Processing of exposure results for composite material with the choice of their optimal composition

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Abstract. The article presents the results of processing a number of compositions of composite materials sustained under cyclic temperature changes, as well as changes in humidity and positive temperatures. A method is proposed for determining the optimal composition of materials, taking into account changes in such characteristics as hardness, modulus of deformation of the material and the elastic modulus of the material during exposure.

1. Introduction

At the present stage of studying concretes, composite concretes and composite materials in general, higher attention is paid to their optimization, the study of their characteristics, the dependence of various properties on operating conditions.

Questions of studying the properties and characteristics of composite materials and concretes are widely covered. The problems of modeling the problems of exposing materials in adverse operating conditions are considered. Experiments are conducted to study the properties of building materials, cement and polymer composites [1-30].

Various methods and algorithms for processing experimental data are used, for example, methods of experiment planning [9, 11-14], regression analysis [25-27], decision-making theory [28-33], optimization [11, 12, 15, 19, 20, 22, 23, 28, 29, 30]. To varying degrees, they are used to analyze the results of exposure of composite materials in adverse conditions [7, 9-11, 13, 14, 27]. Various goals are set. In particular, an important task is to determine the composition of composites, the characteristics of which are most resistant to operational impacts. First of all, it is the hardness of the material, then the modulus of elasticity of the corresponding character. In this paper, they are chosen – the hardness (T), the material's modulus of deformation (Ed), and the equilibrium elastic modulus (Eee). As a result of the tests, their absolute changes were recorded during the following time periods: 0 (indicators of control samples), 15, 30 and 45 days. The task is to select the tested composites of the composition that is least susceptible to adverse operational effects by any criteria. A multi-criteria and multidimensional optimization problem arise. This problem is considered and justified by numerical simulation experiments.
2. Materials and methods

The problem statement consists in the optimal choice of those compositions of composite materials, in which their properties – hardness, modulus of deformation and equilibrium modulus of elasticity change at least during the exposure time. The materials were aged under the influence of positive and negative temperatures, and under the influence of high humidity and variable temperatures.

Thermocyclic tests of samples (composites) were carried out in laboratory conditions in the climate chamber of VIAM (all-Russian research Institute of aviation materials) in two stages. At the first stage, a batch of samples was tested with 15 thermocycles, and at the next stage, the second batch of samples was tested with 13 thermocycles. One 24-hour thermal cycle includes four thermal states. Tests of samples under cyclic influence of positive and negative temperatures included the following operations: cooling of samples from room temperature (+23°C) to –50°C – about an hour (50 – 55 min); exposure of samples at a temperature of –50°C – 9 h; natural heating of samples to room temperature (+23°C) with the camera off – at least 5 h; exposure of samples at room temperature (+23°C) – 9 hours [27].

Tests of samples at high humidity (98%) and varying positive temperatures included other parameters: heating of samples from room temperature (+23°C) to +60°C – about 5 minutes; exposure of samples at a temperature of +60°C – 9 hours; natural cooling of samples to room temperature (+23°C) with the camera off – at least 5 hours; exposure of samples at room temperature (+23°C) – 9 hours [27]. Experimental data of the conducted tests are given in table 1, table 2, where A1, A2, ..., B1, B2 – designations of the studied composites.

Table 1. The results of thermo-cyclic testing.

