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Development of fabrics for adsorbing carbon dioxide and other pollutants from indoor air

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An attempt has been made to develop cotton-treated fabrics to be used as home textile and decorative products inside the room, which can adsorb carbon dioxide and thus reduce indoor air pollution. Cotton fabric has been treated with bentonite clay, aerosol fumed silica and zeolite separately, and then evaluated for adsorption of CO_2 gas using newly developed NITRA fabric gas adsorption efficiency testing equipment. It is found that the fabric treated with a 4% concentration of bentonite clay, 3% concentration of aerosol fumed silica, and 2% concentration of zeolite adsorbs 23.62%, 28.04%, and 21.35% of CO_2 respectively in 24 h. Treated samples are also tested for various physical properties like breaking strength, flexural rigidity, etc.

Keywords: Adsorption, Air pollution, Breaking load, Cotton, Elongation-at-break, Flexural rigidity, Photocatalysis, Volatile organic compound

1 Introduction

Air pollution has attracted many scientists in conducting various research works in finding some solution of the problem. Urbanisation, economic development and increase in consumption has resulted in increased air pollution. In developing countries, such as China, India and Brazil, this problem is reaching beyond tolerable limits and all are concerned about this issue. While outdoor air pollution is noticed by many, the awareness on indoor air pollution is not so common. WHO[1] has defined the norms of indoor air quality and worldwide it is being accepted as standard. The guidelines developed under the coordination of WHO/Europe, address three groups of issues that are most relevant for public health, viz (i) biological indoor air pollutants (dampness and mould); (ii) pollutant specific guidelines (chemical pollution); and (iii) pollutant from indoor combustion of fuel.

Understanding of the hazards is the first step in identifying the action necessary to avoid and reduce the adverse impacts of air pollutants on health [2-7]. Indoor air quality (IAQ) is a major concern to businesses, schools, occupants, tenants, and workers because it can impact the health, comfort, well-being, and productivity of the occupants. The Occupational Safety and Health Administration (OSHA) recognizes that poor IAQ can be hazardous to workers' health and that it is in the best interest of everyone that building owners, managers, and employers take a proactive approach to address IAQ concerns. This OSHA document on IAQ provides practical recommendations that will help in preventing or minimizing IAQ problems in commercial and institutional buildings, and help in resolving such problems if they do arise[2].

Primary sources of indoor air pollution include printers & photocopiers producing volatile organic compounds (VOC), ozone, melamine furniture (VOC, formaldehyde), fireplace, second hand smoke, humidifiers, carpets, paints, the chemicals in hairsprays, deodorants, oven cleaners, paints, pesticides, laundry aids, floor and furniture polishes, glue and ironically air fresheners[8]. Virtually every household and office building is a potential source of excessive amounts of one or another toxic pollutant such as nitrogen dioxide, carbon monoxide, hydrocarbons, formaldehyde, radon (a radioactive product of radium), sulphur dioxide, etc.

The statistics show that the world's largest single environmental health risks, where 3.3 million deaths are blamed on indoor air pollution in contrast with 2.6 million deaths blamed on outdoor pollution in 2012[9]. In developing countries, health impacts of indoor air pollution far outweigh those of outdoor air

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pollution. Survey has revealed that considerable number of people die per year prematurely from illness attributable to the household air pollution caused by the inefficient use of solid fuels and kerosene for cooking[7]. Studies show that atmospheric pollutants concentrate indoors to high levels. Indoor pollutants concentrations are usually 2-5 times and sometimes 100 times higher than outside concentrations[10].

There are multiple and complex factors that affect the range and magnitude of indoor pollutants and associated health problems. Dampness is known as a major factor contributing to this, but the relationships are not fully understood[11]. A comprehensive Italian study conducted on 20,016 children of average 7 years of age and 13,266 adolescents of avg.13 years of age concludes that avoiding mould and dampness alone decreases the occurrence of related illnesses by 4 -7%[12]. Of course, the actual case of exposure is to a wide array of different pollutants in situations where complex social factors are at play[13]. The most used technologies applied in CO_2 capture are cryogenic distillation, membrane purification and adsorption. The most mature technology in the CO_2 capture is the use of amines with excellent behavior, although this methodology also displays several drawbacks related to its high energy requirements needed in regeneration step as well as, the high corrosivity of the amine species[14].

