Review Article

Jinjun Guo, Minghao Gao, Kun Wang*, and Peng Zhang

Mechanisms and influential variables on the abrasion resistance hydraulic concrete

https://doi.org/10.1515/ntrev-2022-0488
received May 16, 2022; accepted September 26, 2022

Abstract: Abrasion damage is inevitable for hydraulic structure concrete, to increase the service life of large water conservancies and to keep them running safely and reliably, hydraulic concrete requires a high abrasion resistance. This review synthesizes current practices defined by scientific literature in a format focused on allowing quick comparison and understanding of the current scenario of anti-abrasion concrete enhancing mechanism, measuring methods, and approaches to enhance concrete abrasion resistance. Besides, the review highlights the application of widely used materials and potential materials application, like silica fume and fibers which are mature research at present, and effective but preliminary used materials like nanoparticles, to better understand the development of higher abrasion resistance of concrete. According to the present research, it indicate that incorporating enhancement materials into concrete to achieve better abrasion resistance are basically through the way of hardening cement paste, controlling internal crack propagation, or using stronger coarse aggregate to enhance its ability for anti-abrasive. Finally, based on the systematic literature review, a discussion on major areas holding the significant potential to improve current practices is presented and practical recommendations are provided to advance toward more direct and optimized methods.

Keywords: abrasion resistance, hydraulic concrete, supplementary cementitious material, fiber reinforcement, nanoparticles reinforced, enhancement methodology

*** Corresponding author: Kun Wang,** Yellow River Laboratory, Zhengzhou University, Zhengzhou, 450001, China; School of Water Conservancy Science and Engineering, Zhengzhou University, Zhengzhou, 450001, China, e-mail: wangkunli@gs.zzu.edu.cn
Jinjun Guo, Minghao Gao, Peng Zhang: Yellow River Laboratory, Zhengzhou University, Zhengzhou, 450001, China; School of Water Conservancy Science and Engineering, Zhengzhou University, Zhengzhou, 450001, China

1 Introduction

A large amount of concrete are damaged because of the hydraulic structures abrasion, and such an adverse occurrence will result in high maintenance costs and shorter life of these structures. The abrasive wear that results from attack by water borne sand/stone at high flow speed or impact from great rocks have become a major problem for hydraulic concrete. Basically, abrasion is the most prevalent and unavoidable failure for hydraulic structures [1], even under the situation of abrasion-resistant materials used in hydraulic structures, still different degrees of damage occurs on the structure surface, which, in some cases, invalidates the regular operation [2]. As a result, preventing abrasion damage to hydraulic structures is crucial for ensuring their safe operation and durability needs. Therefore, summarizing and categorizing the research about abrasion resistance of concrete will be of great help to better understand the mechanism of concrete abrasion, and make it easier to develop higher anti-abrasion concrete materials.

According to the operation of hydraulic structure, abrasion damage generally results from constant friction and impact of waterborne silt, sand, gravel, rocks, ice, and other debris on concrete surfaces during the operation of a hydraulic structure. The rivers in the Yellow River basin have almost rapid flow accompanied by hard sediment and prismatic particles. Concrete for use in hydraulic structures must possess adequate abrasion resistance for fast-flowing water and sediment in each specific application [3]. The sand content and transport data collected at Lijin hydrological station in the Yellow River estuary's coccyx channel from 1964 to 2012 showed that the total sand volume entering the coccyx section during this time was 30.35 billion tons, with an average annual transport of 620 million tons and an average annual sand content of 23.86% [4]. Figure 1 demonstrates the sand content of hydropower stations in the Yellow River basin measured from June to September 2019, significant changes occurred during the operation of the hydraulic structures. The sand content reached a very

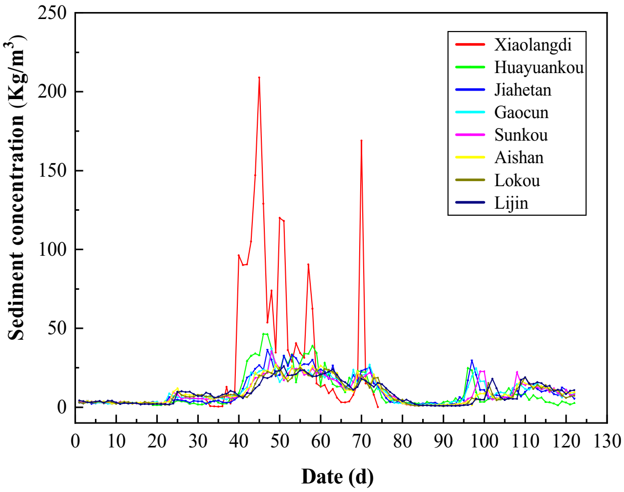

Figure 1: The sand content of the hydropower stations from June to September in 2019.

