The construction of a knitted filter bag fabric

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Some physical, mechanical and filtration properties of 16 circular weft knitted interlock-derivative fabrics incorporating tucking, plating and inlaying have been studied to ascertain the suitability of the selected construction in filtration of white cement dust. Results of this study highlight the decisive role played by the sequential location and thickness of inlay yarns in affecting the physical and mechanical properties of the resultant fabric. A study of filtration efficiency underlines the suitability of the selected construction and indicates the desirable properties of the inlay yarns for a commercially acceptable weft knitted product for industrial baghouses.

Keywords: Dust filter, Filter bag, Filtration efficiency, Inlay, Permeability, Plating, Pressure drop, Weft knitting

1 Introduction

Filtration of dusts can be carried out efficiently by textile fabrics. Woven fabrics are traditionally employed for filtering at low velocity (0.005-0.02 m/s) and for gentle cleaning by shaking or reverse air flow current. Being relatively thin, such fabrics operate on cake filtration principle. Woven scrim reinforced needle-punched fabrics, however, have considerable depth as well as strength and hence work on the principle of non-cake filtration with high velocity of a gas stream of high dust concentration, punctuated at short intervals by quick blasts of high pressure air jets (pulse jet) in a direction opposite to that of fluid flow. Typical properties of some commercial woven and nonwoven dry filter fabrics are given in Table 1 (refs 2, 14 & 15). Filtration performance of such fabrics have been studied extensively.

For actual application in a filtering system, such fabrics are converted into tubular forms (called bags) and mounted loosely on cages which are hung within the exhaust enclosures or baghouses. Such bags are of diameter varying from 5 in. to 20 in. (ref. 16). Dust laden gas is forced across the exposed surface of these bags for filtration and the treated gas is taken out from within the bags into a second chamber for chimney disposal. Such a system of bags need to be sewn out of the woven or nonwoven fabric sheets entailing additional processes of cutting and sewing. Moreover, the sewn joints create a strip along the length of a bag. Such a strip would have properties different from that of rest of the surface of the bag. These problems can be obviated by producing directly a tubular bag on a suitable fabric forming machine.

Tubular fabrics can be made by weaving, needle punching, braiding and knitting. The braided tubes are too narrow for this application. Commercially available needle-punching machines capable of producing tubular fabrics are expensive. Circular weaving is again a relatively expensive proposition and the rate of production is lower than that of either circular knitting or needle punching. Moreover, woven fabrics necessitate high investment in baghouses as a relatively large fabric surface would be needed for filtering and hence are not preferred as such.

Simple circular knitting machines are cheaper than the corresponding circular weaving or needle-punching machines. Such machines are easily available in a range of diameters. Moreover, knitted fabrics are also thicker than the wovens. Hence, developing a weft knitted tubular filter bag was thought to be a viable proposition.

Weft knitted fabrics are however characterised by high extensibility, even at a comparatively low load. An easy deformability of the knitted fabric would
Table 1—Characteristic physical properties of some commercial dry filter fabrics

<table>
<thead>
<tr>
<th>Material description</th>
<th>Areal density g/m²</th>
<th>Thickness mm</th>
<th>Pore volume %</th>
<th>Air permeability m³/min</th>
<th>Tensile strength, N (200 mm x 50 mm)</th>
<th>Extensibility, %</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Length-wise</td>
<td>Cross-wise</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene needle</td>
<td>400-500</td>
<td>1.9-2.1</td>
<td>75-77</td>
<td>12-15</td>
<td>1020-1100</td>
<td>10-11</td>
</tr>
<tr>
<td>punched (Schmid W.)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Polypropylene needle</td>
<td>550</td>
<td>2-16</td>
<td>81.5</td>
<td>8-60</td>
<td>875</td>
<td>30.6</td>
</tr>
<tr>
<td>punched (Local industry)</td>
<td></td>
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<tr>
<td>Polyester needle</td>
<td>400-500</td>
<td>1.4-1.6</td>
<td>79</td>
<td>15-26</td>
<td>1400-1500</td>
<td>14-15</td>
</tr>
<tr>
<td>punched (Schmid W.)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Polyester needle</td>
<td>405</td>
<td>NA</td>
<td>NA</td>
<td>16.5</td>
<td>NA NA NA NA</td>
<td>NA NA</td>
</tr>
<tr>
<td>punched (Morris et al.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester needle</td>
<td>400-560</td>
<td>1.62-1.67</td>
<td>—</td>
<td>14.5-25</td>
<td>Max. 650-750</td>
<td>3% at 100 N</td>
</tr>
<tr>
<td>punched (Balasubramanian et al.)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Polypropylene woven</td>
<td>300-150</td>
<td>0.6-12.2</td>
<td>45-49</td>
<td>18</td>
<td>3435-3480</td>
<td>31-33</td>
</tr>
<tr>
<td>twill (Schmid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester woven plain</td>
<td>130-300</td>
<td>0.32-0.15</td>
<td>64-71</td>
<td>80</td>
<td>758-1020</td>
<td>41-43</td>
</tr>
<tr>
<td>(Schmid)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass fiber woven</td>
<td>290-500</td>
<td>0.54-0.95</td>
<td>67-83</td>
<td>24-38</td>
<td>1750-4500</td>
<td>NA NA</td>
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<tr>
<td>twill</td>
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</tr>
</tbody>
</table>

result, on one hand, in considerable fluctuation in its pore sizes during filtration and, on the other hand, in an unstable barrier layer of dust during cleaning process. The primary aim in developing a knitted filter bag is hence to work out a suitable structure and select yarns such that the desired tensile property can be realised.

