one cannot distinguish their peaks since with the inclusion of impurities, they lose much of their crystallinity, and become a highly amorphous phase.

For those specimens that had HRM, presence of CH was substantial both at 7 (Fig. 4.4) and 28-day (Fig. 4.5) ages. This supports the visual SEM observations of the corresponding specimen. It is worth noting that no ettringite appears in XRD plot at either age of curing. Tobermorite peaks do not appear in these plots which means that with HRM, the resulting CSH gel is almost entirely amorphous. This should lead to higher strength and better fracture toughness, which is noted by Dubey and Banthia [47] and Calderone and Gruber [36,37]. Of particular interest is the fact that one does not see any peaks corresponding to strätlingite (C$_2$ASH$_8$) in either plot. This agrees with the observations of Bredy et al [31] who also report that at the level of HRM incorporated into these specimens (10% cement replacement), there is an absence of strätlingite, which appears only at levels of replacement beyond 30%.

4.6 HRM and silica fume: A study in comparison and contrast

The influence of fillers on the microstructure depends upon its physical and chemical characteristics. Thus, given that HRM and silica fume differ considerably on both levels, it is worth making a comparative study of the resulting hcp.

While silica fume is an extremely fine powder consisting of spherical particles almost wholly composed of SiO$_2$, HRM is on the other hand an alumino-silicate powder of
considerably larger particles which are irregular in shape. This means that silica fume particles perform better both at consuming CH in the matrix and participating as nucleating sites for further hydration. SEM observations confirm that HRM is not as effective as silica fume in consuming calcium hydroxide. Further, there is no indication of the presence of any ettringite with HRM blended pastes.

A point of interest is that while CSH is of tobermoritic type in silica fume blended pastes (and hence appears as peaks on the XRD plots), no such peaks appear during the XRD analysis of HRM blended pastes. One therefore concludes that presence of HRM results in CSH gel which is almost entirely amorphous. It is also reported in literature that the Ca/Si ratio of these gels in case of both pastes is considerably lower than the gel in OPC pastes.

Portlandite (CH) crystals were observed in considerable quantities at both 7 and 28 day-ages in HRM blended cement pastes. They were lighter than their surrounding matrix and were very thin (almost flaky) in appearance. These crystals were always of hexagonal shapes which appeared almost rhomboidal (i.e. 2 opposite sides were very small compared to the other 4). The CH crystals were much smaller than those found with OPC. It therefore indicates that presence of HRM results in formation of smaller CH plates which perhaps renders the hardened matrix stronger than those mixes cement alone.
Conclusion

The scanning electron micrography demands that the specimen be quite dry during observation. This meant that the 1-day old samples had to be dried at 105° C to evaporate all water. This effectively halts hydration; there is no likelihood of thermochemical changes occurring within the system as most changes occur only beyond 200° C in the system. The fracture surface did not yield evidence of CH or ettringite in the case of the control paste. This should not lead one to believe that they were absent in the system. Hence, it becomes vital that an XRD analysis be carried out on all the specimens, in order to get a true account of the composition. One can rely more heavily on XRD as it is based on sound physical relations whereas, an SEM observation is subject to human visual observation and hence it is susceptible to error during interpretation.

Nevertheless, one can get a qualitative idea through a micrograph; it gives an idea of the texture, the porosity and morphology of the hydration products. This alone is sufficient to distinguish, as in the present case, between a pure cement sample and one with silica fume or HRM as replacement.
Slide 4.5
Fig. 4.2  XRD analysis of cement paste (1-day)
Fig. 4.4  XRD analysis of cement-HRM composite (90:10) after 7 days of curing
Fig. 4.5  XRD analysis of cement-HRM composite (90:10) after 28 days of curing
Chapter 5 – Fresh Shotcrete Properties

5.1 Introduction

Shotcrete differs from cast concrete in that while the raw materials are the same, the very act of placement under pneumatic self-compaction renders it with considerably different early-age properties. The most important parameter that is affected is workability. Whereas in conventional cast concrete, one may perform a slump test to determine workability, in shotcrete for obvious reasons, such a test is not permissible. However, a measure of workability is required to gauge the ease with which shotcrete may be pumped, placed and also prevent the in-place material from sloughing off.

In addition, in the particular case of dry mix shotcrete, as explained in Chapter-3, one does not know the exact amount of water in the mix prior to placement. In order to correlate strength at later ages to the mix design, one clearly needs to assess the water content directly or indirectly.

Further, since rebound is one of the main concerns in the case of shotcreting, it is important to monitor this parameter during spraying, in order to minimize and relate this value to the existing mix design, shooting techniques and spraying equipment. Therefore, the study of fiber reinforced dry mix shotcrete in the fresh state involves evaluation of its water content, rebound, build up and consistency.

The steps involved in the assessment of each of these characteristics have already been explained in Chapter-3. This Chapter reports the results of these tests that are relevant to the early-age behaviour of fresh shotcrete.
5.2 Penetration resistance

As a way of standardizing the basis of comparison for various mixes, in this research, the resistance offered by fresh dry mix shotcrete to penetration was chosen as the criterion for selection. Fig 5.1 depicts the penetration resistance offered by the various mixes in this program. The water jet at the nozzle was adjusted so as to maintain the resistance offered to achieve a plateau at about 2±0.5 MPa. This value is chosen as it corresponds to practical considerations of minimum rebound, high strength and satisfactory build-up [6]. Consequently the water content of these mixes was not a constant and had to be indirectly determined and is shown in Table 5.1.
Table-5.1 Water content

