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NOVEL MULTIFUNCTIONAL CONCRETE AGENTS TO IMPROVE THE DURABILITY OF CONCRETE STRUCTURES UNDER SEVERE CONDITIONS

Abstract. This paper presents a new method to functionalize the surface of polymer fibers using selected chemical compounds without structural damages. To demonstrate the performance of this treatment, selected results on the dispersion of treated polymer fibers in mix water are presented and discussed. The effect of chemical bonding between fiber and the hardened cement paste matrix is also presented using experimental data. With these results, it can be shown that the performance of cementitious materials produced with treated polymer fibers is significantly better compared to the use of untreated polymer fibers.

Key words: Construction chemistry, concrete, surface-modified fibers.

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НОВЫЕ МНОГОФУНКЦИОНАЛЬНЫЕ БЕТОННЫЕ СРЕДСТВА ДЛЯ ПОВЫШЕНИЯ ПРОЧНОСТИ БЕТОННЫХ КОНСТРУКЦИЙ В ТЯЖЕЛЫХ УСЛОВИЯХ

Аннотация. В настоящей статье представлен новый метод функционализации поверхности полимерных волокон с использованием выбранных химических соединений без структурных повреждений. Для того чтобы продемонстрировать эффективность этой обработки, представлены и обсуждаются отдельные результаты по диспергированию обработанных полимерных волокон в воде для затворения раствора. Представлен эффект химической связи между волокном и матрицей затвердевшего цементного теста на основе экспериментальных данных. Результаты показывают, что характеристики вяжущих материалов, изготовленных из обработанных полимерных волокон, значительно лучше по сравнению с использованием необработанных полимерных волокон.

Ключевые слова: строительная химия, бетон, поверхностно-модифицированные волокна.

1. Introduction

Infrastructure plays a decisive role in the economic and social development of all countries. However, depending on their use, infrastructure structures are exposed to different environmental impacts, which can significantly reduce the service life of these structures. Deficiencies in planning, execution and maintenance further shorten the service life. As a result, the vast majority of infrastructure structures today require substantial repair after 20-30 years, even though the planned maintenance-free service life is usually 100-120 years. However, repairs are not only technically very complex, they are also very costly and have a high environmental impact. Both the costs and the environmental impact of conventional repairs to reinforced concrete structures are two to three times higher than the impact caused by the initial erection of the structures. It can be directly concluded from this that durable construction is an essential requirement for sustainable infrastructure [1].

Megatrends are not only increasingly influencing societies, but also the construction industry, with infrastructure being particularly affected by the rapidly progressing transformations. In some parts of the world, for example, the scarcity of natural resources such as sand is not only hampering the development of sustainable infrastructure, but is also damaging entire ecosystems through its uncontrolled exploitation from the environment [2].

Maintenance and repair of existing structures requires linking “old infrastructure” (e.g., sewers) with “new infrastructure” (e.g., wastewater treatment plants). If there is an incompatibility between structures of different ages, this inevitably leads to failure of the entire system. The globalization of the construction industry leads to a worldwide standardization of construction, which does not in all cases sufficiently fit in local influencing factors that are critical for a long service life of the local infrastructure.

Digitalization in the construction industry is currently primarily targeted at increasing economic efficiency or profit in construction planning and execution, but does not yet make a sufficient contribution to reducing life cycle costs. Integrated concepts for predicting material behavior or preventing damages would be an essential prerequisite for this [3].

Climate change already plays an important role, and its effects on the construction industry, but especially on infrastructure, are also already evident. For example, the vast majority of materials used in the construction industry may only be applied within a temperature range of 5°C to 30°C. This means that the temperature of the building material must be kept within a certain limit. If materials are applied outside this temperature range due to the pressure of deadlines or costs, the service life of the material or component can be expected to be seriously shortened, which in turn contributes directly to climate change through the emissions caused by the subsequently necessary refurbishment [4].

With regard to climate change, two strategies are therefore required. On one hand, the release of climate gases must be prevented by a high performance and durability of the constructions as a part of infrastructure ("mitigation"), on the other hand, the materials used in the construction industry must be adapted in their performance to the effects of climate change ("adaptation").

The "driving forces" previously outlined also require a new way of thinking in the development of innovative construction chemical products and building materials. While in the past the development of materials in the construction industry was mainly based on empirical approaches, modern research and development strategies should reflect the possibilities of modern materials research.