The use of adsorbents to capture CO_2 has emerged as an alternative to those technologies indicated previously, due to their reduced energetic demands and easier operation conditions. Most efforts are focused on the search and development of adsorbents with high capacity and selectivity for CO_2. However, other parameters, such as rapid /desorption kinetics, good mechanical properties, high hydrothermal and chemical stability, regeneration capacity, and synthesis costs, are hardly taken into account in many studies to implement these adsorbents on a large scale[15-19]. Considering these, many researchers are developing porous material which can act as a molecular sieve because CO_2 has a high quadrupole moment, which enhances its interaction with the electrical field gradients of porous materials[20,21].

Several porous materials have been evaluated as potential molecular sieves for CO_2 absorption. Considering its importance, various attempts are being made by scientists from all over the world. It has been reported that metal organic frameworks (MOFs) and graphene organic framework (GOFs) form 3D ordered structures with narrow and homogeneous pore size distribution, where the CO_2 molecules are retained[22,23]. The main disadvantages are found to be relatively low thermal stability, that is required during regeneration step, and the high cost of preparation of these materials. Many scientists have synthesized porous silica with different porosity and morphology, such as MCM-41, MCM-48, SBA-15, HMS or mesocellular foams. The CO_2 capacity is directly related to micro-porosity of the synthesized porous silica, although CO_2 capacity is limited to the structure of MOFs[20]. Both zeolites[24,25] and activated carbons[19,26] are other structures with narrow pore size, therby showing higher CO_2 absorption. Considering that the CO_2 capture is the most expensive step in Carbon Capture and Storage (CCS) process, it is necessary to develop inexpensive adsorbents to obtain more economic and sustainable processes to be implanted on a larger scale. In this regards, clay materials have become an alternative because of their excellent behavior in catalysis. Clay minerals are inexpensive materials, with an abundant availability around the world. It is efficient for several applications, such as the adsorption of CO_2 due to its chemical and morphological structures. The clay mineral are prone to suffer chemical modification in such a way the textural properties can be improved, increasing the microposity as well as the CO_2 absorption capacity in most cases. The acid treatment of clay increases the micro-porosity by a partial solution of its sheets, resulting in a structure which can act as molecular sieve trapping CO_2 molecules[27]. A study by a group of scientists[28] has shown that the adsorption of CO_2 in the carbonaceous materials was not related to textural characteristics of the solids, such as BET surface area and pore volume. Instead, it is dependent on the chemical surface of the activated carbons. This determined the interaction of the surface with the gas molecule. By increasing the oxygenated and nitrogenous groups on the surface of the activated carbons, it was possible to increase the affinity of the solid for CO_2 molecule which had acidic characteristics, and therefore the electron donating groups favored its adsorption.

Another way of converting textile materials into air cleaner is to functionalise the textile substrate via incorporation of functional additives, such as organic or inorganic nano structured materials[29]. The semiconductor photocatalyst, as a rising and efficient technology for environment remediation, represents

an easy way to eliminate pollution by utilizing the energy of either natural sunlight or indoor illumination light. The mechanism of these functions is based on the in-situ generated highly reactive oxygen species (e.g. OH, O_2-) for mineralization of organic compounds. Photocatalysts, such as TiO_2, ZnO, Fe_2O_3, CdS, WO_3, SnO_2 and ZnS, are employed to degrade a wide range of organics into readily biodegradable compounds, and eventually mineralize them to carbon dioxide and water. Study reported[30]that research papers, titanium dioxide and its composites are the most popular photocatalysts used on textiles. Most functional textiles modified with TiO_2 as catalysts are activated by ultraviolet (UV) light. The important features of photocatalysts are low toxicity, ambient operation temperature and pressure, complete mineralization of organics without secondary pollution, low operation cost, broad activity towards a wide variety of contaminants and photocatalytic activity in both indoor and outdoor light. It is also important to remove Volatile Organic Compounds (VOCs) from indoor air, as some of them are associated with sick building syndrome, causing symptoms such as mucous membrane irritation, headache and fatigue. Among the removal methods of VOCs from indoor air, photocatalytic oxidation is an innovative and promising approach[31]. TiO_2 was applied in most of the investigations for indoor air photocatalytic oxidation. A TiO_2 coated fiber glass mesh (TiO_2 and silica) was first employed for photocatalytic oxidation of benzene, toluene and xylenes in indoor air[32]. The average concentrations of benzene, toluene and xylenes were indeed reduced by a factor of 2-3 in an ordinary non-airtight room. Doped titanium dioxide was also used in photodegradation of VOCs. Sangkhun *et al.*[33] immobilized W-doped TiO_2 on fiber glass fabric and evaluated its VOC removal efficiency as compared to TiO_2 under visible light. The W-doped TiO_2 functionalized fabric showed higher efficiency than that modified by titanium dioxide, approximately 18,3,3 and 2.5 times for BTEX (benzene, toluene, ethylbenzene and o-xylene) respectively. Apart from synthetic fibres, cotton as a natural fibre, was also used as the substrate to load TiO_2 for VOC degradation. Dong *et al.*[34] immobilized DegussaP25 on cotton fabric by two different textile finishing methods, viz coating and pad-dry-cure. In their study two commercial additives, an acrylic binder and a Lutexal thickener, were applied to form the coating paste. TiO_2/cotton prepared from both methods degraded ammonia in the air under UV irradiation. The functionalized cotton textiles and cotton/PET blends were also prepared by impregnation with Al_2O_3 and SiO_2 as binding agents and TiO_2 as the photocatalyst[35]. The resulting textiles showed high photocatalytic activity to acetone vapour.