<table>
<thead>
<tr>
<th>Mix - Description</th>
<th>Fiber type (or Plain)</th>
<th>Compressive Strength –28 day f’c (MPa)</th>
<th>Water content (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Plain</td>
<td>41.70</td>
<td>237</td>
</tr>
<tr>
<td>10 % HRM</td>
<td>Plain</td>
<td>51.8</td>
<td>230</td>
</tr>
<tr>
<td>5 % HRM</td>
<td>Plain</td>
<td>54.8</td>
<td>219</td>
</tr>
<tr>
<td>10 % SF</td>
<td>Plain</td>
<td>48.8</td>
<td>240</td>
</tr>
<tr>
<td>5 % SF</td>
<td>Plain</td>
<td>49.3</td>
<td>236</td>
</tr>
<tr>
<td>5 % SF, 5 % HRM</td>
<td>Plain</td>
<td>50.1</td>
<td>240</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mix Description</th>
<th>Fiber Type</th>
<th>Water Content Kg/m$^3$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cores (f’c)</td>
</tr>
<tr>
<td>Control</td>
<td>FE-73</td>
<td>196 (51.3)</td>
</tr>
<tr>
<td>10 % HRM</td>
<td>FE-73</td>
<td>213 (55.2)</td>
</tr>
<tr>
<td>5 % HRM</td>
<td>FE-73</td>
<td>260 (46.3)</td>
</tr>
<tr>
<td>10 % SF</td>
<td>FE-73</td>
<td>232 (50.7)</td>
</tr>
<tr>
<td>5 % SF</td>
<td>FE-73</td>
<td>218 (53.9)</td>
</tr>
<tr>
<td>5 % HRM, 5 % SF</td>
<td>FE-73</td>
<td>219 (50.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mix Description</th>
<th>Fiber Type</th>
<th>Water Content Kg/m$^3$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cores (f’c)</td>
</tr>
<tr>
<td>Control</td>
<td>Dramix</td>
<td>225 (66)</td>
</tr>
<tr>
<td>10 % HRM</td>
<td>Dramix</td>
<td>230 (48)</td>
</tr>
<tr>
<td>5 % HRM</td>
<td>Dramix</td>
<td>237 (51)</td>
</tr>
<tr>
<td>10 % SF</td>
<td>Dramix</td>
<td>240 (49)</td>
</tr>
<tr>
<td>5 % SF</td>
<td>Dramix</td>
<td>215 (56)</td>
</tr>
<tr>
<td>5 % HRM, 5 % SF</td>
<td>Dramix</td>
<td>257 (49)</td>
</tr>
</tbody>
</table>

Resistance to penetration is a measure of yield under compression. A related parameter namely, yield under tension for fresh shotcrete is qualitatively assessed through the overhead build-up.
5.3 **Overhead build-up**

It is understood that when the build-up achieved during shotcreting is maximized, the rebound is automatically minimized. This is because both are related to the cohesiveness of the fresh material; higher the cohesiveness, higher is the build-up and lower is the rebound. Thus, it is useful to measure overhead build-up while attempting to design a mix to achieve a minimum rebound.

![Fig.5.2 Overhead Build-up (HRM vs. Silica fume)](image-url)
Fig 5.2 shows the influence of silica fume and HRM on the overhead build-up. One notes that silica fume performs better at improving this parameter. It is not surprising that silica fume is equally efficient in reducing rebound. HRM on the other hand does not seem to significantly affect build-up. A detailed study into this is dealt with in section 5.

5.4 Rebound

The chief distinguishing characteristic of shotcrete vis-à-vis cast concrete in general, and dry mix shotcrete in particular, is the phenomenon of rebound during spraying. The mechanisms involved and the key factors influencing rebound have been dealt with in considerable detail in Chapter-2, where it was noted that the mix design plays a key role. Hence when studying the effect of different pozzolans in dry mix shotcrete, it is important to look at any change that may arise in rebound values.

Further, since geometry of a fiber type greatly influences its rebound, one should expect different values of rebound for the flattened-end and the hooked end fibers. Fig. 5.3 indicates the variation in rebound for material and fiber for those mixes incorporated with flattened end fibers while Fig. 5.4 indicates the same for those mixes with hooked end fibers. As is expected, fiber rebound is always in excess of the material rebound and increases proportionately. As a consequence, the volume fraction of fibers in the in-place shotcrete is lower than in the batched mix, and this would translate as a decrease in toughness capacity of the hardened material. Table 5.2 shows the volume fraction of fibers in the material in-place for the various mixes. As expected, higher the rebound, lower is the in-situ volume fraction.
Table-5.2  \textit{In-situ Fiber volume fraction}

<table>
<thead>
<tr>
<th>Mix</th>
<th>Fiber type</th>
<th>$V_f (%)$</th>
<th>$V_f' (%)$</th>
<th>$R_f (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.62</td>
<td>36.73</td>
</tr>
<tr>
<td>10 % HRM</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.66</td>
<td>28.06</td>
</tr>
<tr>
<td>5 % HRM</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.65</td>
<td>33.64</td>
</tr>
<tr>
<td>10 % SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.65</td>
<td>26.41</td>
</tr>
<tr>
<td>5 % SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.61</td>
<td>30.06</td>
</tr>
<tr>
<td>5%HRM+5%SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.62</td>
<td>30.03</td>
</tr>
<tr>
<td>Control</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.61</td>
<td>38.5</td>
</tr>
<tr>
<td>10 % HRM</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.63</td>
<td>30.39</td>
</tr>
<tr>
<td>5 % HRM</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.59</td>
<td>39.8</td>
</tr>
<tr>
<td>10 % SF</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.63</td>
<td>26.05</td>
</tr>
<tr>
<td>5 % SF</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.61</td>
<td>36.97</td>
</tr>
<tr>
<td>5%HRM+5%SF</td>
<td>Dramix</td>
<td>0.76</td>
<td>0.57</td>
<td>34.73</td>
</tr>
</tbody>
</table>

Fig.5.3  \textbf{Rebound of Material And Fiber for mixes containing Flattened-end fibers.}

One also notes that the hooked end fibers exhibit higher fiber rebound in spite of the fact that the material overall rebound is nearly the same as that for both plain mixes and those reinforced with flattened fibers. This clearly indicates the influence of fiber geometry on
its rebound. Armelin and Helene [9] state that fibers tend to align themselves in the plane of the substrate. Furthermore, this study found that the flattened-end fiber tries to align itself such that the flattest face lies in the plane of the substrate. Likewise, the hooked-end fiber showed a preference toward orienting the hooks in the plane of the substrate. This means that for a given fiber to adhere, it must maximize the contact area with the substrate. Rebound therefore becomes a function of the ease with which a fiber can orient itself toward maximum possible area in contact with the substrate.