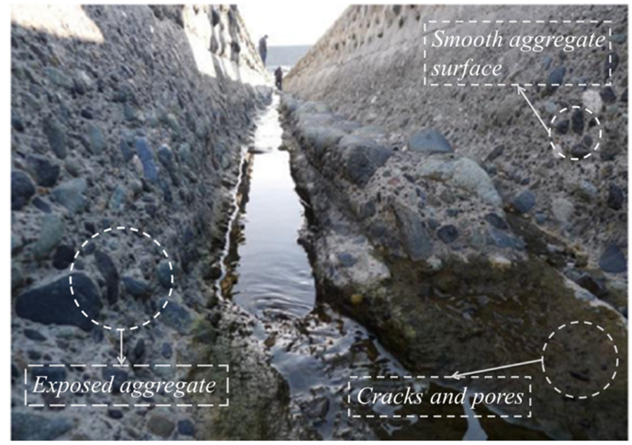

Figure 2: The concrete trough of the sand drainage channel formed by abrasion [5].

high level, which will have a significant impact on the structural safety operation (data courtesy: Yellow River Conservancy Commission of the Ministry of Water Resources).

Correspondingly, many measures have been applied to control the hydraulic structures' abrasion damage in the Yellow River basin, to reduce the difficulty of damage rehabilitation. For example, C60 silica powder concrete was used in Lijiaxia Water Conservancy Hub Project's three-hole drainage channel as the abrasion-resistant layer, which was completed in 2001, and during the pre-flood inspection of the drainage buildings in May 2003, the surface of the open channel section's bottom plate abrasion-resistant layer was discovered with general cracks. Similar destruction forms could be found in the Longyangxia Hydropower Station, during an inspection in 2006, the dried hard cement mortar and silica powder mortar used for the abrasion-resistant protective surface of the spillway, was locally damaged, and peeling was noticed, which impeded the proper operation of the spillway building [3]. As shown in Figure 2, the Xinjiang Jingou River drainage channel suffers abrasion damage, and the coarse aggregate in the worn and damaged concrete has been exposed. After repeated action of abrasive materials, although the coarse aggregate still stays on the matrix, the abrasive material smoothens the surface of the coarse aggregate [5]. Therefore, it is necessary to study a number of anti-abrasion materials to resist abrasion damage for safety operation and higher durability.

Previous studies evaluated that the most effective and widely used method to resist abrasion damage will be applying higher abrasion resistance concrete materials. In recent years, researchers have investigated a variety of approaches to improve the abrasion resistance of hydraulic concrete but there still exists sufficient room for anti-abrasion concrete materials development.

According to previously published studies, the enhancement methods of concrete abrasion resistance can be divided into three categories. The first was to increase the strength of cement paste, a more rigid cement shell will be more resistant to the impact of high speeds of sand-containing water flow, like silica fume concrete, high-strength concrete, and HF concrete are this types of materials, which have a significant improvement in abrasion resistance and at the same time with a considerable increase in compressive strength [6,7]. The second method was to control the cracks generated during the abrasion process, by inhibiting the cracks developed to delay the breaking of concrete, and thus improved the concrete abrasion resistance. The compressive strength of this type of concrete usually depends on its enhancement materials' strength, but the abrasion resistance and splitting tensile strength of concrete were improved significantly, such as fiber-reinforced concrete, epoxy concrete, *etc.* [8,9]. The last type of method was mixing with harder or more wear-resistant concrete coarse aggregates like iron ore, iron steel grit, and other special aggregates [10]. Although the outstanding abrasion resistance manifestation can be seen in concrete made with special aggregates, the application of special aggregates was limited due to their scarce resources. Thus, widely employed in engineering applications has been restricted, and adverse to further research.

Traditional anti-abrasion concrete materials have shown insufficient resistance to the abrasion damage, therefore, studies for the higher abrasion resistance concrete which proposed more stringent requirements to meet the more severe needs are being urgently needed. With the increasing enthusiasm for high dams constructed globally, there are 892 dams over 100 m, 77 are over 200 m, and 22 of them are over 250 m. The Shuangjiangkou Hydropower Station which is under construction in China currently, it already reaching a height of 312 m. The higher hydraulic structure will cause higher water flow velocity, and the spillway, dissipation pools, protection tank, and other parts of the structure's safety and durability will become a critical issue.

With the development of nanomaterials technology, modifying concrete with nanomaterials has been widely employed by many researchers in recent years. In general, nanoparticles can be interpreted as a generic term for a variety of particles with geometrical dimensions between 1 and 100 nm [11]. Thanks to the crystal grains' very small size, the proportion of interfacial elements compared to the nanomaterials will become tremendous, and correspondingly, the crystal grain's boundary defects' volume ratio will also be enormous. So, one of the local interfaces to another with different periods will be the reason for different interface's atoms arrangement, and this will result in an overall different microstructure from the crystalline and glassy states [12,13]. Therefore, nanomaterials have many different properties compared to ordinary materials. However, even modified concrete with nanomaterials has shown many enhancements from different emphasis, but research on the influence effects of nanomaterials on concrete abrasion resistance is still insufficient, no matter from the comprehensive enhancement mechanism study of nanomaterials to concrete, or the actual engineering application with nanomaterials to enhance the concrete abrasion resistance, *etc*., research on the application of nanomaterials to enhance the abrasion resistance of concrete is still in the early stage, but it will undoubtedly lead the direction toward a higher abrasion resistance concrete's future development.