2. Cement-based materials modified with polymer fibers

Depending on the width, cracks in cementitious materials can limit the functionality and durability of concrete components, but can also lead to the total loss of its structural stability. This is caused by the low tensile strength of these materials, which is significantly lower than the compressive strength. For this reason, concretes reinforced with steel have already been used for more than hundred years in dynamically stressed structural elements. However, it has been shown that reinforced concrete can be damaged by corrosion processes after only a few years when exposed to aggressive chemical compounds such as chlorides. The consequences are costly repairs and refurbishment measures.

Therefore, in recent years' new concepts have been developed for cement-based materials that involve the use of corrosion-resistant polymer fibers. Depending on the application, carbon fibers (C) was used in addition to fibers made by polyacrylonitrile (PAN), polyethylene (PE) and polypropylene (PP).

Due to the high Young's modulus of carbon fibers, only these can be used to improve the mechanical behavior of structural concrete such as the fracture energy or the post-cracking behavior. Other fibers with a significantly lower Young's modulus are used in the production of dry-mixed mortars or fiber cement boards with the objective of minimizing the formation of cracks caused by shrinkage.

Common to all polymer fibers, however, is hydrophobicity, i.e. the fiber surface is water-repellent (contact angle > 90°). In contrast, cementitious materials are hydrophilic (contact angle < 90°), i.e. they can be wetted by water.

But this hydrophobic-hydrophilic interaction between the polymer fiber and the cementitious material prevents the two from being "connected" by chemical bonds. The force transfer from the mineral-based matrix to the organic-based polymer fiber can therefore only take place physically, which is described by the term static friction. It can be directly concluded from this that the macroscopic effect of polymer fibers depends on their length and quantity. This has so far limited the use of fibers in practice, since excessive fiber lengths and quantities in

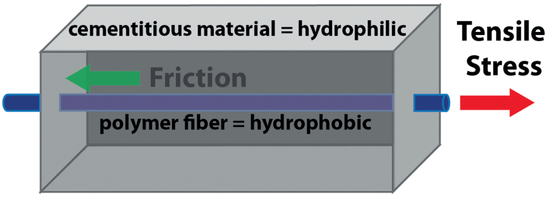

Figure 1. Physical interaction of polymer fibers and cement paste matrix

concretes and mortars restrict the properties of fresh and hardened concrete or mortar.

To overcome these disadvantages, various techniques have been developed recently. Polymer surfaces have been treated with oxidizing chemical compounds, e.g. ozone, to generate reactive end groups [8]. Plasma treatment has also been used as a surface functionalization technique [9]. Other techniques involve coating the fiber surfaces with mineral components in an upstream process to improve the bonding of the modified fiber with the cement paste matrix [10].

All these processes change the polymer surface and can lead to pre-damages of the fiber. Although this would improve the bond to the cement paste matrix, but mechanical fiber properties would deteriorate.

3. Development of surface-modified polymer fibers – principles

In addition to the modification of the topochemical properties of polymer fibers already described, polymer surfaces can also be functionalized with so-called "primers". This is done, for example, in the fabric industry during the manufacture of yarns. The application of these very thin "coatings" on the yarn surface facilitate the processing of yarns into fabrics.

In the technical approach presented here, the fiber-cementitious matrix interaction is also to be improved by functionalizing the fiber surface. The basic principle of this approach is shown in Figure 2, where different concepts have to be applied depending on the fiber type.

On PAN fibers, partial charges are formed by free electron pairs on the nitrile groups. Through electrostatic interactions with partial charges of organic compounds, such as those present in ionic surfactants (in this case poly-(dimethyldiallylmmonium chloride), a strong chemical bond between the two components can be achieved. For the required bonding of the PAN fiber to the hardened cement paste matrix, a further process step is necessary in which the ionic surfactant is linked with a water-soluble silicate (here sodium metasilicate).