Such an exercise was carried out by Anand et al. They selected some single jersey derivatives, one incorporating float (knit-miss) and the other incorporating tuck (cross inlay). They also tried out a single jersey based loop pile construction. However, the most robust of them exhibited a very high coursewise extension of 75% at the breaking load of 1500 N/50 mm sample width. The needle felted samples with which he conducted comparative tests had corresponding breaking extension of around 20% only but a relatively low breaking load of 600 N/50 mm sample width.

From Table 1 it is observed that the extensibility of the commercial samples is by and large below 50% while some of the values are as low as 10-11%.

The present work was therefore aimed at developing a knitted structure that would result in a coursewise extensibility below 50% and a very high coursewise strength such that at low load of 200 N, the deformation would be below 10%. The fabric should also satisfy requirements of air permeability and should be sufficiently thick to permit depth filtration.

2 Structure of the Fabric

Properties of knitted fabrics are governed by the properties of the yarn employed, construction and the loop length selected.

Selection of the yarn material is dictated by the environment in which the filter has to perform. This is aptly illustrated in Table 2 (refs 17-19). The count and texture of yarn would also be expected to play a role in filtration performance. Textured yarns would be expected to provide a greater tortuosity in the path of dust particles passing across the filter medium and the thicker yarns would be expected to result in thicker fabric, thus providing greater filtration depth. These beneficial effects would be further accentuated by multifilament yarns composed of low denier single filaments.

As the focus of the reported developmental work was on the structural aspects of knitting, the problem of yarn selection was reduced to choosing from amongst the commercially available polyester textured multifilament yarns as polypropylene and
acrylic textured multifilament yarns were not available in the domestic market at the time of sample preparation.

While choosing the yarn count a compromise had to be made between yarn thickness, denier of single filament and machine gauge as a knitting machine of given gauge and type can knit a limited range of yarn count. The maximum value of such a range had to be targeted at for the present purpose. However, the corresponding yarn must also be made up of the finest available single filaments, a condition which is usually difficult to satisfy. To bypass this problem of designing the required yarn, it was decided to assemble on the knitting machine the commercially available yarns of finer counts and create loops, each made up of a number of single loops. If these single loops can be stacked on top of each other than the resultant thickness of the assembly would be much higher than that of a loop created by a single yarn of equivalent count. Hence, it was decided to take recourse to 'plating' — a well known technique of feeding yarns at different heights and tensions to the same needle hook by suitable arrangement at feeding points. This would result in the desired layered structure as illustrated in Fig. 1. By varying the count of yarns being fed to the same needle in a systematic manner, this multilayered structure can also be so constructed as to have a graded pore size distribution across the fabric thickness. However, such an exercise comes up in question only during fine tuning of the product parameters. For the present exercise, this line of approach was not pursued and yarns of same count were employed at all feeding points.

On account of desirability of constructing a thick tubular fabric of highest possible length and widthwise rigidity, only an interlock structure comes into question. The interlock fabric is double layered and through introduction of plating, the total number of layers in the fabric would be equal to twice the number of yarns fed to each needle. The corresponding machine had to have as low a gauge as possible so that the thickest possible assembly of yarns could be accommodated. Also, the diameter of this machine had to be so chosen as to result in a bag whose diameter would be acceptable to industrial bag houses. Therefore, a 12 gauge interlock machine of 12 in. diameter was procured from the domestic market.

### Table 2—Relative ratings of some textile materials used in making filter fabrics

<table>
<thead>
<tr>
<th>Property</th>
<th>Cotton</th>
<th>Polyester</th>
<th>PAN (homopolymer)</th>
<th>Polypropylene</th>
<th>Polyamide</th>
<th>PTFE</th>
<th>Acid-resistant ketones</th>
<th>Poly(ketones)</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to stretch</td>
<td>Fair</td>
<td>Good</td>
<td>NA</td>
<td>Good</td>
<td>Excellent</td>
<td>NA</td>
<td>Excellent</td>
<td>V. Good</td>
<td>Good</td>
</tr>
<tr>
<td>Resistance to moisture</td>
<td>Fair</td>
<td>Fair</td>
<td>V. Good</td>
<td>V. Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>V. Good</td>
</tr>
<tr>
<td>Resistance to acids</td>
<td>Good</td>
<td>Fair</td>
<td>V. Good</td>
<td>V. Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Resistance to alkalis</td>
<td>Fair</td>
<td>Fair</td>
<td>V. Good</td>
<td>Poor</td>
<td>V. Good</td>
<td>V. Good</td>
<td>Excellent</td>
<td>V. Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Resistance to high temp</td>
<td>Poor</td>
<td>Good</td>
<td>NA</td>
<td>V. Good</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Resistance to fatigue/impact</td>
<td>Poor</td>
<td>Good</td>
<td>NA</td>
<td>V. Good</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Poor</td>
<td></td>
</tr>
</tbody>
</table>

[Fig. 1—Layered structure by plating of yarns]
market. This machine was then equipped with plating facility.

A pure interlock would exhibit a coursewise modulus that would still be too low to withstand the pressure exerted by dust laden air during filtration process. Any significant deformation at that stage would open up the fabric which would permit many dust particles to pass through. A large deformation is also detrimental to the barrier layer during pulse jet cleaning. It was thus necessary to enhance the coursewise rigidity of the fabric by introducing inlay threads. Such threads are easily inserted on dial and cylinder machines by feeding at a location just preceding the action of upthrow cams on respective dial and cylinder needles. The selected interlock machine was thus additionally equipped with inlay fingers at each feed.

Although the count of inlay yarn has no direct bearing to the machine gauge, the resultant fabric would become thicker and hence a commensurate gap between dial and cylinder had to be provided. This created an upper limit to the maximum possible tightness factor of the knitted structure.