In this context, the present study on abrasion resistance of concrete has been summarized, and discussed the forms, measurement, repair measures, and enhancement materials of concrete abrasion resistance. This study has shown the research state of concrete's abrasion resistance, enabled us to understand the practical problems associated with the abrasion resistance of hydraulic structures, and helped us to seek viable engineering solutions for these problems. Incorporating different materials into the concrete will be the most effective way to enhance the abrasion resistance of concrete. Therefore, a comprehensive summary of the application of different materials used to enhance its abrasion resistance was conducted to investigate the mechanism of abrasion resistance of concrete, with the widely used materials at present and potential material application but with preliminary used materials in the future. Based on this, this study contributes to our understanding of the mechanism and enhancing methods of hydraulic anti-abrasion concrete, combined with the imperfections and restrictions of present materials and the feasibility and possibility analysis of exploring materials, and thereby help to promote the development of the higher anti-abrasion concrete materials.

2 Concrete abrasion resistance research at present

The service life of large water conservancies and reliability of these hydropower stations during the operation is markedly influenced by the abrasion resistance of concrete, so how to improve the abrasion resistance and durability of concrete has become a key point in the hydropower industry. Generally speaking, the research on abrasion resistance of hydraulic structure concrete primarily focuses on the following aspects.

2.1 Concrete abrasion damage forms

The abrasion of concrete is mainly mechanical damage [14]. A generally established approach is to classify the abrasive particles into two types: the suspended load and the bedload, which worked along with the water flow to uniformly wear the surface of hydraulic structures and then peeled off the surface layer of concrete. The surface of structures wears relatively uniformly at first and then produces uneven abrasion craters progressively under a consistent abrasive action [14,15] , because of the heterogeneous nature of the concrete. Therefore, damage to hydraulic structures will disturb the water movement, causing the water flow to separate from the surface of the structures. Thus, various types of vortices form, which decreases local pressure and generates a strong impact force under the compression of the surrounding water body, worsening damage to the surface of the structures.

Hence, we can conclude that for concrete surfaces, the abrasion failure mechanism is thought to be through the formation of plastic craters, followed by protrusion flattening and platelet removal, and frequently includes a specific degree of cavitation damage, as shown in Figure 3. Besides, different abrasive particles also have different influences on concrete structures. Generally, compared to the suspended load abrasion, damage on the surface

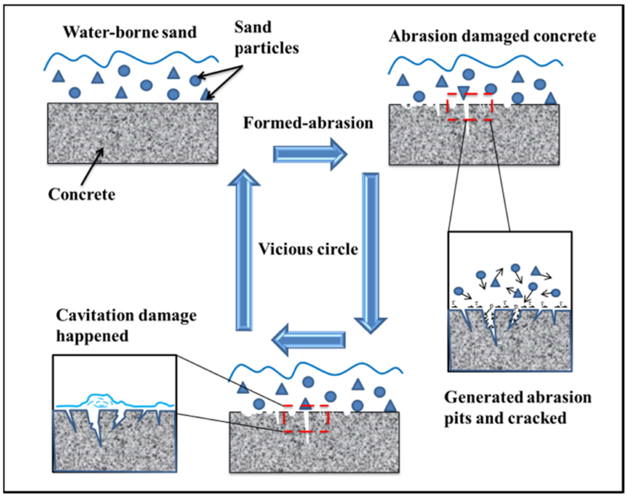

Figure 3: The process of abrasion damage to hydraulic structures.

of structures is more noticeable for the damage dominated by the bedload, the collision effects are more remarkable since it usually has a relatively large particle size, causing the concrete surface to bear higher local stress making the crack expansion more serious. Therefore, after repeated actions, the structure will be destroyed when the material strength reaches a limitation. Correspondingly, wear will be more obvious when the suspended load dominated the abrasion action [16,17].

2.2 Concrete abrasion resistance test

The abrasive resistance of concrete surfaces subjected to impact and impingement of water flow that carried predetermined amount of sand, the flow velocity, the sand content, the size of abrasive particles, the strength of concrete, and the abrasion angle were determined by the degree of concrete abrasion damage. At present, the widely used abrasion resistance test method will be the underwater steel ball method, high-speed annulus abrasion test, and blown sand method specified in current specifications such as ASTM C1138M-2005 or SL 352-2006. These methods were all effective to measure the abrasion resistance of concrete. For hydraulic concrete, the underwater steel ball method will be more suitable for the bedload situation, and high-speed annulus abrasion test will be more accurate for suspended-load simulation. However, in recent years, with the improvement in concrete abrasion resistance, these methods lack in test strength. In order to acquire more accurate measurement findings on concrete abrasion resistance, various emphases have been given to perform more systematic abrasion tests to satisfy this need. Therefore, many scholars have conducted corresponding research from different perspectives to optimize measuring the abrasion resistance of concrete.

