Study of dispersed-reinforced expanding plugging materials to improve the quality of well cementing

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Abstract. The most common complications during the construction and operation of wells, such as gas and water showings and interstratal crossflows, in most cases result from seal failure of the annular space caused by cracking and destruction of the cement ring. The main way to improve the stability and tightness of well support is a rational cementing technology using high-quality plugging materials. Recently, due to the toughening of environmental requirements for a number of chemical reagents used for the treatment of plugging solutions, the most expedient in terms of increasing the fracture strength of a stone has become a method for developing plugging materials from several components with different physicochemical and physicomechanical properties. These are dispersed-reinforced materials, which are a mixture of backfill cement and mineral or artificial fibers, as well as organic fibrous additives from cellulose, jute, cotton, etc. The article discusses the results of studies of expanding reinforced plugging solutions in order to study their main technological and strength characteristics.

Keywords: Cement slurry; Dispersed reinforcement; Cement stone; Linear expansion; Basalt fiber; Polypropylene fiber; Fracture strength

1. Introduction

Damage of cement stone integrity occurs due to the complex of static (pressure in the casing) and alternating dynamic loads, which include round-trip operations, perforation, as well as the operation of underground gas storage (UGS) wells in gas extraction and injection modes, etc. [1-3]

However, even with significant strength of cement stone and low permeability, it has low fracture strength and deformability, which explains its inability to withstand loads, especially of a cyclic nature. Fractures formed in the cement stone under the action of loads are filled with formation fluid and are the channels of its migration, and, as a consequence, the appearance of man-made accumulations and annular pressures.

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The use of a composition that includes ingredients, the interaction of which forms resin-like compounds with various functional groups involved in the processes of structure formation of cement stone, contributes to an increase in its deformation properties and fracture strength [4].

Dispersed-reinforced plugging stone differs from the usual one in that the fiber segments, arbitrarily oriented along its volume with sufficient uniformity of their distribution, more efficiently perceive and distribute part of the load in any direction acting on the cement stone.

The effectiveness of the reinforcing additive effect in the plugging material, determined by the physicomechanical properties of the resulting stone, largely depends on the physicochemical and physicomechanical properties of the fibers themselves [5]. These fibers must have sufficient mechanical strength; have sufficient resistance in the alkaline environment of the plugging solution-stone and adhesion to the cement stone (adhesion).

Artificial fibers are known to have low adhesion to the cement matrix, while organic fibers have low mechanical strength and rapid destruction in aqueous media. Mineral fibers have higher strength and rather low hygroscopicity, and some of them are highly resistant to alkaline conditions.

2. Informal statement of the problem
The practice of construction of oil wells shows the use of traditional plugging materials does not always provide the required quality of well casing while the requirements for the protection of subsoil are toughened. This refers to such complex geological conditions as the alternation of intervals with different reservoir pressures, the presence of horizons with low hydraulic fracturing pressure gradients, large deviations from the vertical, etc. The main problems when casing wells in such conditions are: the absorption of plugging solutions, the undershoot of the cement slurry to the design height, insufficient quality separation of layers and the resulting interstratal crossflows [6-7].

High quality of well casing will be ensured only with reliable contact of the cement stone with its limiting surfaces (casing and rock); therefore the use of expanding plugging materials during cementing is generally accepted. At the same time, it is obvious that their application will not give positive results in intervals with a thick mud cake or in intervals of caverns, i.e. where the space for expansion is greater than the magnitude of the expansion itself.

In addition, such works as secondary exposing of the formation (perforation), well completion and hydraulic fracturing create large dynamic loads on the cement stone, which lead to its destruction. At the same time, the cement ring can be completely destroyed which often leads to premature watering of wells, and companies defray additional costs. In this regard, it is necessary to improve the formulation of plugging cements in order to improve the properties of the stone in relation to high dynamic loads [8-10].

When the cement slurry hardens with a fibrous filler, a dispersed-reinforced cement stone is formed, which is characterized by increased strength and fracture strength. The article discusses the influence of basalt and polypropylene fibers on the deformation properties of cement stone.

Thus, the urgent problem is to obtain dispersed-reinforced expanding plugging cements with improved technological properties.