Addition of silica fume is seen to reduce rebound considerably and this is attributed to the higher cohesion that results from its incorporation in the dry-mix. While HRM does indeed reduce rebound with respect to the control mix, it is not as effective as silica fume. As rebound and build-up are fresh shotcrete parameters, it is therefore logical to infer that any effect that silica fume, HRM or any other mineral admixture might have on them is due to particle-characteristics of the particular filler. A detailed study into this is described in the following section.

Fig. 5.4 Rebound of Material and Fiber for Mixes containing Dramix fibers.
5.5 Influence of mineral admixtures on fresh shotcrete properties

In the research reported here, four mineral admixtures—HRM, silica fume, fly ash, and carbon black—were investigated in plain and fiber reinforced dry mix shotcrete for rebound and other properties. These admixtures represent particle sizes ranging from 0.5µm to 10µm and particle shapes ranging from spherical to “plate like”. Results indicate that while fly ash is not as effective, both silica fume and carbon black substantially reduce the rebound. The performance of HRM lies somewhere in between. On the whole, in the context of dry-mix shotcrete, it appears that the mean particle size of a mineral admixture influences the rebound far more than the shape.

Use of various mineral admixtures in shotcrete has increased several-fold in the last two decades alone. The admixtures, when employed judiciously, enhance the performance of shotcrete in service and perhaps most importantly, some of them also reduce rebound. For example, silica fume is widely known to reduce rebound [11, 74] in dry process shotcrete, and trials with fly ash have also produced encouraging results [35]. It is often felt however, that the exact role of these mineral admixtures in reducing rebound is not clear and that the influence of the type of admixture, size and shape of its individual particles and the optimum dosage rate for the purpose of rebound reduction are not known. This study attempts to answer some of these questions.

Scanning Electron Micrographs of the four mineral admixtures investigated in this study are given in Slides 5.1-5.4. The chosen admixtures are not only those that are most commonly in use in practice and research, they also cover a wide range of particle shapes and sizes. Their physical properties are given in Table-4.1.
5.5.1 Shooting consistency and workability

Table 5.3 reproduces the mix designs with the additional information of water content associated with each mix as found after the shoot. Clearly, there is a certain definite variation in the water content and so, to compare these mixes, once again the penetration-resistance curves were obtained using a digital penetrometer. These curves are shown in Fig 5.5. If the yield offered by a particular panel did not fall between 1.5 and 2.5 MPa, it was rejected.
### 5.5.2 Rebound

The rebound data for the various mixes are plotted in Figure 5.6, where both material and fiber rebound values are shown. Notice that fiber rebound is always greater than the material rebound and increases proportionally with it.

Both silica fume and carbon black significantly reduced the rebound of material and fiber, and their effectiveness increases with an increase in the dosage rate. However, carbon black is more effective at 10% dosage rate than silica fume. This may be due to its particles being on an average only half the size of silica fume. The effect of fly ash, on the other hand, is not that clear. While a 5% fly ash mix produced a reasonably low rebound (as low as mixes with 5% silica fume and 5% carbon black) the mix with 10% fly ash clearly showed a negative effect. Since the particles of fly ash are in the same size range as those of cement, any improvements in rebound presumably result from its shape which is perfectly spherical (Slide-5.1). This is seen in the form of improvement at 5%
replacement rates. However, fly ash also reaches its optimum level of effectiveness at around 5% replacement rate and an increase in the dosage beyond this value actually produces a detrimental effect. This is contrary to the findings of Cabrera and Woolley [35] who have reported reductions in rebound due to fly-ash at higher percentages (30% of binder).

The rebound is plotted as a function of particle size in Figures 5.7 and 5.8, respectively, for 5% and 10% dosage rates. Notice a definite increase in rebound with an increase in the mean particle size of the admixture at 10% replacement rate. The trend for mixes with 5% replacement rate, however, is not that clear. This highlights the influence of admixture dosage rate and implies that generally speaking a higher dosage rate is necessary for a decisive effect on rebound.

HRM is seen to reduce the rebound considerably. However, while it may be far better than fly ash, its benefits on rebound fall short of those with silica fume and carbon black.
While fly ash, silica fume and carbon black are all spherical, HRM (similar to cement) is irregular (Slides 5.1-5.4). HRM platelets (Slide-5.2) are stacked one on top of other in what is often referred to as a "book" structure. Further, as seen in Table 1, cement and fly ash are in the range of 10 µm in size, silica fume and carbon black are in the range of 0.1 µm and the HRM particles are somewhere in between at about 1 µm. The fact that the rebound for HRM (the only non-spherical admixture) also lies in between that for silica fume and fly ash indicates that its rebound values are controlled more by its size than by its shape. One can hypothesize, therefore, that while both the shape and size of the particles have an effect on rebound, size of the particles has a much greater influence on rebound than the shape.
5.5.3 Overhead build-up

As can be seen from Fig 5.9, mixes having fly ash were nowhere near as effective as those with either silica fume or carbon black in terms of build-up. Because of its relative fineness, carbon black performed even better than silica fume.

![Fig 5.9 Overhead Build-up](image)

Having more fines in the mix clearly increased the cohesiveness of the resulting shotcrete and increased the build-up. HRM did not significantly benefit build-up though it performs far better than fly ash in terms of reducing rebound.