| Composition (Alternative) | Duration tests, day | Hardness (T), [MPa] | Module Deformations (Ed), [MPa] | Equilibrium modulus of elasticity (Eee), [MPa] |
|--------------------------|---------------------|---------------------|-------------------------------|---------------------------------|
| A1                       | 0                   | 4010.17             | 9291.38                       | 144975.95                      |
|                          | 15                  | 2037.07             | 3354.78                       | 38384.05                       |
|                          | 30                  | 1701.21             | 2606.26                       | 37544.48                       |
|                          | 45                  | 1349.36             | 1822.47                       | 36664.94                       |
| A2                       | 0                   | 7016.08             | 214592.64                     | 285239.47                      |
|                          | 15                  | 3629.11             | 7971.14                       | 97274.28                       |
|                          | 30                  | 2982.76             | 6072.11                       | 86090.54                       |
|                          | 45                  | 2166.32             | 3674.32                       | 71976.34                       |
| A4                       | 0                   | 5476.90             | 147693.86                     | 183037.86                      |
|                          | 15                  | 3966.10             | 9102.56                       | 103947.96                      |
|                          | 30                  | 3643.01             | 80613.86                      | 89938.26                       |
|                          | 45                  | 3194.28             | 66153.45                      | 70480.34                       |
| A5                       | 0                   | 9746.86             | 354170.95                     | 417368.27                      |
|                          | 15                  | 3786.73             | 85008.56                      | 91850.16                       |
|                          | 30                  | 3273.56             | 69346.72                      | 81875.07                       |
|                          | 45                  | 2488.71             | 45393.31                      | 66619.05                       |
| A9                       | 0                   | 7488.59             | 250219.85                     | 286890.30                      |
|                          | 15                  | 1228.19             | 15722.21                      | 17726.83                       |
|                          | 30                  | 1743.69             | 28292.49                      | 39728.65                       |
|                          | 45                  | 2811.52             | 54330.94                      | 85303.85                       |
| A10                      | 0                   | 3503.34             | 75640.22                      | 111334.81                      |
|                          | 15                  | 2728.51             | 51977.25                      | 63513.81                       |
|                          | 30                  | 2641.86             | 49571.33                      | 65824.93                       |
|                          | 45                  | 2441.90             | 44019.21                      | 71158.28                       |
| A11                      | 0                   | 2472.17             | 44833.37                      | 64208.59                       |
|                          | 15                  | 2451.66             | 44358.11                      | 61429.77                       |
|                          | 30                  | 2199.48             | 38246.00                      | 52036.89                       |
|                          | 45                  | 1465.86             | 20465.32                      | 24712.15                       |
Table 2. The results of tests under cyclic impact high humidity and positive temperatures.

| Composition (Alternative) | Duration tests, day | Hardness (T), MPa | Module deformations (Ed), MPa | Equilibrium modulus of elasticity (Eee), MPa |
|---------------------------|---------------------|------------------|-------------------------------|------------------------------------|
| A1                        | 0                   | 4010.17          | 92914.38                      | 144975.95                         |
|                           | 15                  | 4308.81          | 103122.15                     | 128411.95                         |
|                           | 30                  | 4188.12          | 98968.91                      | 131254.64                         |
|                           | 45                  | 4058.15          | 94496.20                      | 134316.00                         |
| A2                        | 0                   | 7016.08          | 214592.64                     | 285239.47                         |
|                           | 15                  | 4926.15          | 129501.89                     | 165838.56                         |
|                           | 30                  | 5604.37          | 156282.45                     | 192936.22                         |
|                           | 45                  | 6590.88          | 195236.00                     | 232351.00                         |
| B3                        | 0                   | 2065.24          | 34205.20                      | 61323.24                          |
|                           | 15                  | 3492.44          | 75571.86                      | 100653.67                         |
|                           | 30                  | 3432.16          | 73535.70                      | 101391.15                         |
|                           | 45                  | 3356.80          | 70990.50                      | 102313.00                         |
| B4                        | 0                   | 9746.86          | 354170.95                     | 417368.27                         |
|                           | 15                  | 5577.39          | 151786.84                     | 202344.36                         |
|                           | 30                  | 8217.58          | 289799.12                     | 355544.23                         |
|                           | 45                  | 12705.90         | 524420.00                     | 615984.00                         |
| B5                        | 0                   | 4089.57          | 95300.69                      | 111239.79                         |
|                           | 15                  | 8337.79          | 236655.80                     | 327340.94                         |
|                           | 30                  | 10339.26         | 171126.11                     | 451548.63                         |
|                           | 45                  | 14342.20         | 625891.00                     | 699694.00                         |
| B6                        | 0                   | 1187.85          | 14949.93                      | 32376.75                          |
|                           | 15                  | 7496.49          | 236655.80                     | 269806.53                         |
|                           | 30                  | 5633.02          | 171126.11                     | 199181.37                         |
|                           | 45                  | 1207.29          | 15493.10                      | 31446.60                          |
| B7                        | 0                   | 7488.59          | 250219.85                     | 286890.30                         |
|                           | 15                  | 3119.91          | 63500.34                      | 97528.19                          |
|                           | 30                  | 3092.42          | 63674.97                      | 96429.32                          |
|                           | 45                  | 3013.89          | 64173.90                      | 93289.70                          |

As can be seen from the tables 1 and 2, the properties (T, Ed, Eee) of the compositions change relative to their control values during the exposure time. Their relative changes are of interest. In this regard, the values of the tables should be converted to relative values, relative to the control values, relative to the values in the row with the indication zero (0 – the duration of the test). This will allow you to compare the properties of materials with different ranges of changes in a particular property. These two selves may differ by several orders of magnitude.