To investigate the abrasion resistance of concrete, Grdic *et al.* [18] developed a sophisticated method of accelerating sand-containing jets, as can be seen in Figure 4. Similarly, Tian and Jiang [19] designed a new high-speed water-scouring instrument primarily considering the velocity of the water flow to adopt a more reasonable determination approach to measure the abrasion resistance of concrete. Zarrabi *et al.* [20] took into account the impacts of the incident speed, the distance to the impact point, and the incident angle on the abrasion of concrete and designed a water-carrying sand experiment to measure the abrasion resistance of concrete (Figure 5). However, because of the variations in abrasive parameters, the wear mechanism will differ during the abrasion process. Therefore, developing universal and well-considered criteria to measure the abrasion damage to hydraulic structures is highly challenging.

2.3 Structural design to improve concrete abrasion resistance

Optimizing the geometry of hydraulic structures to straighten the water flow, or implementing appropriate energy dissipation facilities, can considerably lessen the cavitation damage [21]. So, the hydraulic concrete's

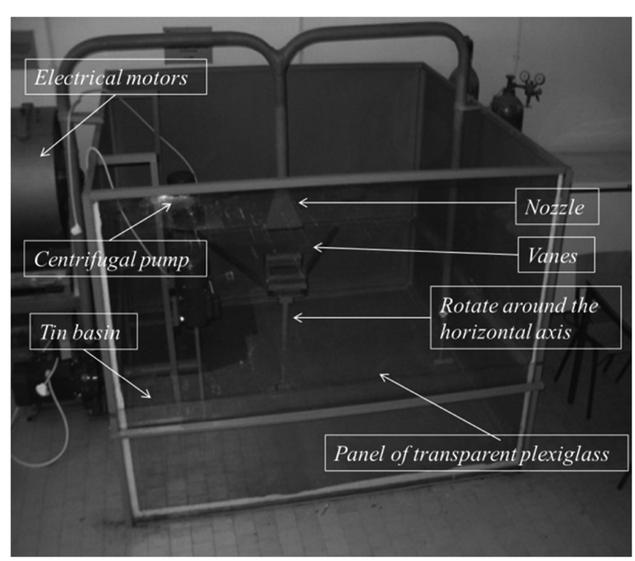

Figure 4: The experiment of accelerating sand-containing jets [18].

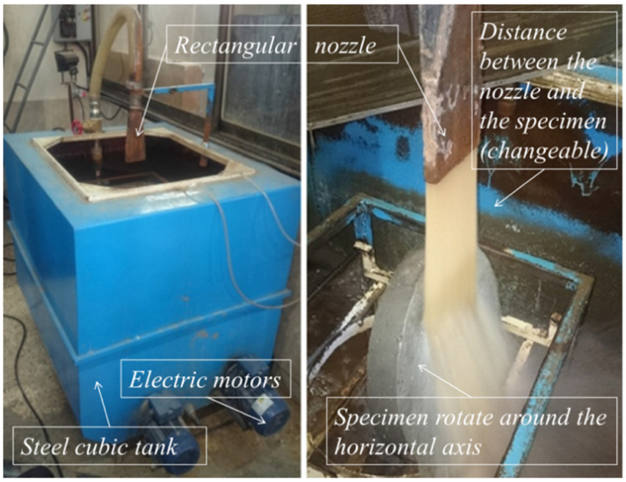

Figure 5: The experiment of water-carrying sand [20].

abrasion resistance can be greatly enhanced by reducing the impact of cavitation damage during the abrasion process.

As suggested by Wang and Zhang [22], when designing the water discharge structures, straight lines should be adopted as much as possible. Besides, a large radius with small corners should be built for the curved sections, straight sections should be inserted after and before the bent part. Similar construction suggestions can be found in the study of Xiu *et al.* [23], which states that leaving a platform with a specific width on both sides of the stilling pool apron and installing a stone canal at the end will effectively enhance the abrasion resistance of hydraulic structures. He *et al.* [21] also discovered that using aerating local water flow technology could significantly weaken the damage from cavitation, thereby enhancing the abrasion resistance of hydraulic structures. Zhang [2] also noted that when the velocity and sediment content of a sand-containing water flow was relatively low, a discharge structure with a reasonable shape was beneficial for preventing abrasion damage, and even the usage of specific abrasion-resistant materials could be overlooked in some situations. Therefore, controlling the water flow pattern can control the abrasion resistance of hydraulic concrete substantially.