The inlay yarn should ideally be flat with high modulus and lie absolutely straight along the course direction in the fabric. By suitably varying the inlay yarn at each feed one can vary the coursewise rigidity of the fabric. Thus, one can choose not to feed any yarn at certain feeds or feed two yarns together at successive feeds followed by feeding of two single yarns at next two feeds and so on. It is obvious that a large number of combinations can be worked out for feeding of inlay yarns alone. A change in the inlay programme would furthermore affect the areal density and thickness of the resultant product while bulk properties, such as load-elongation behaviour, and transfer properties are also expected to be affected as the three-dimensional configuration of the constituent loops would be influenced by the inlay threads passing along the fabric plane of symmetry.

Inlaying of flat threads leads to a problem related to widthwise shrinkage of fabric. A pure interlock fabric made of yarn spun from staple fibres can be expected to undergo a widthwise shrinkage of about 20-25% between the machine state and the dry relaxed state, i.e. the diameter of the dry relaxed tube would be 20-25% less than that of the machine. As the flat inlay thread is inserted along the periphery of a circle formed by the edge of the fabric still connected to the dial and cylinder needles, the diameter of the ring formed by one course of this thread would be nearly equal to that of the cylinder. Hence, in the dry relaxed fabric, this ring of inlay thread would be subjected to compressive forces, resulting in buckling of the same and thus defeating the vary purpose of the insertion of inlay threads. It was hence imperative to introduce modification in the construction of the fabric that would ensure a low widthwise shrinkage of the knitted tube. The obvious solution is introduction of tucks in the structure.

Tucks cause the resultant fabric to spread out widthwise, making the fabric thicker in the process while the pores would, on the average, become larger. However, the presence of inlay threads within the fabric would be expected to block these openings. Thus, introduction of tucks in the interlock construction was expected to ensure a relatively more straight path for the inlay threads in the dry relaxed fabric while making the fabric still thicker.

As a result of the foregoing deliberations, a fabric construction (Fig. 2) was selected for this study. Fig. 2 illustrates schematically the various paths of inlay and knitting yarns, when the same are projected on the fabric plane of symmetry. The construction repeats over 2 wale lines and 4 courses whereby one inlay yarn is shown to have been inserted after each course. Obviously, the inlaying programme can be varied to obtain various combinations. As can be seen from Fig. 2, the inlay yarn interlaces with the tucking threads and passes through the cylinder and dial loops of each wale line. The larger openings created due to lateral pressure of tucks are also blocked by a larger number of inlay threads passing across these openings.

It is also apparent that because of the inlay threads, each loop arm would be pushed considerably away from the fabric plane, reducing in the process the load bearing capacity of the loop arm.

3 Preparation of Samples

Polyester textured yarn of 150 denier having tenacity of 34 cN/tex and extension at break of 24% was used for the ground construction. In spite of the extensive use of tuck stitches, the resultant basic fabric (without inlay yarn) was displaying a
widthwise contraction of around 42% when compared to the machine state dimension. This contraction apparently was being caused mainly by the textured yarns. Hence, for the first series of samples reported here, 300 denier textured polyester yarn of 35 cN/tex and 26% extension at break was employed as inlay material so as to overcome the problem of buckling of the inlay threads. This would effectively mean a lower initial modulus of the resultant fabric and higher elongation at break along the course direction than what was being originally aimed at. Nevertheless, the results of investigation with this somewhat approximated fabric was expected to highlight behavioural pattern of the employed construction as well as indicate the exact value of inlay yarn required for the targeted fabric.

By trial and error, it was found possible to load each needle of the machine up to a maximum of 900 denier i.e. one could feed a maximum of three yarns of 150 denier at a time at each feeder. In view of the construction employed, positive feeding could not be resorted to. Hence, for suppressing the resultant fluctuations in loop length, compensating tension control devices were fabricated and installed at each feeder.

An interlock machine is usually equipped with four types of needle, namely short cylinder (SC), long cylinder (LC), short dial (SD) and long dial (LD). As can be made out from Fig. 2, at any course only one type of needle knits a loop. Moreover, these four types of needle knit as per the following sequence:

- Course C1: SC knits with yarn Y1 and SD tucks
- Course C2: LC knits with yarn Y2 and LD tucks
- Course C3: SD knits with yarn Y3 and SC tucks
- Course C4: LD knits with yarn Y4 and LC tucks

The inlay yarns within a repeat (I, II, III & IV in Fig.2), which were inserted after each course, were thus trapped on each occasion between yarns having different spatial configuration. With a view to exploring the interaction effect between inlay yarn denier and the spatial configuration of two adjoining courses, a programme of sample preparation (Table 3) was drawn up. The inlay sequence depicted in Table 3 indicates the denier of yarns laid-in after the courses C1, C2, C3 and C4 respectively.