5.6 Effect of triple blending

From the Figs 5.3&5.4, it appears that blending both HRM and silica fume in the same mix reduces the material and fiber rebounds only somewhat with respect to the control. The values for these fall between those obtained with 5% replacement of HRM and silica.
fume individually. Further, one observes that having HRM at 5 % cement replacement in the dry mix does not produce any significant changes in fiber rebound and only a marginal change in the material rebound. Thus, it is possible to see why performance with a combination of both pozzolans at 5 % cement replacement rates falls between those with one admixture at a time at the same dosage rate. This fact further corroborates the evidence cited in Section 5.5 indicating the strong influence of admixture particle size on the material rebound.

Conclusion

It appears that finer the particles of the mineral admixture, the lower the rebound and higher the build-up. Further, as cohesiveness depends upon the extent of particle to particle contacts that can be established, one notes that for the same admixture, there is an optimum dosage rate for desired build-up and rebound. The size and density of the filler particles would heavily influence this rate. Therefore, while both the shape and size of the particles have an effect on rebound and cohesiveness, size of the particles has a much greater influence on rebound than their shape.

Rebound is thus a phenomenon controlled in two phases. The first is one of particle kinematics from the nozzle to the target substrate. The second is the substrate itself and the rheological properties of the impinging shotcrete.

Mineral admixtures influence the second phase, by altering the rheology of the sprayed material. It appears that the components of the matrix such as cement, mineral admixtures and very fine sand do not travel as individual particles, rather, the effect of their shape and size is one of altering the rheological characteristics of the substrate of which they
become a part. Having finer particles in the matrix improves cohesiveness thereby reducing rebound of the incoming material.

Coarse aggregates and macro-fibers on the other hand, do travel as individual particles and hence any change in their geometry will affect their particle kinematics. However, all components of the sprayed material are ultimately influenced by the substrate rheology. It is believed that finer the particle, higher the shear resistance ($\tau$) whereas spherical particles tend to reduce the viscosity ($\eta$) of fresh concrete. Having higher $\tau$ and low $\eta$ is seen to yield high build up and low rebound (As is confirmed with silica fume [27]). Thus an ideal admixture for shotcreting purposes should have finer gradation of particles and be spherical in shape.
Slide 5.1 Fly ash

15.86μm
Slide 5.3 Silica fume

372nm

493nm

253nm

039910 20KY x50.0K 600nm
Slide 5.4 Carbon Black

113nm
48nm
131nm
57nm
77nm

039913 20KV x50.0K 600nm
Chapter 6 – Hardened Shotcrete Properties

6.1 Introduction

Shotcrete has been adopted as the material of choice for use in tunnel linings, rock stabilization, underground support and repair. In all these applications, both compressive strength and toughness are of prime importance. Since plain shotcrete (like plain concrete) is brittle, tensile strength is provided through steel wire mesh reinforcement or, as is becoming increasingly popular due to ease of application among other benefits, through steel macro-fibers dispersed randomly throughout the material. Further, as the addition of pozzolanic admixture is known to render high strength and impart improved durability in cast concrete, one seeks to achieve similar benefits in fiber reinforced shotcrete. This chapter looks at the effects that HRM and silica fume on the mechanical properties of hardened dry-mix steel fiber reinforced shotcrete.

6.2 Compressive strength

Silica fume has been well established as resulting in an increase in compressive strength of cast concrete, when incorporated as cement replacing admixture in the range of 5 to 15%. The increase in compressive strength is due to the pozzolanic action between silica fume and the lime present in the hydrating paste, aided by the alkaline environment. However, the extreme fineness of silica fume results in a high water demand which, in cast concrete, is satisfied through the addition of superplasticizers. In conventional dry mix shotcrete on the other hand, water demand has to be met with an increased supply at
the nozzle and at least some of the improvement due to the pozzolanic action may be marginalized due to the higher water/cementitious ratio in the in-situ material. Therefore, one does not expect, and indeed one does not see, very high strengths for dry mix shotcrete with silica fume. Likewise, though HRM is reported to be a highly pozzolanic mineral admixture and is found to improve compressive strengths in cast concrete, once again in dry mix shotcrete, its addition is not expected necessarily to bring about substantial improvements in the strength. Table 6.1 shows the behavior under compression at 28 days accompanied by boiled absorption results for the various mixes in this study.

**Table-6.1** *Compressive strength (28 days) and Permeable voids*

**a) Plain Shotcrete.**

<table>
<thead>
<tr>
<th>Mix Description</th>
<th>w/c ratio</th>
<th>Permeable voids</th>
<th>Boiled absorption</th>
<th>$f'_c$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>0.45</td>
<td>15.91</td>
<td>7.06</td>
<td>41.70</td>
</tr>
<tr>
<td>PM5</td>
<td>0.39</td>
<td>9.94</td>
<td>4.4</td>
<td>54.80</td>
</tr>
<tr>
<td>PM10</td>
<td>0.50</td>
<td>14.55</td>
<td>6.53</td>
<td>51.80</td>
</tr>
<tr>
<td>PS5</td>
<td>0.53</td>
<td>16.19</td>
<td>7.22</td>
<td>49.30</td>
</tr>
<tr>
<td>PS10</td>
<td>0.55</td>
<td>15.75</td>
<td>7.25</td>
<td>46.80</td>
</tr>
<tr>
<td>PMS55</td>
<td>0.44</td>
<td>15.08</td>
<td>6.83</td>
<td>50.10</td>
</tr>
</tbody>
</table>

**b) Flattened-end Fiber reinforced shotcrete**

<table>
<thead>
<tr>
<th>Mix Description</th>
<th>Water/cementitious ratio</th>
<th>Permeable voids</th>
<th>Boiled absorption</th>
<th>$f'_c$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>0.40</td>
<td>13.93</td>
<td>6.13</td>
<td>51.30</td>
</tr>
<tr>
<td>FM5</td>
<td>0.54</td>
<td>16.20</td>
<td>7.25</td>
<td>46.30</td>
</tr>
<tr>
<td>FM10</td>
<td>0.41</td>
<td>13.45</td>
<td>5.91</td>
<td>55.20</td>
</tr>
<tr>
<td>FS5</td>
<td>0.45</td>
<td>15.37</td>
<td>6.92</td>
<td>53.90</td>
</tr>
<tr>
<td>FS10</td>
<td>0.50</td>
<td>15.75</td>
<td>7.14</td>
<td>50.70</td>
</tr>
<tr>
<td>FMS55</td>
<td>0.40</td>
<td>15.95</td>
<td>7.22</td>
<td>50.80</td>
</tr>
</tbody>
</table>
c) Hooked-end Fiber Reinforced Shotcrete