2.3.1 Repairing materials

It is an effective method to use repairing materials in damaged hydraulic structures to prolong the period of anti-abrasion, and particular restoration techniques appropriately used will guarantee the hydraulic structures' safe functioning. However, repairing hydraulic concrete structures is a challenging task requiring much workforce, materials, and financial resources. Mai *et al.* [24], by conducting abrasion tests under sandy water flowing at a velocity of 40 m/s, discovered that the abrasion resistance of epoxy resin with a "sea-island structure" was significantly improved compared to C70 concrete. Sun *et al.* [25] investigated the properties and application scope of using SK abrasion and scratch-resistant polyurea coatings for protecting the overflow surface of Fuchunjiang Hydropower Station against abrasion, and demonstrated that their durability, abrasion resistance, and bonding with concrete were excellent. In another work, Wang *et al.* [26] using the block test on-site comparison method, compared the repairing conditions of seven various abrasion-resistant epoxy mortars in the Xiaolangdi sand drainage tunnel. Comparing results revealed that the construction of epoxy mortars should match the requirements for abrasion resistance performance, while preventing a soft surface so as to lead to the best improvement effect. In all kinds of large and even ultra-large water conservancy projects being carried out vigorously now, hydraulic structures will face the challenge of abrasion damage caused by the higher flow rate and velocity of water flows. Thus, the difficulty of repairing hydraulic structures affected by abrasion damage from high-speed sandy water flows also rises linearly.

2.3.2 Different materials for modifying concrete abrasion resistance

There is a general agreement that using adequate enhancement material in concrete will be the most effective improvement to increase the abrasion resistance of concrete, therefore, most scholars have started research focused on the use of different materials to enhance the concrete's abrasion resistance. At present, research shows that the abrasion resistance of concrete is mainly dominated by the strength of the surface cement mortar, the ability to control the degree of crack development after damage, and the hardening degree of coarse aggregate. Therefore, the research on incorporating different materials into concrete for improving its abrasion resistance can be categorized into the following aspects.

2.3.3 Mineral admixtures

Silica fume is the most extensively utilized substance to enhance the concrete abrasion resistance currently. The silica fume was primarily used for filling the micro voids of the concrete matrix and the interfacial zones between coarse aggregate and mortar. In addition, silica fume is pozzolanic, *i.e.*, it reacts with calcium hydroxide to produce more calcium–silicate–hydrate, thereby reducing porosity and increasing the strength. Generally, the abrasion resistance of concrete can be improved by adding silica fume [27]. Besides, Ashish and Verma [28] Stated that the loss in permeability can be compensated up to some extent with the addition of silica fume. As a result, incorporating silica fume into concrete optimized the cement paste, and markedly enhanced the abrasion resistance of concrete.

Some of the researchers studied the concrete abrasion resistance that only incorporates silica fume. Santanu and Bratish [29] based on the 28 days strength of concrete, discovered that the ideal silica fume content of concrete was not a constant but depended on the water-to-cement ratio of the concrete. But, replacing cement with 15–25% of silica fume will considerably improve the mechanical characteristics of the concrete in the general case. Yogendra *et al.* [30] discovered that for the properties of concrete with a higher water-to-cement ratio, the greater enhancement of concrete properties would appear in the larger admixtures replacement of silica fume situation. As demonstrated in Figure 6, the abrasion resistance of silica fume concrete improved with increase in its silica fume content due to the higher content of hydrated calcium silicate regardless of the test method: the underwater abrasion or the blown sand abrasion [31]. Regarding the silica fume content of concrete, Wu *et al.* [32] studied the interfacial bond strength of concrete containing 0–7% of silica fume at the same mass substitution of cement. They found that the early strength of the bonding interface of concrete was higher

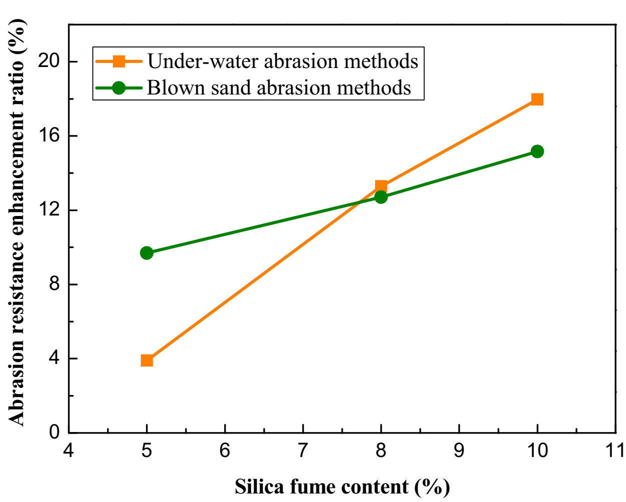

Figure 6: The effect of silica fume on the abrasion resistance of concrete [31].

at 5% than 4% of silica fume, but the 28 days strength of the bonding interface of the concrete was higher at a lower silica fume content. However, the amount of silica fume in the concrete mixture should not generally exceed 30%, because the excessive silica fume causes severe early cracking of the concrete, which is not conducive to the abrasion resistance of concrete under a high-speed sand-containing water flow. Simultaneously, including a large amount of silica fume will significantly impact the workability and fluidity of concrete, which is detrimental to the actual construction process. Most importantly, silica fume concrete has various drawbacks, such as sizeable early shrinkage and high hydration heat concentration, imposing some limitations on the hydraulic structure applications demanding abrasion resistance.