### 4 Evaluation of Samples

#### 4.1 Physical Properties

The resultant samples were evaluated in terms of areal density \( G \) in g/m² as well as courses per inch \( C \) and wales per inch \( W \). The course and wale densities \( (C \text{ and } W) \) represent only those which are visible on fabric surface. Knowing the sum of the deniers of inlay yarns \( D \) within a repeat as well as the resultant denier of yarn fed to each needle (tuck yarns of 450 denier and knitting yarn of 450 denier),
Table 3—Interaction effect between inlay yarn and structural variables

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Inlay sequence</th>
<th>Total inlay denier (D)</th>
<th>Fabric weight (G) g/m²</th>
<th>Wale density (P) courses/in.</th>
<th>Course density (C)</th>
<th>B g/m²</th>
<th>( \bar{l} ) mm</th>
<th>( \bar{l}_k ) mm</th>
<th>Tightness factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600-600-600-600</td>
<td>2400</td>
<td>755.7</td>
<td>13.0</td>
<td>25.0</td>
<td>131.2</td>
<td>12.4</td>
<td>7.1</td>
<td>14.1</td>
</tr>
<tr>
<td>2</td>
<td>600-600-600-300</td>
<td>2100</td>
<td>688.2</td>
<td>13.0</td>
<td>24.0</td>
<td>110.2</td>
<td>12.0</td>
<td>6.9</td>
<td>14.4</td>
</tr>
<tr>
<td>3</td>
<td>600-600-300-600</td>
<td>2100</td>
<td>666.2</td>
<td>13.0</td>
<td>24.0</td>
<td>110.2</td>
<td>11.5</td>
<td>6.6</td>
<td>15.2</td>
</tr>
<tr>
<td>4</td>
<td>600-300-600-600</td>
<td>2100</td>
<td>640.3</td>
<td>13.5</td>
<td>25.0</td>
<td>114.8</td>
<td>10.0</td>
<td>5.7</td>
<td>17.5</td>
</tr>
<tr>
<td>5</td>
<td>300-600-600-600</td>
<td>2100</td>
<td>665.8</td>
<td>14.0</td>
<td>25.0</td>
<td>114.8</td>
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<td>17.2</td>
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<td>6</td>
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<td>1800</td>
<td>688.2</td>
<td>13.0</td>
<td>24.0</td>
<td>94.6</td>
<td>12.3</td>
<td>7.0</td>
<td>14.3</td>
</tr>
<tr>
<td>7</td>
<td>600-300-600-300</td>
<td>1800</td>
<td>675.2</td>
<td>13.0</td>
<td>24.0</td>
<td>94.6</td>
<td>12.0</td>
<td>6.7</td>
<td>14.9</td>
</tr>
<tr>
<td>8</td>
<td>300-300-600-600</td>
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<td>617.8</td>
<td>13.5</td>
<td>23.5</td>
<td>92.6</td>
<td>10.7</td>
<td>6.1</td>
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<td>631.3</td>
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<td>96.8</td>
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<td>645.8</td>
<td>14.5</td>
<td>24.5</td>
<td>96.6</td>
<td>10.0</td>
<td>5.7</td>
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<td>600-300-300-300</td>
<td>1500</td>
<td>663.5</td>
<td>13.0</td>
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<td>1500</td>
<td>613.4</td>
<td>13.0</td>
<td>24.0</td>
<td>78.8</td>
<td>11.1</td>
<td>6.3</td>
<td>15.9</td>
</tr>
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<td>1500</td>
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<td>10.1</td>
<td>5.8</td>
<td>17.2</td>
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<td>300-600-300-300</td>
<td>1500</td>
<td>561.4</td>
<td>14.0</td>
<td>23.0</td>
<td>75.6</td>
<td>9.7</td>
<td>5.6</td>
<td>17.9</td>
</tr>
<tr>
<td>16</td>
<td>300-300-300-300</td>
<td>1200</td>
<td>572.4</td>
<td>14.0</td>
<td>23.5</td>
<td>61.8</td>
<td>10.0</td>
<td>5.7</td>
<td>17.5</td>
</tr>
</tbody>
</table>

The following formulae were employed for finding out average loop length (\( \bar{l} \)):

\[
B = \text{weight (g/m²) contributed by the inlay yarns} = \frac{C.D.}{457}
\]

\[
\bar{l} = \left[ \frac{(G-B)(2.54)}{W.C.} \right] \text{mm}
\]

Assuming a 3:4 ratio between the length of a tuck loop and that of a knit loop, the theoretical average value of the length of a knitted loop for each sample (\( \bar{l}_k \)) was also worked out as follows:

\[
\bar{l}_k = \frac{\bar{l}}{1.75} \text{mm}
\]

The value of \( \bar{l}_k \) was used to calculate the tightness factor (TF) of each sample. As each needle was loaded with 900 denier yarn, TF was calculated on the basis of the following relationship:

\[
TF = \frac{\sqrt{900}}{0.3_{\bar{l}_k}}
\]

Table 3 shows the calculated values of B, \( \bar{l}_k \), \( \bar{l} \), and TF for each sample.

Fabric thickness (T) was obtained according to ASTM D1777 and used for calculating percent pore volume of the respective sample as per the following formula:

Pore volume (%) = \( 100 - \frac{G}{13.8T} \)

The values of percent pore volume are listed in Table 4.

Permeability to clean air (ASTM D737) and tensile properties in course and wale directions (ASTM D5035: 200 mm \times 50 mm strip) were also measured and are given in Table 4. The sample No.8 showed very inconsistent results and hence has been left out of the discussion.

4.2 Filtration Properties

For studies on filtration behaviour of fabrics, only four samples out of the 16 produced were selected. Filtration efficiency of each sample over one cycle of operation was investigated with white cement dust (Table 5) on a laboratory scale set-up and the detailed long-term studies involving cleaning efficiency and dust emission were not attempted as the fabrics made from textured inlay yarns do not quite have the requisite mechanical properties.