In opposite to this, carbon or PE fibers have no partial charges at the surface. Therefore, it is first necessary to treat the non-polar fiber surfaces with a surfactant that consists of both a polar and a non-polar molecular group (here ethoxylated sulfobetaine sulfinate). While

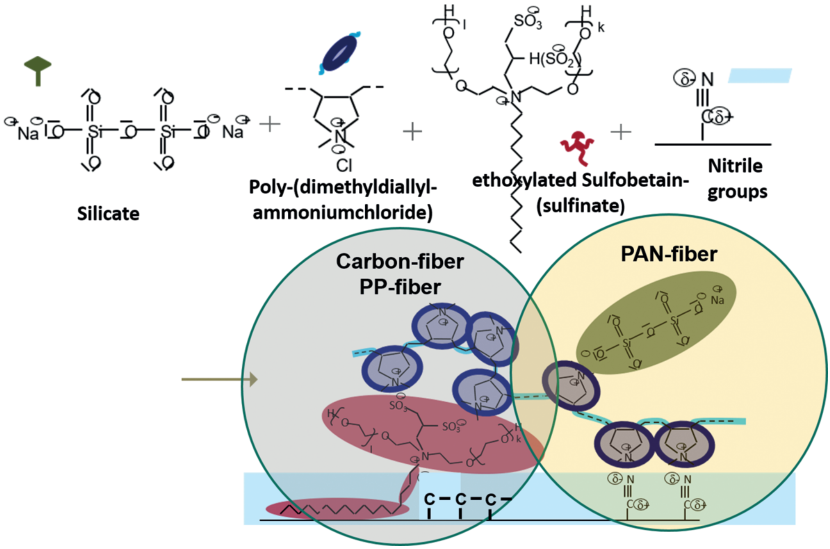

Figure 2. Functionalization of polymer fiber

the non-polar molecule part bonds to the non-polar polymer surface, the polar molecule group forms a structure with the already introduced chemical compounds, which allows bonding to the cement paste matrix.

The fibers prepared in this way are first dispersed in the mixing water and then stirred with the typical raw materials for concrete and mortar production, i.e. Portland cement and aggregates. During cement hydration, the functionalized fiber is then bonded to the hardened cement paste matrix via the silicate group.

In the next sections, the performance of surface-functionalized carbon fibers will be shown by selected results regarding their dispersion in fresh mortar and their influence on the mechanical behavior of hardened concrete.

4. Surface-modified polymer fibers – fiber distribution

Both untreated carbon fibers (Fig. 3, a-c) and treated fibers were used for cement preparation. In the first step, both types of fibers were first dispersed in the mixing water. Practically, 0.1 vol.%, related to the cement weight was added to the water. It was observed that the functionalized fibers dispersed uniformly in the water after only a short time, despite low stirring energy. In opposite to this, the untreated fibers formed bundles which did not separate even at increased stirring energy and long stirring time.

In the next step, the mixing water and the fibers dispersed in it were mixed with a white cement, CEM I, 42.5 to prepare test specimens. After 28 days of underwater storage, the specimens were crushed and the fiber distribution in the material was examined by light and electron microscopy, respectively (Fig. 3).

Figure 3 a shows the specimen made with the untreated fibers after crushing. The black colored fibers are clearly visible hardened cement paste matrix. Light microscopic examination confirms the lack of dispersion of the untreated fibers (Fig. 3 b). Instead of individual fibers, fiber bundles are found exposed after crushing, and a firm bond to the cement paste matrix is not visible. Electron microscopic examinations also show that the untreated carbon fibers show only a few cement paste deposits.

In contrast, individual carbon fibers can be distinguished in the mortar produced with the treated carbon fibers (Fig. 3 d, e). These fibers

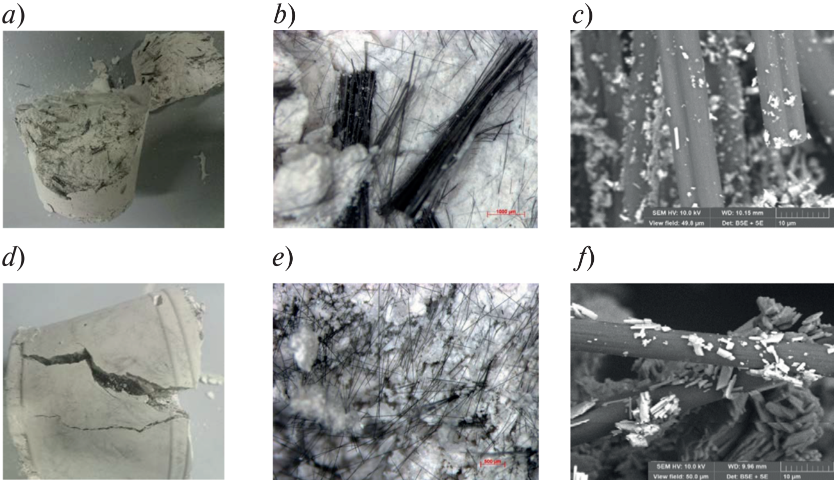

Figure 3. Mortar, modified with untreated (*a*-*c*) and treated (*d*-*f*) carbon fibers

are not only more uniformly distributed, but are also more covered with hydration products.