Table 3. The results of tests under cyclic impact high humidity and positive temperatures.

| Composition (Alternative) | Duration tests, day | Hardness (T) | Module deformations (Ed) | Equilibrium modulus of elasticity (Eee) |
|---------------------------|---------------------|--------------|--------------------------|----------------------------------------|
| A1                        | 0                   | 1.000000     | 1.000000                 | 1.000000                               |
|                           | 15                  | 1.074471     | 1.109862                 | 0.885747                               |
|                           | 30                  | 1.044375     | 1.065162                 | 0.905355                               |
|                           | 45                  | 1.011965     | 1.017024                 | 0.926471                               |
| A2                        | 0                   | 1.000000     | 1.000000                 | 1.000000                               |
|                           | 15                  | 0.702123     | 0.603478                 | 0.581401                               |
|                           | 30                  | 0.798789     | 0.728275                 | 0.676401                               |
|                           | 45                  | 6590.88      | 195236.00                | 0.814582                               |
For an explanation, see table 3, which summarizes the relative values for the first two compounds (A1, A2) from table 2.

Regardless of the purpose of a particular composite, the natural requirement is primarily the immutability of its properties. In this case, the relative values of the properties will be equal to one. At the same time, the actual state of things may not meet the requirement that the property indicators remain unchanged during the exposure time under the specified operating conditions. For comparison of the desired requirement of immutability of properties and their actual changes in figure 1, figure 2 charts are presented in relative units.

Figure 1. A property is invariant for the tests.
Figure 2. The property depends on the test.

As shown in tables 1 and 2, relative changes in properties may exceed the level of the control sample property during the test. In this regard, it is proposed to calculate the area under the polyline curve (figure 3, figure 4) and compare it with the area of the rectangle \( S_{\text{rect}} \) with a height equal to one. In the case of figure 1, \( S_{\text{rect}} \) is equal to 45 square units.

Figure 3. Monotonous decrease of the property value.
Figure 4. Non-monotonic change in the values of the properties.

When the values of the controlled property (for example, hardness) of the composite are monotonously reduced, one of the criteria for determining the best composition can be the ratio of \( S_{\text{polygon}} / S_{\text{rect}} \) areas, which will tend to zero in the ideal case. If there is a non-monotonic change in the
value of the controlled property (figure 4), the area of the polygon $S_{\text{polygon}}$ may differ little from the area of the rectangle for the composite property with the unchanged nature of the change from the test time. However, the given area ratio can be taken as a criterion in the problem of determining the optimal composition. In [15], a two-criteria optimization problem was considered, and the criteria used to determine the preferred composition of composites were described. Here we propose an addition to the criteria for searching for the optimal composition of a number of composites that have been tested under test operating conditions. For the first criterion, we use the $S_{\text{polygon}} / S_{\text{rect}}$ area ratio.

Figure 5 and figure 6 show the construction to determine the criteria $K_i$, $H_i$, $i = 1, 2, 3$.

![Figure 5. To determine the $H_i$ criterion.](image)

![Figure 6. To determine the $K_i$ criterion.](image)

The criterion $S$, which takes into account the area ratio, is formed in the form $S_i = S_{\text{polygon}} / S_{\text{rect}}$. Another criterion, the $J_i$ criterion, is defined as the sum of the specified criteria, i.e.

$$J_i = S_i + K_i + H_i, \quad i = 1, 2, 3.$$

(1)

It is obvious that for a composite whose properties change slightly during the exposure period, the entered criteria will tend to zero. However, the number of exposure points is not limited (within reasonable limits). These ratios will be determined for each composite composition, in particular in accordance with table 1 and table 2. There will be seven for each exposure point, i.e. 28 for each controlled property.

Thus, as in the decision-making theory [24, 25], we accept composite compositions (A1, A2,...) as alternatives, and $S_i$, $K_i$, $H_i$, $J_i$ ($i = 1, 2, 3$) as criteria. However, the criteria values should be defined for each property. The following tables are compiled in accordance with ELECTRA methods:

- table of values for criteria and alternatives,
- table of ratings for the values of each criterion,
- table matrix of the estimates.

In this case, the task of selecting the composition is to determine the optimal sum of ratings from the rating matrix. The size of the rating matrix is set based on possible changes in each controlled property of the composites. The estimation matrix is formed taking into account monotony and arbitrary changes in a particular property during the exposure period. Summation of scores based on the rating matrix is based on comparison of the values of the rating matrix and criteria for a predetermined value. The value of this value is defined as a half digit of significant digits in the data array. For the data shown in tables 1 and 2, it is equal to 0.005. The comparison is performed based on the absolute value of the nearest values of the rating matrix with the values of the calculated criteria.
cyclic algorithm is used with a nesting value equal to three-the number of criteria (controlled properties of composites), the exposure points, and the number of alternative samples.