3. Methodology and results of experimental studies
Studies [3] of the effect of reinforcing additives of basalt fiber (BF) and polypropylene fiber (PPF) on the strength characteristics of a cement stone made of cement plugging material PCT I-G-CC-1 were carried out. The parameters of plugging solutions, as well as the results of strength tests, are shown in the Table 1.
Table 1. Test results of cement stone samples

| № | Filler content, % by weight of cement | Water/Cement | Flowing, cm | Density, kg/m³ | Two-day strength limit of cement stone, MPa |
|---|-------------------------------------|-------------|-------------|---------------|------------------------------------------|
|   | BF                                  | PPF         |             |               | bending | compression | compression |
| 1 | –                                   | –           | 0,48        | 16,0          | 1,60   | 3,21        | 3,01        |
| 2 | 0,05                                | –           | 0,50        | 15,5          | 1,92   | 3,76        | 3,53        |
| 3 | –                                   | 0,05        | 0,50        | 15,0          | 1,78   | 3,30        | 3,09        |

* Compressive strength determined using a lever press

Reinforcement of cement stone BF increases its flexural strength by 20%, and PPF - by 11%. Compressive strength increases by 32% and 16%. In our opinion, the strength of the cement stone with BF is higher than the strength of the stone with PPF due to the greater adhesion of the mineral fiber to the cement stone than organic-based artificial fiber [3].

To assess the deformability of a cement stone, tests of its compressive strength were carried out using a lever-type press (Figure 1).

![Lever-type press](image)

1 - rack; 2 - dial indicator; 3 - stock; 4 - metal plates; 5 - a sample of cement stone; 6 - bed; 7 - lever; 8 - cargo; 9 - suspension; 10 - guide post

Based on the results obtained, a graph of the dependence of cement stone deformation on the applied load was built (Figure 2) and their compressive strength was determined.
The obtained dependence of deformation on load during compression tests of "pure" and reinforced cement stone with BF is typical for samples made of brittle materials (stone, cast iron). The deformation graph of a cement stone reinforced with PPF is approximated by a straight line, which is also typical for brittle bodies.

The brittleness of cement stone is usually characterized by the ratio of compressive and flexural strengths and should tend to decrease in order to increase its fracture strength. This is observed when the stone is reinforced with fibrous fillers, as evidenced by the results of determining the brittleness index of the tested samples of cement stone with BF and PPF in comparison with unreinforced cement stone (Table 2).

Table 2. The results of determining the brittleness index of cement stone

| №  | Filler content, % by weight of cement | Britteness index of cement stone (λ), determined taking into account the compressive strength obtained according to GOST 310.4-81 using a lever press |
|----|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| 1  | BF –                                 | 2,01 1,88                                                                                                                       |
| 2  | 0,05 – BBF –                         | 1,96 1,84                                                                                                                       |
| 3  | 0,05 – 0,05 –                        | 1,85 1,74                                                                                                                       |

From the data in Table 2, it follows that the brittleness index λ of the cement stone in the case of its reinforcement decreases, and to a greater extent - with the addition of PPF than BF. At the same time, the strength characteristics of cement stone with BF are higher than with PPF.
The photographs from the surface of the cement stone chip (Figure 3) show that with the same content of reinforcing additives in the cement stone, PPF is in it in the form of separate independent inclusions, while BF is densely embedded in the cement matrix [1].

![Figure 3. Photos (× 56) from the cleavage surface of cement stone from PCT I-G-CC-1](image)

\[ a – cement stone with 0.5 \text{ wt.} \% \text{ BF} \quad b – cement stone with 0.5 \text{ wt.} \% \text{ PPF} \]

The effect of reinforcing additives in the composition of cement on the coefficient of linear expansion (CLE) during hardening [11] is reflected in table 3.

| Test number | Water/Cement | Expanding additive, % | Type of reinforcing additive (0,5 %) | T, °C | CLE (24 hours) |
|-------------|--------------|-----------------------|--------------------------------------|-------|----------------|
| 1           | 0.8          | 10                    | -                                    | 22    | 0.914          |
| 2           | 0.8          | 10                    | -                                    | 22    | 1.16           |
| 3           | 0.8          | 10                    | BF 3 mm                              | 22    | 1.605          |
| 4           | 0.8          | 10                    | BF 6 mm                              | 22    | 1.548          |
| 5           | 0.8          | 10                    | PPF                                  | 22    | 1.913          |
| 6           | 0.8          | 10                    | Asbestos                             | 22    | 1.514          |

Fibers have a real effect on the expansion of cement solutions during hardening, the best results are obtained with the addition of PPF [11].

Earlier works [2, 5, 8] showed that BF has high adhesion to the cement matrix. Figure 4 shows electron microscopy images, which show a dense area of contact between the fiber and the matrix and the absence of gaps and any cracks between them.