Despite numerous research studies, the practical use of these findings hasn't been explored in creating home textiles, which can adsorb CO_2 and other harmful gases. Hence, an attempt has been made to develop home textile products by treating cotton fabrics with specific chemicals. It is expected that this work will open up an easier solution to reduce damage to human health.

2 Materials and Methods

The study is divided into four parts. In the first part, identification of finishing chemicals that have the ability to adsorb air pollutant gases from the atmosphere is undertaken. In the second part, these identified chemicals were applied to the cotton fabric with different concentrations. In the third part, testing of air pollutant gases adsorption capability of treated and untreated fabric samples was done. Finally in the fourth part, analysis of fabric samples for changes in various physical characteristics due to treatment with finishing chemicals was done.

In this study, three finishing chemicals, namely (i) bentonite clay(procured from Gayatri Dyes & Chemicals with 99.9% Purity), (ii) aerosil fumed silica (procured from M S Lab Line Enterprises with 98% Purity), and (iii) Zeolites (procured from Aya Nutritions with 99% Purity) were identified, which have the ability to adsorb the air pollutant gases (CO_2, SO_2, CO and NO_2) from the atmosphere.

Cotton fabric to be treated and tested for air pollutant gas adsorption capability was procured from the local supplier. Basic characteristics of the fabric were tested and results are shown in Table 1. A dispersion pigment binder (Tubifast AR 40) based on acrylic copolymeremulsion (made from methyl

Table 1 — Basic characteristics of cotton fabric to be treated with finishing chemicals

Characteristics	Value	Test method
Count, Ne		
Warp	42.19	IS3442
Weft	43.08	
Weave	Plain	Visual
Weight per unit area, g/m^2	139.7	IS1964
Ends per inch	140.4	IS1963
Picks per inch	88.6	IS1963

methacrylate monomer and a common real catalyst) was also procured from CHT (India) Pvt Ltd.

2.1 Preparation of Dispersion

In this study, three experiments were carried out using bentonite clay, aerosil fumed silica and zeolite dispersion, each of 1%, 2%, 3%, 4% & 5% concentrations.

For the preparation of dispersion of 1% concentration, 50 mL of water and 50 mL of pigment binder were mixed properly with the help of stirrer, and then one gram of finishing chemical was added slowly in this 100 mL dispersion. This dispersion was ultra sonicated for stable dispersion. In the same way, dispersions of 2%, 3%, 4% & 5% concentrations using 2, 3, 4 & 5 g of finishing agents in 50:50 water: binding pigment solution respectively were prepared.

2.2 Application of Dispersion on Cotton Fabric

Five cotton fabric samples of dimensions 26×26 cm^2 were prepared. The sample size was taken as per the requirement of an apparatus to determine air pollutant gas adsorption capability of fabric, developed by NITRA.

Dispersion of 1% concentration of finishing chemical was applied on the cotton fabric sample using the padding mangle technique 2 dips and 2 nips process. The pressure was set at 1.8 bar and the speed was kept at 1 m/min. This sample was dried at 60ºC for 30 min in the hot air oven. Similarly, rest four fabric samples were also prepared using dispersion of 2%, 3%, 4% and 5% concentrations. Samples obtained after finishing were coded as S-1.1 to S-1.5 for bentonite clay, S-2.1 to S-2.5 for aerosil fumed silica and S-3.1 to S-3.5 for zeolites.