<table>
<thead>
<tr>
<th>Mix Description</th>
<th>w/c ratio</th>
<th>Permeable Voids</th>
<th>Boiled absorption</th>
<th>$f_c'$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>0.41</td>
<td>14.30</td>
<td>6.35</td>
<td>66.00</td>
</tr>
<tr>
<td>HM5</td>
<td>0.56</td>
<td>17.35</td>
<td>8.00</td>
<td>51.10</td>
</tr>
<tr>
<td>HM10</td>
<td>0.46</td>
<td>15.65</td>
<td>7.01</td>
<td>48.80</td>
</tr>
<tr>
<td>HS5</td>
<td>0.46</td>
<td>14.63</td>
<td>6.57</td>
<td>56.10</td>
</tr>
<tr>
<td>HS10</td>
<td>0.50</td>
<td>15.28</td>
<td>6.95</td>
<td>49.30</td>
</tr>
<tr>
<td>HMS55</td>
<td>0.46</td>
<td>18.38</td>
<td>8.41</td>
<td>49.50</td>
</tr>
</tbody>
</table>

The variation of compressive strength is not so much with respect to the rate of incorporation of the pozzolan but rather has more to do with the water content as one can readily see. The water demand depends upon the ease with which a particular mix can be shot and compacted. Some admixtures (silica fume, carbon black) may be very fine and hence difficult to compact, and some (carbon black for example) may also develop repulsive forces, so that the final compaction is significantly affected by their particle characteristics. As a result, the hardened material may develop a higher porosity which would mean a reduced strength. It must be borne in mind therefore, that unlike the conventional cast concrete, factors other than the mix design affect properties of shotcrete at mature ages. Table 6.2 shows compressive strength of 9 mixes of dry mix fiber reinforced shotcrete incorporating four different mineral admixtures with varying particle characteristics. This leads to a variation in water demand and the entrained air.
Table-6.2  
*Compressive strength and Boiled Absorption and Permeable Voids*

<table>
<thead>
<tr>
<th>Mix</th>
<th>Compressive Strength, MPa</th>
<th>Mix Porosity</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 day</td>
<td>28 day</td>
<td>Boiled Absorption (%)</td>
<td>Permeable Voids (%)</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>37.30</td>
<td>49.90</td>
<td>5.86</td>
<td>13.42</td>
<td></td>
</tr>
<tr>
<td>FA-5</td>
<td>43.40</td>
<td>51.00</td>
<td>5.84</td>
<td>13.18</td>
<td></td>
</tr>
<tr>
<td>FA-10</td>
<td>34.80</td>
<td>48.00</td>
<td>6.10</td>
<td>13.62</td>
<td></td>
</tr>
<tr>
<td>CB-5</td>
<td>19.20</td>
<td>23.80</td>
<td>9.33</td>
<td>19.75</td>
<td></td>
</tr>
<tr>
<td>CB-10</td>
<td>20.00</td>
<td>20.10</td>
<td>9.61</td>
<td>20.18</td>
<td></td>
</tr>
<tr>
<td>SF-5</td>
<td>46.30</td>
<td>53.90</td>
<td>6.96</td>
<td>15.42</td>
<td></td>
</tr>
<tr>
<td>SF-10</td>
<td>29.90</td>
<td>50.70</td>
<td>7.40</td>
<td>16.39</td>
<td></td>
</tr>
<tr>
<td>HRM-5</td>
<td>37.15</td>
<td>46.30</td>
<td>6.95</td>
<td>15.63</td>
<td></td>
</tr>
<tr>
<td>HRM-10</td>
<td>37.58</td>
<td>55.20</td>
<td>5.86</td>
<td>13.39</td>
<td></td>
</tr>
</tbody>
</table>

Table-6.3  
*Carbon Black and silica fume in cast concrete-Compressive strength [45]*

<table>
<thead>
<tr>
<th>w/c ratio</th>
<th>Plain cement</th>
<th>Silica fume*</th>
<th>Carbon black*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>40.5</td>
<td>39.2</td>
<td>35.7</td>
</tr>
<tr>
<td>0.35</td>
<td>35.4</td>
<td>32.9</td>
<td>32.8</td>
</tr>
<tr>
<td>0.50</td>
<td>30.0</td>
<td>28.4</td>
<td>27.2</td>
</tr>
</tbody>
</table>

* 28 day strength (MPa)

<table>
<thead>
<tr>
<th>w/c ratio</th>
<th>Plain cement</th>
<th>Silica fume*</th>
<th>Carbon black*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>43.1</td>
<td>42.1</td>
<td>39.6</td>
</tr>
<tr>
<td>0.35</td>
<td>39.8</td>
<td>38.3</td>
<td>37.6</td>
</tr>
<tr>
<td>0.50</td>
<td>33.4</td>
<td>34.6</td>
<td>32.1</td>
</tr>
</tbody>
</table>

* Replacing cement @ 10% by weight

Now, while Detwiler and Mehta [45] report good compressive strengths with carbon black which in their study is comparable to control mix (having only cement) even up to 10% cement substitution (Table-6.3), this study found a marked reduction in strength with carbon black at both 5 and 10% substitution. Given that HRM and silica fume are highly pozzolanic, while fly ash is less so, one can readily see why both HRM and silica fume improve compressive strength so substantially compared to both control and fly ash blended mixes. But, pozzolanic reaction takes place gradually over weeks and its effects appear only after 10 days of curing. Hence any early variation in the strength of these
mixes with respect to control is due to the physical effect of the individual admixture. The physical changes effected by fine admixtures have been studied in cast cement paste and concrete by Detwiler and Mehta, Bentur and Cohen [11], Goldman and Bentur [53, 54], Nilson et al. [82]. These effects are grouped as the 'filler effect'. Due to their relative fineness, particles of silica fume are seen to fill voids, bridge microcracks and act as nucleating agents for further hydration. This means that the reduction in strength due to reduced cement content is compensated by the filler effect and thus at early ages, strength will still be more or less comparable. Since this has nothing to do with the pozzolanic activity of the mineral, one expects the same with carbon black (which is slightly finer than silica fume and inert). However, boiled absorption and permeable voids for carbon black mixes indicate that more air is entrained during the process of spraying carbon black mixes, which results in reduced mechanical strength.

