The main goal of this project is to create a new generation of magnetically active polymeric materials (MPM) of the new generation, capable of changing in a controllable manner their physical properties under the influence of external magnetic fields. MPM are composites based on ferromagnetic particles dispersed in liquid (magnetic fluids) or elastomeric (magnetic elastomers) media. Under the action of an external magnetic field, the magnetic particles magnetize and begin to interact with each other by means of magnetic forces. The result of this interaction depends on the type of dispersion medium. In magnetic fluids, particles freely move and line up into so-called chain structures along magnetic field lines, which leads to the appearance of a yield point and a very fast (fractions of milliseconds) transition from a liquid to an almost solid state. In elastomeric media, particle motion is limited by the elasticity of the polymer matrix, and in this case, the resulting mesoscopic structures that form magnetic particles depend on the elastic modulus of the elastomer: the smaller the modulus, that is, the softer the matrix, the larger displacements of particles from the initial equilibrium position can be realized under the action of an external magnetic field. A change in the internal structure of an elastomeric material in a magnetic field leads to a whole series of new physical effects, in particular, to a significant increase in the elastic modulus of magnetoactive elastomers, to large deformations, etc. Due to their unique properties, magnetoactive materials are promising for a wide range of practical applications.

The project aims at (1) development of new polymeric dispersion media based on comb-like polymers with a high density of side chains (polymer brushes) and multiarm stars, whose properties can be regulated at the molecular level, this will allow to control the restructuring of the filler microstructure under the influence of an external magnetic field, and, consequently, the physical properties of the composite material, which depend on its microstructure and (2) the development of new theoretical approaches for describing the properties of magnetoactive polymeric materials.

At the first stage of the project, a lot of synthetic work was done to create the main components of a new generation of MPM, namely, magnetic fillers and dispersion media. Synthesis methods have been developed and magnetic magnetite nanoparticles of various sizes and shapes have been synthesized: spherical magnetite with a size of 10-20 nm, cubic nanomagnetite with a narrow size distribution in the range of 120 - 140 nm, needle-shaped magnetic magnetite particles with a length of 0.5 μm and a length / diameter ratio of six. As an option to expand the properties of needle-like magnetite, a mixed cobalt magnetite-ferrite oxide was synthesized. This type of particle has the same size as needle magnetite, but has a significant coercive force.

To ensure compatibility of the magnetic particles with the silicone matrix, particles coated with a hydrophobic silicone shell were obtained. A two-stage technology for modifying the surface of particles has been developed. According to this method, at the first stage, magnetic particles are modified in an aqueous solution with polyelectrolytes, and at the second stage, they are modified in an organic toluene solution with GKZh-94 and GKZh-94m water repellents with additives of silicone oil.

By the method of sedimentation analysis, it was shown that all magnetic particles are stabilized by modifiers, and the time of their sedimentation after modification increases. Depending on the pH of the medium, the degree of particle stabilization reached with each modifier was studied. Two methods have been developed for assessing particle aggregation — the sedimentation method and the method of sequential analysis of aggregate sizes over time using a laser dispersion analyzer.

The magnetic properties of dispersions of all synthesized magnetic fillers were studied. Differences in the magnetic properties of cubic magnetite nanoparticles obtained using different iron salts were revealed.

New dispersion media for MPM were obtained on the basis of 1) multiarm stars with a number of arms 4, 6 and 12 and an average arm length of 28 siloxane units, 2) polymer brushes based on poly (dimethylsiloxane) (PDMS) with different ratios of the length of the main chain and side chains and 3) elastomers with side chains acting as a diluent for the system. Their rheological and viscoelastic properties were studied depending on the structure.

MPMs were obtained on the basis of linear, brush, and star-shaped PDMSs with different concentrations of magnetic filler (carbonyl iron microparticles), their rheological and viscoelastic properties were studied. It has been shown that the viscosity of all MPMs increases significantly in a magnetic field (by more than 2 orders of magnitude). The maximum relative growth of the dynamic module is demonstrated by the MPM based on a star-shaped PDMS with an iron concentration of 70 mass%. The elastic modulus grows by more than 4 orders of magnitude, and the loss modulus increases by more than 2 orders of magnitude. It was shown that the yield stress of MPM based on star-shaped PDMS reaches 20 kPa in a maximum magnetic field of 1 T. There is no viscosity hysteresis, and the elastic modulus exhibits a slight hysteresis in the magnetic field.

A new type of soft polymer matrices with a shear elastic modulus ~ 2 kPa based on PDMS elastomers was synthesized without the use of low molecular weight oil, the low modulus values were due to the introduction of side chains into the polymer network. Monofunctional oligomers capable of forming a chemical bond with a polymer network are effective “plasticizers”. It was shown that the stiffness of the polymer matrix can be controlled in the range from soft (~ 2 kPa) to medium hardness (~ 20 kPa) by varying only the concentration of the crosslinking agent.

The obtained magnetoactive elastomers demonstrate a high response to magnetic fieldы: the relative growth of the real part of the dynamic shear modulus of soft samples exceeds two orders of magnitude and reaches 400 in a magnetic field of 1 T. Such values so far have been achieved only by adding a low molecular weight plasticizer to the system, which reduced the operational characteristics of the material.

A significant part of the project work is associated with the creation of new theoretical approaches for describing the properties of MPM. At the first stage of the project, a model of a ferromagnetic filler particles cluster in a magnetically active polymer material is proposed and constructed. Within the framework of the model, the cluster is represented by a fractal object evolving under the influence of an external magnetic field. A statistical description of a discrete fractal system of particles is provided, as well as a description of the dynamics of an effective fractal medium obtained by transforming a discrete system into a continuous one. The basic equations of the model are fractional differential equations with the fractional order corresponding to the mass fractal dimension of the cluster. A model of the polymer medium response to the motion of a single filler particle induced by a magnetic field is also constructed. The fractional differential equation of motion for a viscoelastic medium with an excitation source is obtained. The solution of the problem for the inertia-free case is obtained using the Green function. Using the finite element method and the energy functional minimization, the problem of the behavior of a system of non-interacting anisotropic ferromagnetic particles distributed in a layer of a polymer material is solved in the presence of an external magnetic field. The response of the material to the excitation caused by the magnetic field is calculated.

According to the results of the work, two articles were written, one of which was published in the journal Soft Matter with a high impact factor, and the second paper was accepted for publication in the journal Polymer Science. The results were reported at three international conferences. The results were used in the lecture courses “Magnetorheological materials: obtaining, properties, application” (for 3rd year students of the bachelor's program in the Faculty of Physics of Lomonosov Moscow State University, 5th semester, 34 hours) and “Fundamentals of Mechanics and Rheology of Polymers” (for graduat students of Moscow State University).