The major criterion of selection of fabric was air permeability. From Table 4 it is observed that samples 1-3, 5-7 & 10 exhibit air permeability.
Table 4---Critical bulk properties of experimental samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Inlay sequence</th>
<th>Total inlay weight (D)</th>
<th>Fabric weight (G) g/m²</th>
<th>Fabric thickness (mm)</th>
<th>Pore volume (%)</th>
<th>Air permeability m³/m²/min</th>
<th>Breaking strength, N</th>
<th>Breaking elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600-600-600-600</td>
<td>2400</td>
<td>756</td>
<td>1.88</td>
<td>70.9</td>
<td>7.2</td>
<td>963</td>
<td>4200</td>
</tr>
<tr>
<td>2</td>
<td>600-600-600-300</td>
<td>2100</td>
<td>688</td>
<td>1.84</td>
<td>72.9</td>
<td>9.9</td>
<td>887</td>
<td>3635</td>
</tr>
<tr>
<td>3</td>
<td>600-600-300-600</td>
<td>2100</td>
<td>666</td>
<td>1.78</td>
<td>72.9</td>
<td>9.8</td>
<td>840</td>
<td>3533</td>
</tr>
<tr>
<td>4</td>
<td>600-300-600-600</td>
<td>2100</td>
<td>640</td>
<td>1.76</td>
<td>72.9</td>
<td>10.7</td>
<td>940</td>
<td>3554</td>
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<tr>
<td>5</td>
<td>300-600-600-600</td>
<td>2100</td>
<td>666</td>
<td>1.68</td>
<td>71.3</td>
<td>9.7</td>
<td>850</td>
<td>3421</td>
</tr>
<tr>
<td>6</td>
<td>600-600-300-300</td>
<td>1800</td>
<td>688</td>
<td>1.82</td>
<td>72.6</td>
<td>9.3</td>
<td>915</td>
<td>3325</td>
</tr>
<tr>
<td>7</td>
<td>600-300-300-600</td>
<td>1800</td>
<td>675</td>
<td>1.80</td>
<td>72.8</td>
<td>9.5</td>
<td>895</td>
<td>3106</td>
</tr>
<tr>
<td>8</td>
<td>300-300-600-600</td>
<td>1800</td>
<td>618</td>
<td>1.69</td>
<td>73.5</td>
<td>13.4</td>
<td>917</td>
<td>2872</td>
</tr>
<tr>
<td>9</td>
<td>300-300-600-300</td>
<td>1800</td>
<td>631</td>
<td>1.71</td>
<td>73.3</td>
<td>11.2</td>
<td>925</td>
<td>2933</td>
</tr>
<tr>
<td>10</td>
<td>600-300-600-300</td>
<td>1500</td>
<td>697</td>
<td>1.80</td>
<td>71.9</td>
<td>9.3</td>
<td>793</td>
<td>3450</td>
</tr>
<tr>
<td>11</td>
<td>300-600-300-600</td>
<td>1500</td>
<td>646</td>
<td>1.78</td>
<td>73.7</td>
<td>11.2</td>
<td>798</td>
<td>2017</td>
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<tr>
<td>12</td>
<td>300-300-600-300</td>
<td>1500</td>
<td>664</td>
<td>1.84</td>
<td>73.9</td>
<td>11.5</td>
<td>960</td>
<td>3025</td>
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<tr>
<td>13</td>
<td>300-300-300-300</td>
<td>1500</td>
<td>613</td>
<td>1.73</td>
<td>74.3</td>
<td>14.0</td>
<td>879</td>
<td>2908</td>
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<tr>
<td>14</td>
<td>300-300-300-300</td>
<td>1500</td>
<td>588</td>
<td>1.74</td>
<td>75.5</td>
<td>14.7</td>
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<td>2402</td>
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<tr>
<td>15</td>
<td>300-300-300-300</td>
<td>1500</td>
<td>561</td>
<td>1.73</td>
<td>76.5</td>
<td>14.6</td>
<td>850</td>
<td>2175</td>
</tr>
<tr>
<td>16</td>
<td>300-300-300-300</td>
<td>1200</td>
<td>572</td>
<td>1.72</td>
<td>75.9</td>
<td>14.6</td>
<td>885</td>
<td>2167</td>
</tr>
</tbody>
</table>

Table 5---Particle size distribution of experimental dust

<table>
<thead>
<tr>
<th>Range (Microns)</th>
<th>Percentage of dust</th>
<th>Cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 1.0</td>
<td>1.30</td>
<td>1.30</td>
</tr>
<tr>
<td>1.0 - 2.0</td>
<td>4.78</td>
<td>6.08</td>
</tr>
<tr>
<td>2.0 - 3.0</td>
<td>7.80</td>
<td>13.88</td>
</tr>
<tr>
<td>3.0 - 4.0</td>
<td>12.60</td>
<td>26.47</td>
</tr>
<tr>
<td>4.0 - 5.0</td>
<td>17.01</td>
<td>43.48</td>
</tr>
<tr>
<td>5.0 - 6.0</td>
<td>16.91</td>
<td>60.39</td>
</tr>
<tr>
<td>6.0 - 7.0</td>
<td>8.42</td>
<td>68.81</td>
</tr>
<tr>
<td>7.0 - 8.0</td>
<td>5.33</td>
<td>74.13</td>
</tr>
<tr>
<td>8.0 - 9.0</td>
<td>1.77</td>
<td>75.9</td>
</tr>
<tr>
<td>9.0 - 10.0</td>
<td>2.02</td>
<td>77.91</td>
</tr>
<tr>
<td>10.0 - 20.0</td>
<td>16.07</td>
<td>93.99</td>
</tr>
<tr>
<td>20.0 - 30.0</td>
<td>4.63</td>
<td>98.61</td>
</tr>
<tr>
<td>30.0 - 40.0</td>
<td>1.39</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Values less than 10. To cover the greatest possible range of inlay denier combination as well as air permeability values, samples 1, 2, 7 and 10 were selected for this limited study. The experimental set-up for this study is schematically represented in Fig. 3. It consists of a regulated dust feeder, a filter fabric holder, an absolute filter (thimble), an orifice meter and a suction pump with a by-pass valve. Water manometers are converted with pressure tappings at A, B, C and D. The orifice meter is calibrated for flow rate of air with the help of the suction pump, bypass valve and manometer. This permits

studying permeability of filter fabric to clean air at different flow rates. The corresponding values of pressure drop across the filter fabric can also be monitored with the help of manometer. Thus, it is possible to relate permeability of fabric to pressure drop.