2.3 Analysis of Gas Adsorption Capacity of Finished Fabrics

All the treated samples were tested for air pollutant gas adsorption capacity for carbon dioxide (CO_2) gas, which is majorly responsible for indoor air pollution. To check the air pollutant gas adsorption capability of treated and untreated fabric, an apparatus to determine air pollutant gas adsorption capability of fabric, developed by NITRA (Indian Patent application no. 202111062044, dt. 31.12.21) and indoor air quality & monitoring kit with direct sense probe were used. The instrument, developed by NITRA (Fig. 1) consists of a closed chamber where an arrangement is available for the attachment of the fabric sample. Pollutant gas cylinders are attached to this instrument. Through inlet valves, air pollutant gases are taken inside the chamber. Quantity of pollutant gas can be taken as per requirement. One gas or mixed gases can be taken inside the chamber of equipment through inlet valves. As per need, gases inside the chamber can be exhausted by way of opening the butterfly valve and starting the exhaust fan. The indoor air quality & monitoring kit with direct sense probe, hereafter it will be referred to as "Probe", is placed inside the chamber which reads the pollutant gas level present in the chamber.

The probe reads the quantity of air pollutant gas present in the chamber and gives the results on the computer screen.

3 Results and Discussion

In an earlier study of authors[36], it has been observed that the fabric treated with clay results in adsorption of CO_2, CO, NO_2 and SO_2 from the polluted air. In the following cases, the results have been reported for the adsorption of CO_2 by the fabrics,

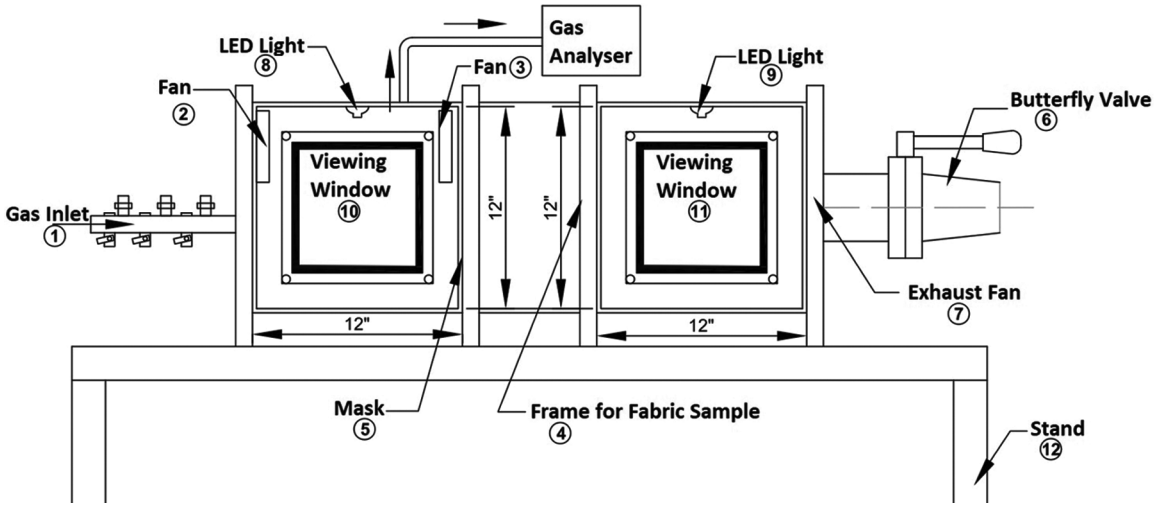

Fig. 1 — Schematic diagram of apparatus to determine air pollutant gas adsorption capability of fabric (NITRA)

as the majority of pollutant gas in the indoor air is found to be CO_2.

3.1 Study on FinishedFabrics

3.1.1 Bentonite Clay Finished Sample

100% cotton fabric samples are treated with bentonite clay in different concentrations (1%, 2%, 3%, 4% and 5%). Untreated sample is also used for the comparison with the treated one. The gas adsorption behavior of bentonite treated fabric at different concentrations is shown in Fig. 2 (a). It shows that at 4% concentration, the adsorption of CO_2 gas by the bentonite clay treated sample is maximum (23.62%), which is indicated by the red dashed line (S-1.4). Apart from this, samples treated with 1%, 2%, 3%, or 5% concentrations show less CO_2 gas adsorption. So, a 4% concentration level can be treated as optimum for getting better adsorption results. As far as the untreated sample is concerned, pollutant gas adsorption is 7.42% in 24 h, which is indicated by the blue dot line (S-1).