To overcome the drawbacks of abrasion resistance of silica fume concrete, the most effective way to enhance the inadequacy of silica fume concrete is to combine different materials with silica fume, using the advantages of other materials to compensate for the shortcomings of silica fume concrete.

The primary purpose of mixed other mineral admixtures was to reduce concrete cracking due to the excessive heat of hydration [33,34]. Liu and Fang [35] discovered that fly ash (FA) had a low hydration activity, which could delay the hydration rate of cement, thereby effectively reducing the high hydration heat of silica fume concrete in the early stages and preventing the formation of early cracks; Gil and Golewski [36] stated that the basic physical mechanism of interaction of FA and silica fume with concrete is primarily to seal the composite microstructure; de Gutiérrez *et al.* [37] found that FA particles were unique, spherical, glassy, and bead-shaped, which could effectively disperse the cement particles and fill the pores in the cement paste, thereby densifying the cement paste; Naik *et al.* [38] experimented with investigating the impact of FA on the abrasion resistance of concrete by using three different types of materials. Their results demonstrated that the type of FA significantly impacted the abrasion resistance of concrete, FA reduced the abrasion resistance of concrete regardless of its type, and the weakness of concrete was more pronounced in the early curing periods than in the later stages. Finally, there is a best content for FA to influence concrete abrasion resistance, which in this study will be 40%, abrasion resistance will be greatly reduced if this content is exceeded, as depicted in Figure 7. However, it is still an effective way to add FA into silica fume concrete to enhance its mechanical property. Through experiments, Ma [34] found that the strength of concrete was enhanced by increasing the silica fume content in the range of 3–8%, but the viscosity of

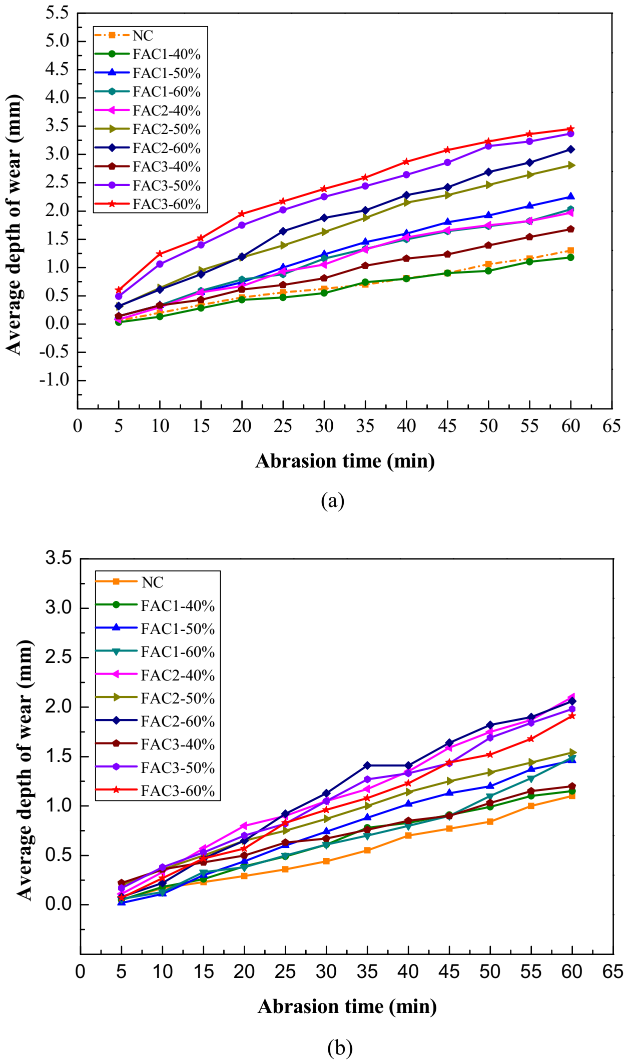

Figure 7: The effect of FA content on the abrasion resistance of concrete at a curing period of (a) 28 days and (b) 91 days [38].

concrete will also be increased at the same time, considerably raising the possibility of early cracking of concrete. Therefore, incorporating FA into concrete can dramatically improve its abrasion resistance compared to concrete mixed solely with silica fume.