Dust can then be mixed up with clean air being sucked through the fabric by the pump. The dust concentration as well as the flow rates can hence be varied in a planned manner. For this study, the dust concentration was kept fixed at 20 g/m³ with a flow rate of 0.21 m/s. At regular intervals during the filtration process the pressure drop was noted, flow was stopped and filter removed for weighing the dust collected. The filter with dust was then placed back carefully in the filter holder and the experiment continued by taking measurements of pressure drop and collection efficiency from time to time.

5 Results and Discussion

5.1 Physical and Mechanical Properties

From Table 3 it is observed that the ratio of wale to course spacing of the various samples (C/W) exhibits a value around 2, indicating short but very broad loops. In reality, however, the wale lines occupy about 50% of the space along the fabric width, the rest 50% being occupied by the
connecting tuck arms covered up by inlay threads. Thus, the actual shape factor of a knit loop in the construction depicted in Fig. 2 is around 1.0.

It is further observed from Table 3 that the wale and course densities of the fabrics remain effectively unchanged over the entire denier range of inlay yarns. The wale density on the surface of fabric varies from 13 to 14.5 whereas the corresponding course density varies from 23 to 25. Even considering the product of these two variables it is observed that with \( D = 2400 \), the surfacial stitch density is 325 whereas with \( D = 1200 \), the corresponding value is 329. It may be mentioned here that the actual stitch density in the fabric is four times the surfacial stitch density.

Remarkably, the values of loop length exhibit a clear dependence on the total inlay denier; the higher the total inlay denier the greater is the loop length. Thus, for a 100% increase in the value of \( D \) from 1200 to 2400, the value of \( l_k \) shows a 30% rise. This observation violates the basic tenet of knitted loop geometry, first established by Munden and later on verified by various authors, according to which a unique relationship exists between loop length and stitch density such that an increase in one is always accompanied by a decrease in the other.

The apparent contradiction with regard to relationship between loop length and stitch density being exhibited by the 16 samples under study is caused by the effect of thick inlay yarns on the third dimension of a loop, i.e. the one along the normal to the fabric plane of symmetry. In the construction employed (Fig. 2), the inlay yarns not only interlace with the arms of the tuck loops but also pass between two columns of loop belonging to the same wale line. As a matter of fact each arm of a loop has to pass over four inlay yarns, the effect of which is illustrated in Figs 4a-d. These figures show the projection of axis of a loop arm on the YZ-plane whereby the Y direction coincides with wale line and Z-axis is perpendicular to the fabric plane of symmetry. Owing to the couples generated by the interlacement of loops, moments \( M_z \) could cause axis of the loop arm to bend, as shown in Fig. 4a. The path of such a loop arm would not be affected if the inlaid yarns are thin enough to be accommodated within the space between the bent

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**Fig. 3—Schematic representation of experimental set-up for filter characterisation**
arm and the Y-axis (Fig. 4b). However, thicker inlay yarns (Fig. 4d) or even a rearrangement of the same yarns (Fig. 4c) would alter the path of the axis. Clearly then, extra length of yarn would be needed to make up the loop although the total fabric area occupied by a loop may not change at all. The effect of the thick inlay yarn on loop length would be further accentuated by crimp generated in the much thinner arms of each tuck loop owing to interlacement with the former.

The foregoing discussion brings into focus the necessity of a more generalised theory of loop geometry than the one propounded by Munden.

It is further observed from Table 3 that a rearrangement of the total inlay yarns within a repeat, while maintaining the total inlay denier at the same level, does affect the loop length. Thus, for example, a systematic change in the position of the finer inlay yarn (as depicted in the sequences for samples 2-5) causes a reduction in loop length by about 15%. Very similar is the drop observed between sample Nos 6 and 9 for the value of $D = 1800$, whereas for $D = 1500$, the drop between sample Nos 12 and 15 is about 19%. However, the inlay sequences pertaining to sample No.2 ($D = 2100$), sample No.6 ($D=1800$) and sample No.12 ($D = 1500$) result in very similar values of loop length. Moreover, the sequences of sample Nos 10 and 11 behave very differently compared to those pertaining to sample Nos 6-9 although the value of $D$ for all the samples is 1800.

It is obvious from the above that the data thrown up by the sixteen samples is inadequate and a more elaborate plan of experiment needs to be drawn up to understand the phenomenon governing the relationship between loop length and relative location of inlay yarns for construction such as the one investigated here.

Referring to the approximately 14% coursewise shrinkage of all fabric samples from the machine state value of 12 wales/in. to around 13.5-14 wales/in. and comparing this with the 42% widthwise shrinkage of these very fabrics when knitted without inlay yarns, it is concluded that the buckling resistance offered by the small segments of textured inlay yarns spanning the gaps between adjacent wale lines results in about 28% reduction in widthwise shrinkage of fabrics. From another viewpoint it can be inferred that the buckling resistance resulting out of 14% lengthwise compression of textured yarns is sufficient to counteract the coursewise shrinkage force developed in the fabric for the residual 28% contraction. This is of great relevance in selecting the right kind of inlay yarn that would totally withstand coursewise shrinkage force.