6.3 Flexural performance

The flexural behavior of dry-mix shotcrete reinforced with steel fibers is indicative of the toughness of this material under static loading. It has been well established that plain shotcrete is not in any way tougher than plain concrete and this led to the incorporation of steel macro fibers in the mix design. Studies on conventional cast concrete have shown that there is a specific geometry for the steel fibers which allows for maximum benefits from a toughness point of view. In general, longer the fiber and larger the fiber aspect ratio, better is its toughness performance [10, 56]. Further, one notes that certain minor features in the fiber such as its ends being flattened or hooked may lead to substantial variation in the toughness for the material as a whole. Armelin [10] classified the fiber-
end variations into two categories: 'dead' anchor and 'drag' anchor. While a dead anchor allows for higher maximum pullout resistance, a drag anchor imparts a higher toughness to the material. Hence, most commercially available fibers include one or the other variant in the geometry. However, when used in dry mixed shotcrete, the key issue is not merely the fiber's performance in hardened concrete under tension, rather it is the ability of the fiber to be part of the in-situ shotcrete in the first instance. That is to say, a longer fiber with a greater aspect ratio may certainly provide better toughness properties to the cast concrete which it reinforces, yet in the shotcreting process, it is the very same longer fiber (having greater aspect ratios) which tends to rebound more. Hence, while in cast concrete, we deal with only one parameter namely, that of higher toughness, with shotcrete, we have to concede a trade-off between the toughness desired and the rebound which must be minimized. Therefore, research such as the present one on steel-fiber reinforced dry mix shotcrete, focuses on minimizing fiber rebound through use of different mineral admixtures so that we may achieve optimum levels of toughness as well as rebound.

6.3.1 Result of tests according to ASTM C 1018

The flexural performance was investigated according to ASTM C1018 '94 and JSCE-SF4, as has been described in Chapter-3. The chief flaw with ASTM C 1018 lies in the ambiguity in its definition of 'first crack', which forms the basis for further investigation. In this study therefore, the location of the first crack was determined in the following manner:

1. For a given mix design, load-deflection curves was plotted for the plain shotcrete beams under flexural loading.
2. The 'initial tangent modulus' for each beam was computed as $E_{IT}$.

3. The chord modulus $E_C$, corresponding to strain $\varepsilon=0$ and $\varepsilon=\varepsilon_{\text{max}}$ was also calculated.

4. The change in the modulus was calculated as $\delta E = E_C/E_{IT}$ and considered a material property for the particular mix whether plain or reinforced, during its pre-peak load behavior. To minimize variation within a mix, $\delta E$ was averaged over 3 beams.

5. Thus, for a fiber-reinforced specimen with a particular dry mix design, upon obtaining its load-deflection behavior under flexure, the initial tangent modulus $E_{IT}$ was first calculated. Then, the supposed chord modulus at first crack, $E_{CF}$ was computed as $E_{CF}=E_{IT}\times\delta E$, where $\delta E$ is already determined according to (4) above for a corresponding plain shotcrete beam.

6. A straight line bearing the equation $p=E_{CF}\Delta$ is drawn, where 'p' is the load in kN, '\Delta' is the corresponding deflection in mm and $E_{CF}$ is as defined in (5) above.

7. The point of first crack on the flexural load-deflection response is determined as the point of intersection between the load-deflection curve and the straight line as defined in (6) above.

8. The load and deflection corresponding to this point of intersection namely, $p=p_{\text{fc}}$ and $\Delta=\Delta_{\text{fc}}$, are defined as the load and deflection at first crack respectively.

9. The above procedure for the determination of first crack is repeated for every mix and further analysis according to ASTM C1018 is carried out.

The curves for both plain and fiber reinforced shotcrete beams for a particular mix are shown in figs.6.1-6.3. As can be seen, there is no indication of any improvement in
toughness accruing from the incorporation of HRM in the matrix, for the pre-peak part of the curve. In addition, we do not see any difference in toughness properties for the two types of fiber geometries.

![Graph showing load vs. deflection with equations and coefficients](image)

**Fig. 6.1 Locating first crack (Plain shotcrete with 5% HRM)**

### 6.3.2 Result of analysis according to JSCE SF-4

JSCE toughness parameters are based on the total amount of energy required to deflect the beam specimen by a specified amount. The flexural toughness factor $\sigma_b$, are reported in Table 6.4. The JSCE analysis also accords the same lack of clarity on the effect of HRM on the toughness. While it does appear that HRM addition does improve the toughness factor $\sigma_b$, as was reported by Dubey and Banthia [47] for cast concrete, there is no clear indication whether this increase is due to the effect of the pozzolan or other parameters such as water/cementitious ratio, lower rebound, etc.
Fig. 6.2  Locating first crack (Flattened end fiber with 5% HRM)

\[ y = 513.44x - 0.5953 \]

\[ \delta E = \frac{513.44}{90.16} = 0.87 \]

---

Fig. 6.3  Locating first crack (Hooked end Fiber with 5% HRM)

\[ y = 491.62x + 1.1471 \]

\[ \delta E = \frac{427.71}{491.62} = 0.87 \]
6.4 Effect of triple blending

From the Table 6.4, it is evident that at comparable water/cementitious ratios, the combination of HRM and silica fume does improve compressive strength relative to control shotcrete mix. However, due to the large scatter in the water content (which is inevitable in the case of dry mix shotcrete), it is not possible to be certain on this; a clear picture does not emerge from this study. However, in a related study, Dubey and Banthia [47] found that in cast concrete, having both silica fume and HRM contributed more strength to the resultant concrete both at 7 and 28 days of curing. The combination of both resulted in a higher strength than with silica fume alone and was exceeded only by the mix having HRM at 10% cement replacement.