Although the addition of FA declines the concrete abrasion resistance strength when the dosage of silica fume is significant [31,39], it could reduce the amount of cement, ease the burden of temperature control, alleviate the risk of early concrete cracking, and enhance the workability and fluidity of concrete under the premise of satisfying various technical requirements. Hence, considering the resistance of concrete to cracking, abrasion resistance, and the construction performance, it is still recommended that 20% FA be mixed with cement to ensure that the crack resistance of the concrete is not too poor to affect its regular use. Meanwhile Ashish and Verma [40] have pointed out that when using supplementary cementitious materials like silica fume, FA, *etc.*, in concrete, a water–cement ratio in addition to pozzolanic material by weight must be considered. There is a close relationship among water–cement and water–cementitious material ratio, and water–cementitious material ratio could provide the particular amount of water needed for the hydration process. Therefore, starting the research focus on the content of supplementary cementitious materials in concrete have become a prominent necessity.

Besides, there existed the study on different additives mixed with silica fume concrete to examine their impact on the abrasion resistance of concrete. Additives primarily considered the regularly used additives such as water-reducing agents, shrinkage reducers, and expansion agents. Scholars such as Hu [3] and Ding [41] have reached a more consistent conclusion, that among these additives, shrinkage reducing agents and expansion agents negatively influence the abrasion resistance of concrete and should be avoided in engineering practice to ensure project quality. However, Li *et al.* [42] reported that the addition of expansion agents could prevent the cracking of the high-strength concrete (strength C60–C80) mixed with silica fume and equipped with stressed steel bars. Nevertheless, studies have reported both positive and negative impacts of water-reducing agents on the abrasion resistance of concrete depend on the type and rate of water reduction, and the actual influence of water-reducing agents is not noteworthy. Thus, they can be employed in engineering applications.

2.3.4 Fibers

Fibers are also a widely used material to enhance the concrete abrasion resistance at present. Unlike silica fume, fibers are mainly used in concrete to bridge cracks formed by stress shrinkage, temperature, or dry shrinkage during hydration, thereby effectively relieved the stress concentration at the tip of cracks, delayed the development of cracks, and controlled the internal cracks in concrete. In this case, the internal cracks in concrete were effectively controlled, strengthened the continuity of the concrete, and prevented the cracks from further expanding after the concrete cracks, thus, the resistance of concrete to high-speed sandy water flows is enhanced. From the works conducted in this context [43–47], it can be concluded that, unlike ordinary concrete, the cement matrix peeled off and left pits on the surface of the concrete after abrasion damage. Fiber-reinforced concrete made the damaged pieces stay on the surface of the concrete due to the restraining effect of fibers, allowing it to withstand the abrasion damage. Therefore, the resistance of concrete abrasion has significantly improved.

Concrete is known to be intrinsically porous and brittle making surface cracking inevitable, and the abrasion of concrete that results from impact of water borne particles and matrix removal by fracture is a mechanical degradation process, and fiber used can effectively control it. Therefore, the different lengths, thicknesses, and shapes of fiber modified in concrete had been conducted by many researchers to examine the impact on abrasion resistance of hydraulic concrete. For example, Nihat [48] studied the effects of the length of basalt fibers (12 and 14 mm), the fiber content, and the water-to-binder ratio on the abrasion resistance of concrete. As shown in Figure 8, the abrasion resistance of the concrete improved as its water-to-binder ratio declined, for the characteristics of the basalt fibers. At higher fiber contents of the concrete, the abrasion resistance weakened as the length of the basalt fibers increased. However, when the fiber content of the concrete is at a low situation, longer basalt fibers will improve the abrasion resistance of concrete more prominently. Moreover, many researchers have proposed the study of combining fibers of the same type but with different morphological characteristics, using different types of fibers, or employing fibers together with other materials. Then they compared the results to the single-fiber composite concrete's situation, to complete the research on the mechanism of the abrasion resistance of fiber-reinforced concrete [49–51]. For example, the use of the polypropylene (PP) fiber effects in limited solidifying contraction and

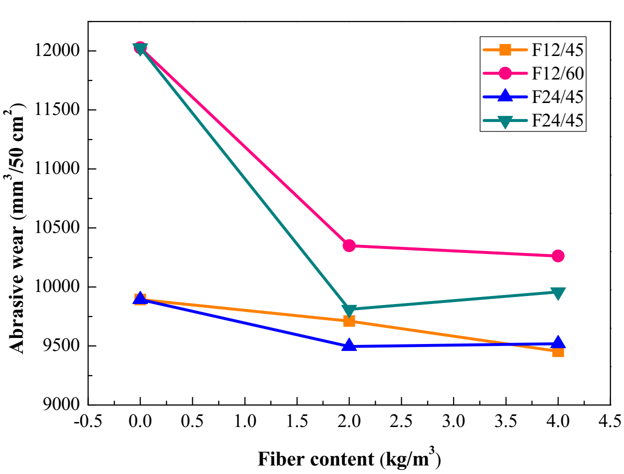

Figure 8: The effect of the basalt fiber content on the abrasion resistance of concrete [48].

the use of steel fiber increases the compression and tensile strength. In conclusion, fiber reinforced concrete has only high strength but also high durability in specific environmental conditions.