Results of fabric thickness test (Table 4) also reveal a dependence on the location of inlay yarns. For each of the loops having a total inlay denier of 1500, 1800 or 2100, the thickness values are nearly the same, i.e. between 1.7 mm and 1.84 mm.

Recalling that the inlay yarns are multifilament in nature, their thickness would depend on the compressional forces acting on them. Assuming a circular cross-section, the diameter of 600 denier multifilament polyester yarns at 50% packing is about 0.18 mm whereas at 80% packing it is approx. 0.14 mm. Diameter values for 300 denier yarn under the same conditions would be 0.13 and 0.1 respectively. Thus, the difference in the diameters of these two yarns is about 0.04-0.05 mm only and, therefore, if laid side by side and subjected to similar compressional forces, the difference would be insignificant in a fabric of thickness 1.7-1.9 mm. The inlay yarns are however expected to be compressed not only normally between a pair of loops belonging to the same wale line but also laterally within the space.
between two successive needle loops. Depending on
the balance of these mutually normal forces, the
eventual sectional view of an individual inlay yarn
might be highly elliptical on one hand while, on
the other hand, the neighbouring yarns might be forced
to ride on each other. Depending on the location of
such a riding, the arms of the loop may also be
forced to a higher curvature. Thus, the fabric thick-
ness values can be expected to exhibit significant
increase in the event of riding of an inlay yarn over
the other; otherwise, these values would hover
around a base value dictated by the thick interlock
fabric. The extent of increase in thickness would be
governed by the extent of riding. Following the ar-
gument developed in the foregoing it would appear
that relative location of the inlay yarns influences
the extent of riding amongst neighbouring inlay
yarns.

The inlay yarns influence both fabric thickness
and loop length in such a way that at higher values
of loop length it appears to be positively correlated
with fabric thickness. A similar phenomenon was,
however, also observed by Postle\(^2\) for plain knit
fabrics. Apparently, with loose structures the
textured inlay and knitting yarns are able to open up
laterally more and impart greater thickness to the
fabric. Such a process would then also be expected
to affect pore volume. But a perusal of the fabric
thickness and porosity data from Table 4 does not
exhibit any direct correspondence. Recalling that
the porosity of the fabrics under investigation is, to a
large extent, the result of openings created by the
opening process; it is to be expected that the overall
porosity would primarily be affected by the
thickness of inlay yarns which are stretched across
such pores. The effect of opening up of yarns owing
to reduced tightness factor would only be
superimposed on that of the thickness of inlay yarns.
It is observed from Table 4 that for total inlay denier
of 2400, 2100, 1800, 1500 and 1200, the average
pore volumes of the samples are 70.9, 73.4, 73.5,
75.1 and 75.9 respectively. However, a comparison
of the values of per cent pore volume within each
group of the total inlay denier of 2100, 1800, 1500,
etc. reveals an increasing trend with fall in loop
tightness factor.

It may hence be concluded that the thickness of
the fabric samples is primarily affected by the
relative location of the inlay yarns whereas porosity
is by and large influenced by the denier of the inlay
yarns.

Per cent pore volume and air permeability of the
samples show expectedly a very close relationship.
Overall, the air permeability of samples increases
with decrease in total inlay denier. Thus, the average
values of permeability for the total inlay denier of
2400, 2100, 1800, 1500 and 1200 are 7.2, 10.0, 10.0,
13.7 and 16.2 \(\text{m}^3/\text{m}^2/\text{min}\) respectively (Table 4). Re-
calling that the decrease in total inlay denier is
accompanied by an increase in tightness of loop; it is
somewhat of a paradox to conclude that fabrics of
higher tightness factor are more permeable to air.
But then in the structure under consideration the
openings are created basically by the tucking pro-
cess and these openings get less obliterated by thin-
ner inlay yarns, giving rise to the observed phe-
nomenon.

As opposed to loop length and fabric thickness,
air permeability is not affected by the relative
location of the inlay threads.

Considering the tensile properties along the two
principal directions, a very close dependence is
observed between the coursewise breaking strength
and the total inlay denier; as the total denier
gradually decreases from 2400 to 2100, 1800, 1500
and then to 1200, the average value of coursewise
breaking strength decreases from 4200 to 3536,
3121, 2628 and then to 2167 N respectively. The
inlay yarn employed had a tenacity of 3.9 cN/denier
and a simple calculation would show that in a two
inch strip fabric there would be about 100 inlay
threads supporting the coursewise load. Thus, for
the average inlay thread denier of \(D/4\), the
theoretical maximum breaking strength of the 100
inlay yarns would be (3.9 \(D/4\)) Newton. Hence, the
maximum load at which the inlay yarns with \(D =
2400, 2100, 1800, 1500\) and 1200 are expected to
break would be 2340, 2048, 1755, 1462 and 1172 N
respectively. These values are breaking strengths
and tend to suggest that the net contribution to
strength by rest of the yarn elements, which are
aligned coursewise in the fabric, increases in direct
proportion to the total inlay denier. Apparently, the
fabric assistance factor goes up proportionately with
the total inlay denier.

The coursewise breaking extension (Table 4)
corresponds to the respective point of the inlay
yarns after which the stress decreases and the strain
increases rapidly, rendering the fabric useless as a filtering medium. Although the breaking extension of a single yarn is around 26%, the net coursewise fabric strain at the point of rupture is, on the average, around 40%, indicating about 14% extra length of inlay yarn along the fabric circumference. This extra length is accommodated during the coursewise shrinkage of the fabric from the machine state of 12 wales/in. to 13, 13.5 and 14 wales/in. on the body (Table 3), accounting for 8%, 12% or 16% crimp in the inlay yarn. Clearly, depending on the extent of this crimp the initial coursewise modulus would vary and affect the permeability of the filtering fabric at varying pressure drop.

