Improving workplace safety for construction workers handling dry construction mixtures

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Abstract. To improve the reliability of respiratory protection available for workers handling dry mixtures, when dust and noxious gases penetrate the work area, it is necessary to both upgrade the design of the respirators currently in use, and develop new porous layer materials to enhance the protection level along with user convenience. An ion-exchange filtering material has been developed, which offers both protective and hygienic properties. A mathematical model has been created to simulate the half-mask casing of a Snezhok GP-V type respirator. The finite element method was used for stress analysis of the casing.

Nomenclature

\[ [K] \] - rigidity matrix of a structure;
\[ \{\Delta\} \] - combined vector of nodal displacements;
\[ \{F\} \] - combined vector of nodal loads.

1. Introduction

The studies of workplace conditions available to workers in the construction industry showed that, even when aspiration systems are operating, the content of noxious substances dispersed in the air in work areas exceeds the maximum allowable concentrations (MAC), which also significantly increases the probability of developing an occupational disease.

The recent years have seen a dramatic growth in the scope of repair and construction works involving broad use of dry construction mixtures with their composition varying depending on the work specifics. For example, cement-based dry mixtures with the addition of hardeners, in particular, sodium fluoride, as modifying agents, are used for making poured flooring. When these mixtures are further mixed with water, dust penetrating the work area may also bring in gaseous fluoric compounds (hydrogen fluoride or tetrafluoride silicon).

Given a significant content of noxious substances in the work area, respiratory protection is normally ensured by all-purpose respirators protecting the respiratory organs against exposures to harmful gases and solids. In many cases, heavy-duty respirators are viewed by workers as extra load and interference creating a feeling of discomfort. This is explained by the fact that the user perceives a respirator not only in terms of its protective efficiency, but also from the ergonomic and physiological
performance perspective (breathing resistance, weight, visibility restriction, likelihood of skin irritation, pressure sores, painful sensations).

One of the best in breed among lightweight respirators are Snezhok GP-V type all-purpose gas and dust proof respirators, however their wide application is hindered by the absence of the required range of textile ion-exchange materials with improved hygienic properties to serve as the filtering layer. This is why it is essential that the upgrading of the design of respirators themselves is combined with the development of materials capable of enhancing not only the protection level, but also the user experience.

2. Review

To improve the protective properties of filtering elements of all-purpose gas and dust proof respirators and reduce the amount of inward leakage by ensuring tighter fitting of the half-mask along the sealing line coupled with greater user convenience, an unwoven material has been developed [1]. It consists of a double layer fibrous canvas with one layer made of anion-exchange modified polyamide fiber [2], and the other layer made of hydrophilic modified polyamide fiber [2]. The material is held together by employing the sewing and knitting technology with a Malipole machine, where plush sinkers are used without cutting plush strips. The distance between the layers is 6mm. The sewing thread is made of a yarn consisting of mixed hydrophilic modified polyamide fiber and high-shrinking viscose fiber, with the latter accounting for 35% of the mix. The sewing thread, secured by tricot weave, forms plush strips between the layers. The surface density of the material is 400 g/m². The weight ratio of the modified anion-exchange polyamide fiber layer, sewing thread and the hydrophilic modified polyamide fiber layer is 1:0.2:0.5.

Figure 1 shows the unwoven filtering material containing the fibrous canvas 1, system of holding loops 2, sewing thread 3, plush strips 4 and fibrous layer 5.

![Figure 1. Sorption based filtering material.](image)

The material is further thermally treated on a calender at a temperature of 80 degrees and a pressure between the shafts of \((2 \times 10^5)\)Pa for 60 seconds. In the process of thermal treatment, a complex spring-like structure of plush strips emerges due to thermal shrinkage of the viscose high-shrinking fiber.

The material suggested has the enhanced protective properties as applied to acid gases and significant mechanical resistance (table 1). Thanks to its structure, the new material helps improve the protective properties of respirators by reducing the amount of inward leakage while ensuring tighter fitting of the half-mask along the sealing line. The worker's face contacts the layer of hydrophilic modified fiber, which makes the respirator more comfortable for use.
The development of a respirator design ensuring uniform air distribution as well as minimized local pressures along the sealing line requires the knowledge of the distribution of local loads applied to the casing and the mechanism of their transfer to the face seal.

To prevent penetration of noxious substances inside the mask through gaps occurring along the sealing line, the force applied from the headband to the casing of the respirator half-mask is required to be within 4 - 10N. The lower boundary of the range indicates the pressure at which penetration of dispersed particles along the sealing line stops, and the upper value indicates the ultimate pressure above which a respirator starts feeling uncomfortable and causing pressure sores. However, as soon as the force exceeds 12N, the respirator’s fitting along the sealing line becomes non-uniform, and the maximum pressure concentrates in the nasal bridge and chin areas [3].