5. Surface-modified polymer fibers – mechanical behavior

The better distribution of treated fibers in cement-based materials should also influence their mechanical behavior positively. To verify this hypothesis, concrete specimens were made for mechanical testing. First, carbon fibers (1st series) were functionalized for the tests. In order to investigate the influence of storage after functionalization, a part of the fibers was used immediately after treatment („wet“). The other part of this batch was stored until the fibers appeared visually dry. Test specimens were also prepared with this batch. Reference specimens were made with untreated Series 1 fibers. Practically, 0.05 vol% carbon fiber, related to the concrete weight, was added to the concrete mix during manufacturing. In order to evaluate the influence of the production conditions during carbon fiber production, comparable concrete specimens were produced with a 2nd series of carbon fibers, which came from the same manufacturer but were produced at a different time. Figure 4

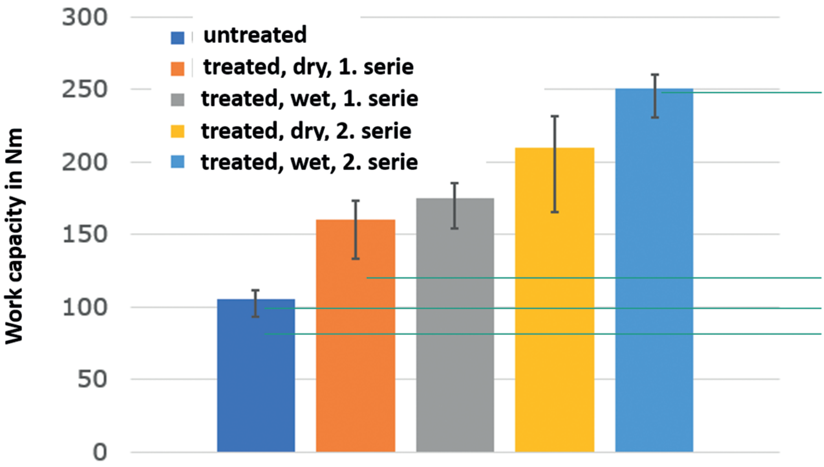

Figure 4. Influence of the type of carbon fiber on the work capacity in Nm

shows the results of the mechanical tests where the work capacity was determined in Nm.

The results for the specimens (series 1) show that the work capacity for the concrete specimens made with the treated carbon fibers is approximately two times higher compared to the reference specimens. Also, a small influence of the curing of the treated carbon fibers can be observed. The values for the dried carbon fibers are slightly lower for series 1 compared to the carbon fibers which were used directly after functionalization.

That there are variations in the production of carbon fibers is shown by the results of series 2. Overall, the values for both types of test specimens („dry“ and „wet“) are significantly higher compared to series 1. But also the influence of the storage conditions („dry“ and „wet“) is clearly more significant in series 2.

6. Conclusion

New developments in construction chemistry can make a significant contribution to the development of sustainable infrastructure. Based on results from basic research, a novel functionalization for polymer fibers was developed which can be used, among other things, to prevent shrinkage cracks as well as to strengthen structural concrete elements.

The results presented here show that by functionalizing fiber surfaces, a homogeneous distribution of the fibers in the material is achieved. Fiber bundles, which have a rather negative effect on the mechanical behavior, can be avoided in this way. It is also possible to functionalize fibers directly on the construction site and to use them directly, which is currently not possible with existing technologies.

Based on the results obtained so far, it can also be assumed that the improved mechanical properties such as working capacity or the reduction of shrinkage cracks, can attributed to the chemical-based bonding of the fibers to the binder matrix.

This new basic chemistry has been further developed in the meantime and is used, for example, for the production of concrete additives, which can reliably prevent the alkali-silicate reaction (ASR).

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