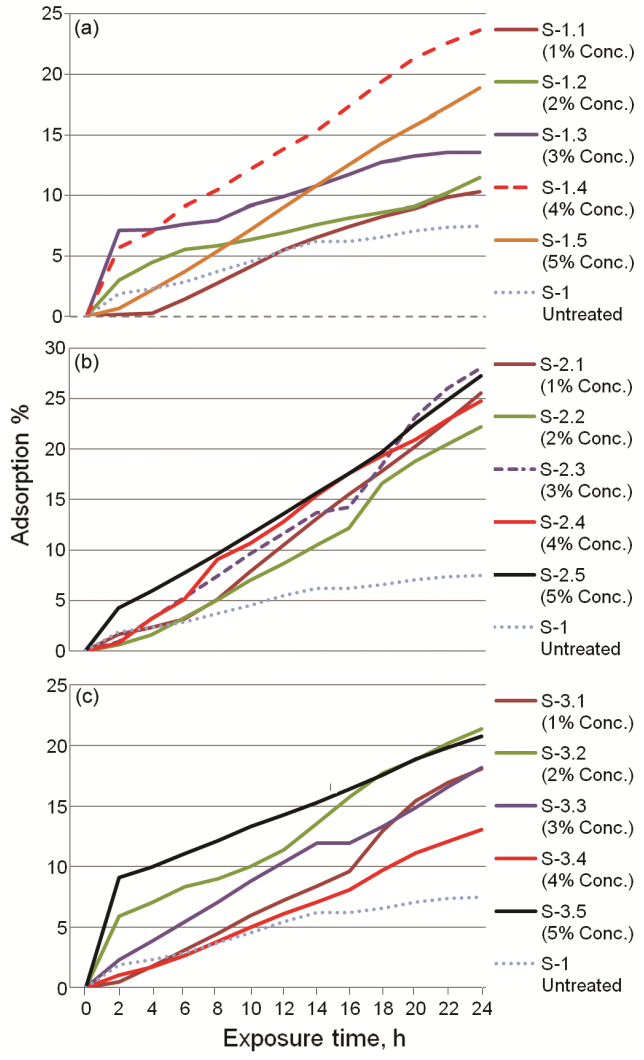

Fig. 2 — Adsorbency of various fabrics treated with (a) bentoniote clay, (b) aerosol fumed silica and (c) zeolites

3.1.2 Aerosil Fumed Silica Finished Sample

The results of CO_2 gas adsorption on fabric treated with aerosil fumed silica in 1%, 2%, 3%, 4%, and 5% concentrations are shown in Fig. 2 (b). Adsorption of CO_2 gas by treated samples has been observed for 24 h. The change in CO_2 % is observed at 2 h intervals. In 24 h, treated fabric samples with 3% concentration show 28.06% of CO_2 gas adsorption (S-2.3), which is the maximum and can be considered an optimum (S-2.3). Fabric samples treated with 1%, 2%, 4%, and 5% concentrations show less gas adsorption.

3.1.3 Zeolites Finished Sample

Figure 2(c) shows the CO_2 gas adsorption behaviour of fabric treated with 1%, 2%, 3%, 4%, and 5% concentrations of zeolites. From the figure, it is clear that highest air pollutant gas (CO_2) adsorption is observed at 2% concentration level of zeolites, which seems optimum (S-3.2), whereas, fabric samples treated with 1%, 3%, 4% and 5% concentrations show less gas adsorption.

3.2 Physical Characteristics of Finished Samples

3.2.1 Bentonite Clay vs Untreated

Application of any chemical or other material on a fabric changes its various physical properties of fabric such as tensile properties, bending properties, moisture absorption capacity, drapability, resistance to friction, etc. For home textiles and other similar uses, tensile properties, bending properties and drapablity play a very important role. In this study, the influence of the finishing treatment has been studied on breaking load, elongation at break, and flexural rigidity (as bending and drapability are dependent on this value).

(i) Fabric Tensile Properties – Treated and untreated samples were tested for breaking strength (N) and elongation at break (%) in warp and weft directions (Fig. 3). In this study, the breaking strength and elongation-at-break of all treated samples increase as compared to the untreated sample in both warp and weft directions, because the finishing chemicals have the tendency to act as a binder to bind the warp and weft threads.