**Table 1. Properties of sorption filtering material.**

| Description                                                                 | Value   |
|-----------------------------------------------------------------------------|---------|
| 1. Duration of protective action against hydrogen fluoride, hr               | 24      |
| 2. Efficiency of dust collection, %                                         | 99      |
| 2. Inward leakage at respirator mask, %                                     | 0.03    |
| 3. Air permeability, dm³/m² s                                               | 250     |
| 4. Initial resistance to continuous air flow with a 30l/min volumetric flow rate, Pa | 25      |
| 5. Breaking load, cN                                                        |         |
| Lengthwise                                                                 | 830     |
| Widthwise                                                                  | 824     |
| 6. Tensile elongation, %                                                    |         |
| Lengthwise                                                                 | 73      |
| Widthwise                                                                  | 66      |
| 7. Flexural rigidity, cN                                                    |         |
| Lengthwise                                                                 | 14.3    |
| Widthwise                                                                  | 14.0    |

For the moment, one of the most common methods for studying the stress-strain condition of structures is the finite element method (FEM) [4].

A respirator casing can be figured as a spatial frame where bars act as finite elements. The nodal joints between these elements are assumed to be rigid type, and the peripheral joints – hinge type. In our case, the FEM is used as a displacement method, which is easy to adapt to an algorithm and simple enough for understanding and computing.

After the local rigidity matrices are prepared for the elements, dependences are developed, which connect the nodal force with nodal displacements. For the element \(i - j\), the dependence between the nodal values can be written as equation (1), (2):

\[
\begin{bmatrix}
    f_i \\
    f_j
\end{bmatrix} =
\begin{bmatrix}
    k_{ii} & k_{ij} & \ldots & k_{ij} & \ldots & k_{ji} \\
    \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
    k_{ji} & k_{jj} & \ldots & k_{jj} & \ldots & k_{ji}
\end{bmatrix}
\begin{bmatrix}
    \delta_i \\
    \delta_j
\end{bmatrix},
\]

(1)

where \(f_i, f_j, \delta_i, \delta_j\) are the vectors of end forces and displacements of the bar \(i - j\), respectively, where each vector consists of six components;

\(k_{ii}, k_{ij}, k_{ji}, k_{jj}\) – 6x6 units of the rigidity matrix \(i - j\).

\[
\begin{bmatrix}
    f_j
\end{bmatrix} = \begin{bmatrix}
    k_{ji}
\end{bmatrix}\cdot\begin{bmatrix}
    \delta_j
\end{bmatrix} + \begin{bmatrix}
    k_{jj}
\end{bmatrix}\cdot\begin{bmatrix}
    \delta_j
\end{bmatrix}
\]

(2)
Let us cut the $i$-th node out of the structure (figure 2).

**Figure 2.** Design layout of the $i$-th node.

Equilibrium equations of the $i$-th node:

\[
\begin{align*}
\sum x &= \sum_{l=1}^{L} \tau_{x_i}^{(l)} + F_{x_i} = 0; \\
\sum y &= \sum_{l=1}^{L} \tau_{y_i}^{(l)} + F_{y_i} = 0; \\
\sum z &= \sum_{l=1}^{L} \tau_{z_i}^{(l)} + F_{z_i} = 0; \\
\sum M_x &= \sum_{l=1}^{L} m_{x_i}^{(l)} + M_{x_i} = 0; \\
\sum M_y &= \sum_{l=1}^{L} m_{y_i}^{(l)} + M_{y_i} = 0; \\
\sum M_z &= \sum_{l=1}^{L} m_{z_i}^{(l)} + M_{z_i} = 0.
\end{align*}
\]  
\tag{3}

The forces are totalized for all bars which come together in the node of interest. The equations (3) in matrix form

\[
\sum_{l=1}^{L} \{ \tau_i^{(l)} \} + \{ F_i \} = 0.
\]  
\tag{4} 

where

\[
\{ \tau_i^{(l)} \} = \begin{bmatrix}
\tau_{x_i}^{(l)} \\
\tau_{y_i}^{(l)} \\
\tau_{z_i}^{(l)} \\
m_{x_i}^{(l)} \\
m_{y_i}^{(l)} \\
m_{z_i}^{(l)}
\end{bmatrix}; \quad \{ F_i \} = \begin{bmatrix}
F_{x_i} \\
F_{y_i} \\
F_{z_i} \\
M_{x_i} \\
M_{y_i} \\
M_{z_i}
\end{bmatrix}.
\]  
\tag{5}