There are various ways to choose the optimal compositions [4, 7, 12, 15, 19, 21–24, 28, 30]. Here we propose a developed heuristic approach for processing experimental data in order to select the optimal composition of test-tested composites.

3. Results

Taking into account the fact that the selected criteria should be minimized, then the formation of estimates for the criteria will be arranged in descending order. The size of the matrix of possible criteria values should be assumed to be greater than the number of alternatives – the number of compositions. This will allow you to divide the estimates in a wider range, which, in turn, will almost eliminate the coincidence of the sum of estimates for alternatives. In the conducted experiments, the size of the matrix with estimates is assumed to be equal to twice the size of the number of alternatives.

Table 4 shows a matrix of estimates of composites exposed during cyclic temperature tests.

Table 4. The final matrix of the evaluations for cyclic temperature testing.

| Alternatives | Total score | T | Ed | Eee |
|--------------|-------------|---|----|-----|
|              |             | S | K  | H  | J  |
|              |             | S | K  | H  | J  |
| 128 A10      | 13          | 11 | 11 | 14 | 14 |
| 124 A11      | 14          | 13 | 14 | 11 | 14 |
| 105 A4       | 11          | 10 | 9  | 10 | 10 |
| 74 A1        | 8           | 6  | 6  | 4  | 5  |
| 73 A2        | 8           | 6  | 7  | 4  | 8  |
| 70 A5        | 7           | 5  | 5  | 3  | 3  |
| 59 A9        | 5           | 4  | 3  | 2  | 2  |

In table 4, the alternatives are the teams ranked by total points. Experimental data are taken from table 1. As can be seen, the optimal composition of the composite corresponds to A10, which more than the rest meets the conditions for optimal selection among a given number of samples that have been tested at a temperature change for 45 days. For visual control of the relative change in the hardness of the first group of composites, a diagram is shown in figure 7, which shows that the performed ranking

![Figure 7. Relative change in the hardness of composites (A1, A2, A4, A5, A9, A10, A11).](image)
of samples (table 4) is consistent with the nature of the change in the hardness of each composition (alternative) during the test time.

A similar table (table 5) is provided for optimal selection of composites that have been maintained in conditions of high humidity and positive temperatures.

Table 5. Final rating matrix for composite exposure in conditions of high humidity and positive temperatures.

| Total score | Alternatives | The studied properties of the composites: T, Ed, Eee |
|-------------|--------------|---------------------------------------------------|
|             |              | T        | Ed       | Eee  |
|             |              | S  | K  | H  | J  | S  | K  | H  | J  |
| 98          | A1           | 5  | 2  | 3  | 14 | 14 | 2  | 1  | 14 |
| 97          | B6           | 14 | 14 | 14 | 1  | 1  | 2  | 14 | 14 |
| 66          | B5           | 9  | 6  | 10 | 2  | 2  | 2  | 8  | 9  |
| 51          | B7           | 3  | 1  | 2  | 2  | 1  | 2  | 9  | 12 |
| 49          | B3           | 6  | 3  | 5  | 3  | 3  | 4  | 4  | 5  |
| 45          | A2           | 4  | 2  | 3  | 3  | 4  | 3  | 4  | 4  |
| 44          | B4           | 4  | 2  | 3  | 2  | 2  | 6  | 7  | 3  |

According to the results of table 5, we conclude that the most preferred composite is A1 when tested in conditions of high humidity and positive temperatures.

4. Conclusions

The paper considers the results of experimental studies of various ready-to-use composite materials. In contrast to the known similar studies [7, 9, 11, 13], the paper highlights the results of studies with a periodicity of 15 days: 0-15-30-45. The tests were carried out according to the requirements of climatic tests-from sub-zero temperatures to high positive values. To a certain extent, a heuristic method for solving a multi-criteria multidimensional optimization problem is proposed, which allows it to be used in experimental studies to determine the optimal composition of a number of composites under study. The authors have defined and proposed criteria for finding the optimal composition of composites that have passed test tests with the measurement of three properties of composites. At the same time, the number of properties can be quite arbitrary, according to the authors. The number of exposure points can also be arbitrary. At the same time, the authors are aware that if the results are extrapolated, they may differ to some extent from the experimental results obtained over a longer period of time, more than 45 days.

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