Fabric assistance has further contributed to the increase in the breaking strength and elongation at

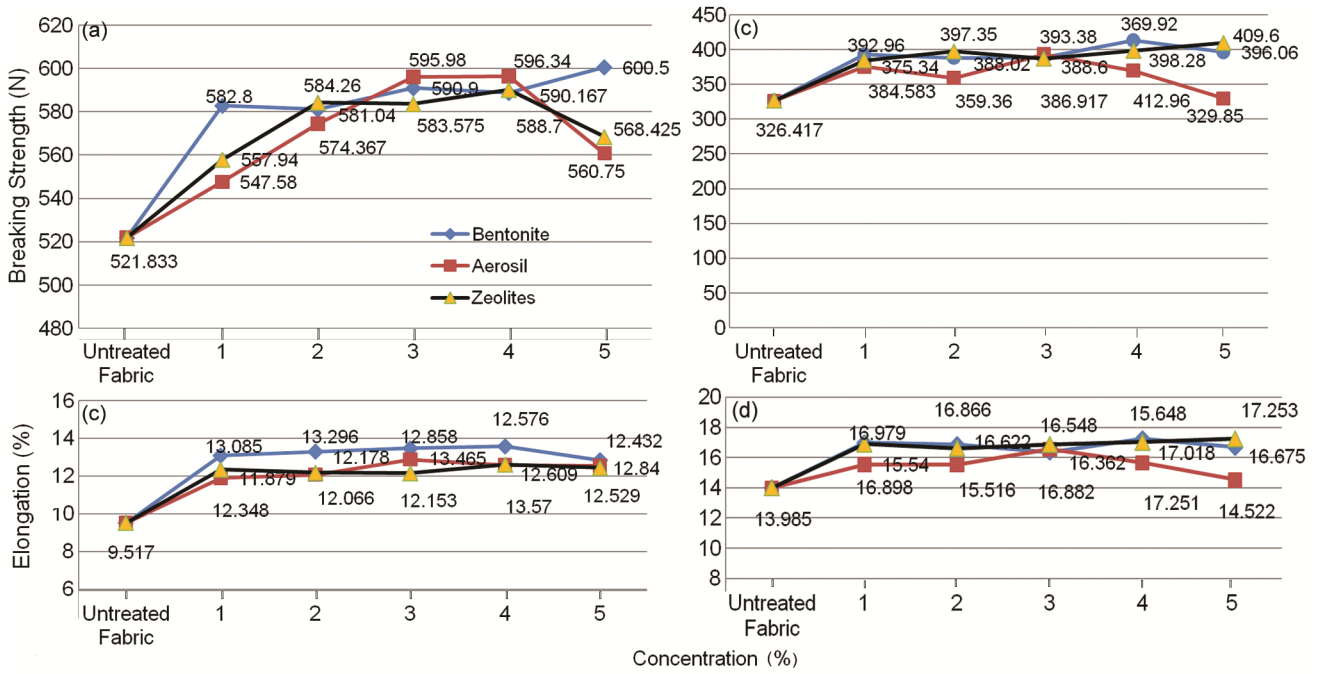

Fig. 3 — Breaking strength for bentonite clay, aerosil and zeolites treated fabric samples in (a) warp directions & (b) weft direction; and elongation at break for bentonite clay, aerosil and zeolites treated fabric samples in (c) warp direction and (d) weft direction

break value of the fabric in both warp and weft directions.

Test of significance (t value) shows that there are no significant changes in the breaking strength and elongation-at-break of samples treated with different concentrations ($t_{cal}<t_{tab}$).

(ii) Fabric Flexural Rigidity – Treated and untreated samples are tested for flexural rigidity and shown in Fig. 4. The flexural rigidity (G) of treated sample is observed to be high in comparison to the values of the untreated sample due to the application of the bentonite clay chemical.