The $\{ \tau_i^{(l)} \}$ vector contains projections of internal forces onto the coordinate axes, which gives:
By placing the equations (2) and (3) in (6), we obtain:

\[-f_i = \bar{f}_i\]  \hspace{1cm} (6)

or

\[
\sum_{j=1}^{m} \left[ k_{ii} \delta_i \right] + \sum_{j=1}^{m} \left[ k_{ij} \delta_j \right] = \{F_i\}
\]

\[
\sum_{j=1}^{m} \left[ k_{ii} \delta_i \right] + \sum_{j=1}^{m} \left[ k_{ij} \delta_j \right] = \{F_i\}
\]

The equation system for all structural components will be as follows

\[
\begin{align*}
\sum [k_{11}] \delta_1 + \sum [k_{1j}] \delta_j &= \{F_1\} \\
\sum [k_{22}] \delta_2 + \sum [k_{2j}] \delta_j &= \{F_2\} \\
\sum [k_{33}] \delta_3 + \sum [k_{3j}] \delta_j &= \{F_3\} \\
\vdots &
\end{align*}
\]

... ... ... ... ... ... ...

\[
\sum [k_{NN}] \delta_N + \sum [k_{NJ}] \delta_J &= \{F_N\}
\]

or

\[
[K][\Delta] = \{F\}. \hspace{1cm} (9)
\]

where \([K]\) - rigidity matrix of a structure;

\{\Delta\} - combined vector of nodal displacements;

\{F\} - combined vector of nodal loads.

The finite element, an all-purpose bar, is shown in figure 3. The bar is placed in the local right-hand rectangular system of coordinates X₁, Y₁, Z₁, for which forces are determined and the local load is set. The X₁ axis runs lengthwise along the bar axis from the beginning to the end. The Y₁ and Z₁ axes are the key inertia centerlines. The Z₁ axis is always directed toward the upper half-space. For arbitrarily oriented bars, the Y₁ axis is assumed to be parallel to the XOY horizontal plane of the global coordinate system, and for vertical bars, it is assumed to be parallel to the Y axis of the global coordinate system and oriented in the opposite direction.

Figure 3. An all-purpose bar as the finite element.
There are several options for securing the bar to the layout nodes: with absolutely rigid inserts located along the local axes; by removing a tie in any direction (removing a linear tie provides slipping; removing an angular tie provides free swing, that is a cylindrical hinge).

The rigidity matrix is built for the flexible part of the bar. The references for local loads are additionally set in respect of the elastic part of the bar.

When the reference ties overlap, the directions are selected in which the displacement of the X, Y, Z, UX, UY, UZ nodes is to be prohibited.

To solve the task, the following element's rigidity parameters are required: modulus of elasticity (E); geometric dimensions of the element's cross-section; specific weight of the material.

The respirator loads were assumed according to the following rules: a positive force value corresponds to action directed against the axis; a positive moment value corresponds to clockwise rotation when viewed from the axis end; a positive set displacement corresponds to action directed along the axis; a positive set turn corresponds to counter-clockwise rotation when viewed from the axis end.

The following parameters were assumed for computing: the type of rigidity matrix profile optimization is the tree algorithm; the accuracy of matrix decomposition is seven decimal places.

Figure 4 shows a topside view of the spatial 3D model based on a design layout. Figure 5 provides the numbering of the layout components and elements.
The computation results for certain elements are given in table 2. The load was assumed in a generic $F$ form; accordingly, the computation results are also given in force $F$ fractions.

Figure 6 shows the respirator deformation under load: thin lines contour the initial layout; bold lines contour the layout after loading. The side projection clearly shows a gap between the respirator and the abutting face.

Table 2. Computation results

| Units of force: $F$ | Units of moment: $F\cdot m$ |
|-------------------|-----------------------------|
| Elements          |                            |
| 1-1               | 58                         |
| 2-1               | 11                         |
| 3-1               | 12                         |
| 4-1               | 13                         |
| 1-2               | 58                         |
| 2-2               | 11                         |
| 3-2               | 12                         |
| 4-2               | 13                         |
|                  | 12                         |
|                  | 13                         |
|                  | 13                         |
|                  | 14                         |
|                  | 14                         |
| N                 | -0.887                     |
| M                 | -0.002                     |
|                  | 0.0016                     |
|                  | 0.0002                     |
|                  | 0.00039                    |
|                  | 0.00039                    |

Figure 6. Respirator layout diagram: a) full face view; b) profile view.

3. Conclusions

1. In order to improve the reliability of respiratory protection available to workers handling dry mixtures, when dust and noxious gases penetrate into the work area, it is necessary to both upgrade the design of the respirators currently in use, and develop new porous layer materials to enhance the protection level along with user convenience.

2. An ion-exchange filtering material has been developed, which offers high protective and hygienic properties. The structure of the new material improves the protective properties of respirators by reducing the amount of inward leakage while ensuring tighter fitting along the sealing line.

3. A mathematical model has been created to simulate the half-mask casing of a Snezhok GP-V type respirator. The finite element method was used for stress analysis of the casing.

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