With the flexural tests, the toughness of triple blended mixes was the lowest. This is because the fiber rebound of triple blended mixes having both HRM and silica fume was among one of the highest and these specimens had very low in-situ fiber volume fractions. This would explain why their toughness performance was not even as good as that for the mix with silica fume alone. However, here too, in the study carried out by Dubey and Banthia [47], they found that cast concrete reinforced with 0.1% steel fibers and both HRM and silica fume had better absolute toughness and flexural toughness factor compared to the mix with silica fume alone. On the other hand, this combination had less toughness than both mixes without any admixture and with HRM alone. This shows that silica fume imparts a brittle character to the matrix while having HRM in addition to silica fume mitigates the influence of silica fume to an extent.
### Table 6.4  Flexural Response of Dry-Mix Fiber reinforced Shotcrete.

<table>
<thead>
<tr>
<th>Mix-Description</th>
<th>Fiber</th>
<th>$V_f$</th>
<th>$V'_f$</th>
<th>R%</th>
<th>$R_f$%</th>
<th>28-day $f'_c$</th>
<th>MOR</th>
<th>$\sigma'_b$</th>
<th>$\sigma'_b$/MOR</th>
<th>$R_{10,20}$</th>
<th>$R_{30,60}$</th>
<th>$I_{50}/V'_f$</th>
<th>(w/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.62</td>
<td>29.15</td>
<td>36.73</td>
<td>51.3</td>
<td>8.75</td>
<td>4.09</td>
<td>0.47</td>
<td>57.63</td>
<td>44.88</td>
<td>47.08</td>
<td>0.4</td>
</tr>
<tr>
<td>10%HRM</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.68</td>
<td>22.09</td>
<td>28.06</td>
<td>55.2</td>
<td>5.71</td>
<td>4.01</td>
<td>0.7</td>
<td>80.03</td>
<td>68.06</td>
<td>55.96</td>
<td>0.41</td>
</tr>
<tr>
<td>5%HRM</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.65</td>
<td>26.8</td>
<td>33.64</td>
<td>46.3</td>
<td>6.66</td>
<td>3.88</td>
<td>0.58</td>
<td>68</td>
<td>57.57</td>
<td>51</td>
<td>0.54</td>
</tr>
<tr>
<td>10% SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.65</td>
<td>19.84</td>
<td>26.41</td>
<td>50.7</td>
<td>6.55</td>
<td>3.87</td>
<td>0.59</td>
<td>54.55</td>
<td>44.55</td>
<td>40.86</td>
<td>0.45</td>
</tr>
<tr>
<td>5% SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.61</td>
<td>18.62</td>
<td>30.06</td>
<td>53.9</td>
<td>5.43</td>
<td>3.84</td>
<td>0.7</td>
<td>73.82</td>
<td>67.33</td>
<td>53.13</td>
<td>0.5</td>
</tr>
<tr>
<td>5% HRM +5% SF</td>
<td>FE-73</td>
<td>0.76</td>
<td>0.62</td>
<td>19.31</td>
<td>30.03</td>
<td>50.8</td>
<td>5.71</td>
<td>3.74</td>
<td>0.66</td>
<td>68.67</td>
<td>49.1</td>
<td>49.95</td>
<td>0.4</td>
</tr>
</tbody>
</table>

| Control         | Dramix| 0.76  | 0.61  | 28.78 | 38.5   | 66         | 7.51 | 3.78      | 0.5           | 40.43     | 24        | 28.16       | 0.41 |
| 10%HRM         | Dramix| 0.76  | 0.63  | 20.24 | 30.39  | 48.8       | 7.04 | 4.09      | 0.58          | 82.25     | 54.86     | 57.57       | 0.46 |
| 5%HRM          | Dramix| 0.76  | 0.59  | 21.6  | 39.8   | 51.1       | 5.67 | 3.12      | 0.55          | 57.98     | 47.38     | 48.61       | 0.56 |
| 10% SF         | Dramix| 0.76  | 0.63  | 16.38 | 26.05  | 49.3       | 5.77 | 3.79      | 0.66          | 93.73     | 72        | 67.38       | 0.5 |
| 5% SF          | Dramix| 0.76  | 0.61  | 20.6  | 36.97  | 56.1       | 6.46 | 3.52      | 0.54          | 53.43     | 38.56     | 39.52       | 0.46 |
| 5% HRM +5% SF  | Dramix| 0.76  | 0.57  | 18.21 | 34.73  | 49.5       | 5.61 | 2.94      | 0.52          | 66.53     | 44.82     | 49.35       | 0.46 |

$V_f$ = Fiber volume fraction as batched  
$V'_f$ = Fiber volume fraction insitu  
R% = Rebound of material overall  
$R_f$% = Rebound of Fibers  
MOR = Modulus of Rupture  
$\sigma'_b$ = Flexural Toughness factor (JSCE SF-4)  
w/c = Water to cementitious ratio
Conclusion

As mentioned earlier, from basic steel fiber reinforced concrete (SFRC) technology, it is well known that, for a given fiber content, fibers of smaller diameter and longer lengths lead to increased flexural toughness performance. However, the very same condition namely, a higher aspect ratio, is found to result in high rebound. Further, from studies into SFRC, it has been found that while hooked end fibers provide higher maximum pull-out resistance, flattened end fibers result in a greater pull-out energy.