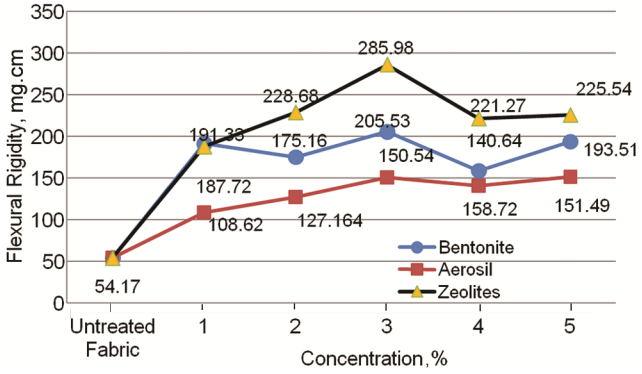

Fig. 4 — Flexural rigidity(G) for forbentonite clay, aerosil and zeolites treated fabric samples in weft directions

3.2.2 Aerosil Fumed Silica vs Untreated

(i) Fabric Tensile Properties – Treated and untreated samples are tested for breaking strength (N) and elongation-at-break in warp and weft directions (Fig. 3).

From the figures, it is observed that the breaking strength and elongation-at-break of fabric in the warp and weft directions have increased in comparison to untreated samples. The main cause is the treatment with finishing chemicals, which act as a binder to bind the warp and weft threads. Interlacement has further contributed to the increase of breaking strength and elongation-at-break in the fabric in both directions, and it can be explained as the impact of fabric assistance.

Study of test of significance (t value) shows that there has been significant increase in breaking strength (in warp direction) of samples treated with 3% & 4% concentrations in comparison with breaking strength at 1% concentration ($t_{cal}>t_{tab}$). Whereas, in weft direction, there is no significant change in breaking strength of samples treated with different concentrations ($t_{cal<}t_{tab}$).

Test of significance study is also conducted for elongation at elongation-at-break in warp direction. There is significant increase in elongation in the samples treated with 3% and 4% concentrations in comparision with treated samples with 1% concentration ($t_{cal>}t_{tab}$). Whereas, in the weft direction,

there is no significant changes in elongation-at-break of the samples treated at different concentrations ($t_{cal<}t_{tab}$).

(ii) Fabric Flexural Rigidity – Treated and untreated samples are tested for flexural rigidity (Fig. 4). Flexural rigidity is observed to be high in comparison to the values of the untreated sample due to the application of the aerosil fumed silica chemical.

3.2.3 Zeolites vs Untreated

(i) Fabric Tensile Properties – Treated and untreated samples are tested for breaking strength (N) and elongation-at-break in warp and weft directions (Fig. 3).

It can be observed that breaking strength and elongation-at-break of treated fabric samples in warp and weft directions have increased. This increase in both the tensile characteristics of treated fabric samples may be due to treatment with finishing chemicals and the effect of fabric assistance.

Study of test of significance (t value) shows that there are significant increase in breaking strength in warp direction of the samples treated with 4% concentration in comparision to the breaking strength of samples treated with 1% concentration ($t_{cal>}t_{tab}$).

In weft direction also, there is a significant increase in breaking strength of the sample treated with 5% concentration in comparison with breaking strength of sample treated with 1% concentration ($t_{cal>}t_{tab}$). This may be due to the presence of more materials physically in the fabric, causing an increase in inter yarn friction.

In case of elongation-at-break in warp direction, there is no significant increase or decrease in the case of the samples treated with different concentrations ($t_{cal<}t_{tab}$). Whereas, in case of elongation-at-break value of treated samples in weft direction, there has been significant decrease in the sample treated with 2% concentration in comparison with sample treated with 1% concentration ($t_{cal<}t_{tab}$).

(ii) Fabric Flexural Rigidity – Treated and untreated samples are tested for flexural rigidity (Fig. 4). In the case of flexural rigidity (G), as compared to untreated sample, the flexural rigidity (G) of treated sample is more at any concentration of the treated sample due to the application of zeolites chemical**.**

4 Conclusion

A preliminary study has shown that cotton fabric treated with suitable finishing materials in optimized concentration has the capability of adsorbing air pollutant gases namely Carbon dioxide (CO_2), Carbon monoxide (CO), Sulphur dioxide (SO_2), and Nitrogen dioxide (NO_2). It is observed that the flexural rigidity of treated samples increased due to the application of finishing materials. Chemical treatment also increases breaking strength and elongation-at-break% in both the directions (warp and weft) of fabric treated with different concentrations. It is concluded that the treatment of samples with finishing materials has enhanced the air pollutant gas adsorption capability.

As no instrument was available for testing of air pollutant gas adsorption capability of air cleaner textiles, an instrument was designed and developed by NITRA. This instrument can determine the air pollutant adsorption capability of any type of fabric. This instrument may be very useful to the textile industry engaged in the manufacturing of air cleaner home textiles.

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