Figure 5 shows the interaction between BF, hardening products and expansion additive. The presence of an expanding additive was proved by conducting elemental analysis of the nucleus. We can
confidently assert this, since the core practically contains only calcium hydroxide. It can also be concluded from the figure that all components are in close contact with each other.

![Figure 4](image1.png)

Figure 4. The area of contact between the fiber and the cement matrix (x 950)

![Figure 5](image2.png)

Figure 5. Influence of BF on expansion (x 1100)

Experiments are carried out to determine the specific impact strength of cement stone destruction with the addition of various types of fibers, which showed very interesting results (Table 4). Specific impact strength (A, J/cm³) was calculated by dividing the total potential energy expended on destruction by the volume of the test specimen.
### Table 4. Influence of cement reinforcement on the specific fracture strength of cement stone

| Test number | Formulation       | Density, kg/m³ | Water/Cement | Specific impact strength, J/cm³, after hardening, day |
|-------------|-------------------|----------------|--------------|-----------------------------------------------------|
| 1           | PCT               | 1530           | 0,8          | 0,035, 0,044, 0,065                                  |
| 2           | PCT+0,25 % BF     | 1540           | 0,8          | 0,069, 0,069, 0,088                                  |
| 3           | PCT+0,5 % BF      | 1540           | 0,8          | 0,094, 0,140, 0,108                                  |
| 4           | PCT+0,75 % BF     | 1540           | 0,8          | 0,125, 0,161, 0,177                                  |
| 5           | PCT+1 % BF        | 1540           | 0,8          | 0,187, 0,187, 0,203                                  |
| 6           | PCT+0,25 % PPF    | 1530           | 0,8          | 0,051, 0,064, 0,162                                  |
| 7           | PCT+0,5 % PPF     | 1540           | 0,8          | 0,093, 0,051, 0,107                                  |
| 8           | PCT+0,75 % PPF    | 1540           | 0,8          | 0,086, 0,079, 0,107                                  |
| 9           | PCT+1 % PPF       | 1540           | 0,8          | 0,106, 0,121, 0,130                                  |
| 10          | PCT+0,25 % Asbestos| 1550           | 0,8          | 0,035, 0,086, 0,086                                  |
| 11          | PCT+0,5 % Asbestos | 1540           | 0,8          | 0,045, 0,056, 0,101                                  |
| 12          | PCT+0,25 % Asbestos| 1530           | 0,8          | 0,051, 0,054, 0,092                                  |
| 13          | PCT+0,1 % Asbestos | 1530           | 0,8          | 0,051, 0,072, 0,069                                  |

The table shows that the introduction of fibers has a positive effect on the shock resistance of the cement stone: the best results were obtained with the addition of BF; when 1% BF was added to the plugging solution, the shock resistance increased by 3.1 times. PPF shows good results, from the data obtained it can be concluded that in order to increase the specific impact strength by 2 times, it is enough to add 0.25–0.5% PPF. Experiments show that this amount of fiber has no negative effect on the mobility and pumpability of cement slurries [1].

When producing expandable cements, it is important to reconcile the hydration kinetics of the base cement and the expanding additive. The optimal time of expanding additive action is from 6 to 24 hours [12, 13].

In [12], it was substantiated that the expansion of 1.5–2.5% should be sufficient for expanding plugging cements, providing a tight contact and creating small internal stresses that will not destroy the cement stone, and the formed microcracks could be healed with continued hydration of the cement. For high-temperature wells, in which a stronger cement stone is formed, the expansion should not exceed 1.0–1.5% [14].

### 4. Conclusion

Leakage of the annular space of wells caused by fracturing and destruction of the cement ring under the impact of a complex of static and dynamic loads can be prevented by using dispersion-reinforced plugging materials.

The use of expansion additives of the oxide type is preferred in plugging solutions compared to additives of the sulfoaluminate type and outgassing additives.

Late hydration of the expanding additive leads to the destruction of the structural framework of the resulting cement stone.
...growth rate and the rate of strength gain of the cement stone during the hardening process should be limited. This can be achieved by treating the cement slurry with chemical reagents with the introduction of reinforcing fibrous fillers in an amount necessary to change the nature of the deformation of the cement stone: from pronounced brittle fracture to elastoplastic with the appearance of a descending section on the load-deformation curve, indicating an increase in the fracture strength of the cement stone when exposed to static and dynamic loads.

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