It is not possible to make any such inferences from the present study as we can see from the results in Table-6.4. To investigate the effect of a fiber type on the flexural toughness of dry mix shotcrete, it is necessary to isolate as far as possible other influences such as variation in mix design, water content, fiber volume fraction etc. to prevent them from clouding the data. This is especially difficult in the present case for, as has been explained earlier, in the dry process production of shotcrete, little control exists on water content and rebound. This means that in spite of maintaining consistency (through a constant penetration resistance), there will still be enough variation in water/cementitious ratio, permeable voids and fiber volume fraction in-situ, so that it is impossible to compare toughness data as obtained in this study. For instance, a variation in water/cementitious ratio and permeable voids leads to a corresponding change in the compressive strength and therefore in the modulus of rupture. As higher strength cementitious materials exhibit an inherent tendency towards brittle behavior, the effect on toughness due to the admixture in the mix design or a change in fiber rebound, is completely lost on the test results.
Chapter 7 – Discussion and Recommendations

Is dry mix shotcrete merely another form of concrete, distinguished only by the mode of its production? If such were the case, then one would have only to account for rebound and all subsequent analysis should result in behaviour similar to that of conventional cast concrete. However, while it is true that rebound is the chief issue of concern with shotcrete, it appears that the very process of self-compaction through pneumatic propulsion, renders shotcrete with certain unique properties, all of which lead us to conclude that dry mix shotcrete is NOT just another concrete, rather it is an altogether different material in its own right.

Some of the evidence in support of this opinion from this study is:

1. Conventional cast concrete is a strength dependent material, i.e. the mix design is according to the desired characteristic compressive strength at failure. However, dry mix shotcrete is a workability dependent material. This means that mixes are shot to a constant consistency and the resultant hardened material far exceeds its strength requirements. The emphasis is on flowability and shootability; therefore hardened properties are more the effect rather than the cause.

2. The workability box, which is adopted while preparing cast concrete, is quite different from that recommended for shotcrete. In order to enable ease of placement for concrete, both shear resistance and viscosity must be fairly low. Shotcrete on the other hand must possess low yield and low viscosity at high shear rates (during the spraying), but should exhibit higher viscosity and high
yield at low shear rates (upon contact with the substrate) in order to satisfy ease of flow and optimum conditions of rebound and build-up.

3. Fiber reinforced cast concrete has random distribution of fibers which results in a 3-D distribution within the matrix. On the other hand, it has been observed that fibers shot to reinforce shotcrete orient themselves in a 2-D plane, perpendicular to the direction of shooting and in the plane of the target substrate. While this results in the phenomenon of fiber rebound, it also implies that the fibers within the matrix are efficiently utilized under flexural loading.

4. While steel fibers with high aspect ratios perform better in toughness tests in cast concrete, high aspect ratio also results in a high rebound while shotcreting. Therefore, to optimize the dual needs of low rebound and high toughness, fibers suggested for use in shotcrete are constantly undergoing geometrical alterations.

Studies on cast concrete have indicated some promising possibilities for HRM [4, 31, 36, 37, 38, 40, 43, 94]. Not only does it improve mechanical properties such as compressive strength and flexural toughness; it also imparts better durability by reducing permeability. Further, in comparison to silica fume, HRM required much less superplasticizer in order to attain the same workability. In spite of such positive effects on cast concrete, this study did not find HRM favourable with respect to silica fume, when used as a pozzolanic admixture in dry mix shotcrete. The reasons for this must be understood in the backdrop of the afore-mentioned differences that distinguish dry mix shotcrete.
The essential difference between wet mix and dry mix shotcrete arise due to the instant of introduction of water. With dry mix shotcrete, water is introduced at the nozzle just prior to placement. This means that during the pumping, the dry mix does not come in contact with water and so we are still looking at a bone-dry powder propelled by an air jet. Thus, each particle constituting the dry mix may be said to travel independently. This condition is hardly altered in the fraction of a second for which these particles travel in space in the presence of water, before impacting with the target substrate. Hence, one may apply rigid body kinematics directly to the motion of each particle to determine its tendency to rebound upon impact.

For wet mix shotcrete on the other hand, water is introduced at least 20-30 minutes before placement and all the materials are thoroughly agitated in a mixer. Therefore, when this mix is propelled during shotcreting, plastic lumps are ejected out of the nozzle (and not individual particles) which upon impact dissipate energy by undergoing considerable deformation. It is in sharp contrast to the rigid particles impacting in the dry process (which therefore have a higher energy to rebound) and this is the main reason why wet mix shotcrete witnesses far less rebound compared to the dry process.

Any admixture in the dry mix must reduce rebound in order to be useful later in the hardened shotcrete. This is where HRM performs less favourably in comparison with silica fume. As has been reported in Chapter-5, use of different admixtures as partial replacement for cement indicates that the key parameter controlling rebound in dry mix shotcrete is the admixture fineness. This results in a domino effect on several other properties as seen in Chapters-5&6. Higher rebound results in a lower fiber in-situ volume fraction. As a result, the toughness imparted is far lower than that desired.
Further, as rebound and build-up are related by the same material property namely the fresh shotcrete cohesiveness, we get less build-up with HRM and consequently it requires a greater number of passes in order to achieve a certain thickness.

Therefore, it appears that in order to promote the use of a given mineral admixture in dry mix shotcrete, it would be advisable to investigate first the effect of that admixture on the fresh concrete rheology. Tests should be carried out to evaluate shear resistance and plastic viscosity (at low shear rates) of fresh concrete incorporating the admixture. Admixtures, that reduce the plastic viscosity without significantly reducing the shear resistance, are highly recommended for use in dry mix shotcrete. They are ideally suited to reduce rebound and in addition, if they possess pozzolanic properties, they will improve strength and durability. Silica fume is one such material and needless to say, it outperforms HRM. In this manner, it is possible to evaluate the effectiveness of other admixtures such as powder accelerators, recycled aggregates and other industrial by-products for potential use in dry mix shotcrete.
Bibliography