The walewise tensile behaviour of the fabric is characterised by the relatively low breaking strength and very high breaking extension. The total denier as well as the relative location of the inlay yarns do not seem to affect tensile properties in this direction.

5.2 Filtration Properties

The relationship between permeability and pressure drop in clean air for the four selected samples is shown in Fig.5. The air permeability values (Table 4) were measured at a pressure drop equivalent to 10 mm water gauge (10 mm wg = 100 Pa). It is observed from Fig. 5 that the samples 1 and 2 always exhibit the lowest and highest permeability respectively at any given pressure drop. The behaviour of samples 7 and 10 is intermediate between those of samples 1 and 2. Interpreting an increase in air permeability as being due to increase in per cent pore volume of the fabric, which in turn is caused by the multiaxial fabric deformation caused by the increasing pressure differential across the fabric surface, curves in Fig. 5 reveal bulk deformation characteristics of the fabric samples. Accordingly, the relatively high initial resistance offered by the four samples varies in magnitude; beyond 30 mm wg pressure drop, the rate of deformation is similar for all, terminating with a moderate increase in resistance. The initial high resistance to bulk deformation is not reflected in the low initial modulus of fabric during uniaxial deformation. In this sense, Fig. 5 reveals valuable information pertaining to load-elongation behaviour of the fabrics.

The behaviour of these samples in dust laden air is shown in Fig. 6. Sample 1 shows the highest rate of change in pressure drop with change in permeability whereas the sample 2 exhibits the lowest rate. Recalling that the change in pressure drop here is caused by the deposition of dust on the fabric and not by the change in flow rate, the sample...
1 is apparently exhibiting a superior behaviour compared to the other three samples in the sense that in spite of a build-up of dust deposition, the fabric permeability does not change appreciably. However, the deposition of dust leading to increase in pressure drop from 20 to 60 mm wg results in a decrease in permeability from nearly 0.06 m/s to about 0.04 m/s whereas the corresponding drop with clean air leads to a permeability change from 0.5 m/s to 0.1 m/s. This indicates a sharp increase in filter drag with accumulation of dust cake (from 0.5 m/s to 0.06 m/s) followed by an early levelling off. Sample 2 exhibits, however, a very different behaviour; the virgin fabric drag is much lower than that of sample 1 but the filter drag keeps on increasing steadily not showing any sign of levelling off. This is depicted more clearly in Fig. 7 from which it is observed that the sample 1 shows very little change in permeability over 12 min of dust flow. The sample 10 appears to get choked very quickly whereas the sample 2 also tends to the same state at a later instant of time. The sample 7 seems to be levelling off to a finite value of permeability.

The plots of time dependent collection efficiency (Fig. 8) demonstrate moderately good performance of all the four samples in the sense that 97-99% efficiency could be achieved within 5 min of filtration. It is interesting to note that the sample 2 exhibits a high efficiency of 98.5% after 2 min of filtration whereas the efficiency of sample 1 climbs steadily from 97% (after 1 min) to about 98.5% after 12 min. This is another manifestation of the same phenomenon causing the sample 1 to stabilise at a much lower filter drag (or higher air permeability value) whereas the sample 2 does not stabilise and probably would get clogged. Tests with the sample 10 had to be abandoned after 5 min as it became clogged whereas sample 7 showed a moderate rise in efficiency from around 97% to 98% over the entire period.

The manner in which the pressure drop increases with collection efficiency is shown in Fig. 9. The sample 1 appears to be quite superior to sample 2 in terms of energy input for filtering the same volume of air.

From the foregoing discussion on relative merits
of the four knitted samples it is clear that the sample 1 exhibits the best filtration performance with the given cement dust. Samples 2 and 10 have a tendency to clog early whereas the efficiency of sample 7 is unacceptably low. Comparing the physical characteristics of the four samples it is observed that the sample 1 is heaviest, thickest and toughest with lowest porosity. The other three samples have similar properties barring the thickness which is higher for the sample 2. Clearly, the slightly low collection efficiency of the sample 1 can be improved by employing suitable inlay yarn that would ensure small tightness factor and thickness of the fabric samples.

Comparing the physical properties baring the thickness which is higher for the sample 2. Clearly, the slightly low collection efficiency of the sample 1 can be improved by employing suitable inlay yarn that would ensure small change in per cent pore volume at working values of pressure drop.

6 Conclusions

The physical properties of 16 knitted samples made of textured yarns and based on interlock construction incorporating tucking, platting and inlaying, demonstrate the decisive role played by the count of the inlay yarn in determining air permeability, porosity and coursewise rigidity and that by the location of inlay yarns in determining the tightness factor and thickness of the fabric samples.

A somewhat limited study of four knitted samples, selected on the basis of their low air permeability values, on their suitability to filter cement dust showed that the heaviest, thickest and toughest fabric (Sample 1) with the lowest air permeability is the best. Although the maximum collection efficiency exhibited by the best sample is somewhat lower than that expected of a good filter fabric (> 99%), the results point to encouraging potential of the structure chosen for the filter material. The limitations arising from the use of textured inlay yarns can be overcome by employing flat inlay yarns of suitably high buckling rigidity as well as high modulus, tenacity and work of rupture.

Acknowledgement

The experimental data reported here were generated in the laboratories of NITRA, Ghaziabad, and Pollution Control Research Laboratory and Textile Testing Laboratory of IIT-Delhi in the course of a project on Industrial Textiles, funded by the Ministry of Textiles, Government of India.

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