PP fibers have been widely used on concrete to improve its abrasion resistance. The concretes with PP fiber are beneficial in restricting the drying shrinkage, increasing the split tensile strength, and restraining the initiation and development of cracks in cement pastes and concrete. Horszczaruk [52] investigated the effect of three different PP fibers on the concrete abrasion resistance using a fiber content of 0.9%, and discovered that regardless of the length and Young's modulus of PP fibers, the PP-fiber-reinforced concrete samples' surface will be uniformly abrasive, indicating the significant enhancement of the abrasion resistance of hydraulic concrete. Meanwhile, Liu and Wang [44] reported that PP fibers could directly improve the resistance of concrete to micro-cutting wear damage. de Gutiérrez *et al.* [37] also found that when PP fibers were evenly distributed inside the concrete, the compressive strength of concrete change slightly, and in a few cases, there might even be a modest reduction in compressive strength. Nonetheless, PP fibers still dispersed the energy generated by concrete shrinkage, enhanced the internal continuity of the concrete material, reduced the scale of micro-cracks, and weakened the concrete stress concentration during the stressing process, resulting in an improvement in the brittleness and abrasion resistance of concrete. Similar results were also reported by Lu *et al.* [45] and Andrzej [53]. Additionally, Zoran *et al.* [18] conducted a corresponding experiment on the influence of different PP fibers on the abrasion resistance of concrete. They concluded that in the case of a low water-to-binder ratio, the PP fiber compacted the pore and decreased the pore size to better enhance the abrasion resistance of concrete, as shown in Figure 9. It can be concluded that the group of composed fibrillated fibers have a better performance in concrete mechanical properties, than the monofilament fibers with a circular cross-section and smooth surface. On the whole, the abrasion resistance of fiber-reinforced concrete is far preferable to that of ordinary concrete.

We can conclude that the strengthening mechanism of PP fibers will be controlling, easing, and restricting [18,47,54]. The PP fibers distributed in a large number in the unit volume of concrete, hindered the development of micro-cracks, and consumed a large amount of energy, making it more difficult for cracks to spread further. When cracks form, PP fibers restricted the expansion of the crack tips. Therefore, a large amount of energy must be consumed to break or bypass the fibers so that cracks

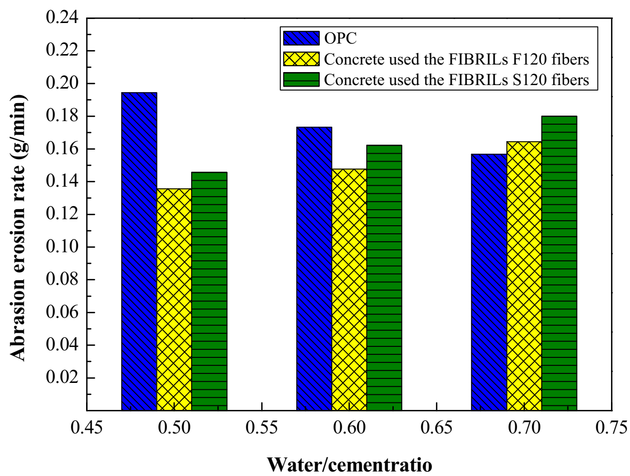

Figure 9: The effect of PP fiber type on the abrasion resistance of concrete [18].

can continue developing. In other words, PP fibers can control the crack expansion and ease the stress concentration. Furthermore, after high-speed sand-containing water damages the surface of concrete, the shattered concrete blocks were strongly constrained and stayed on the concrete surface, so the impact of cavitation damage correspondingly weakens, which indirectly improved the abrasion resistance of the concrete.

However, the work of Sheng and Fang [55] on the bonding of PP fibers with concrete demonstrated that the bonding between the cement matrix and untreated PP fibers is very weak, the fibers drawn from the matrix have a smooth surface and hardly stick to cement. Thus, the effect of untreated PP fibers on improving the abrasion resistance of concrete is minimal, so they must be modified. Changing the hydrophobicity or increasing the surface roughness of PP fibers to enhance their bonding with the cement matrix, is illustrated in Figure 10. Hence, using PP fibers to achieve stronger abrasion resistance of concrete can be a research direction. For this purpose, Liao *et al.* [56] modified PP fibers by blending and spinning them with additives and reported that the "wall-attachment" effect of low-molecular-weight additives boosted the hydrophilicity of the fibers while guaranteeing that the fibers were well dispersed in the cement. Shi [57] also modified PP fibers with additives and carried out convex and concave thread treatments on the surface of the PP fibers to further strengthen their bonding with concrete. The modified PP fibers enhanced the toughness and abrasion resistance of concrete prominently.

Regarding the improvement in the abrasion resistance of concrete reinforced with steel fibers, Ji *et al.* [58], through experimentation, found that steel fibers acting as

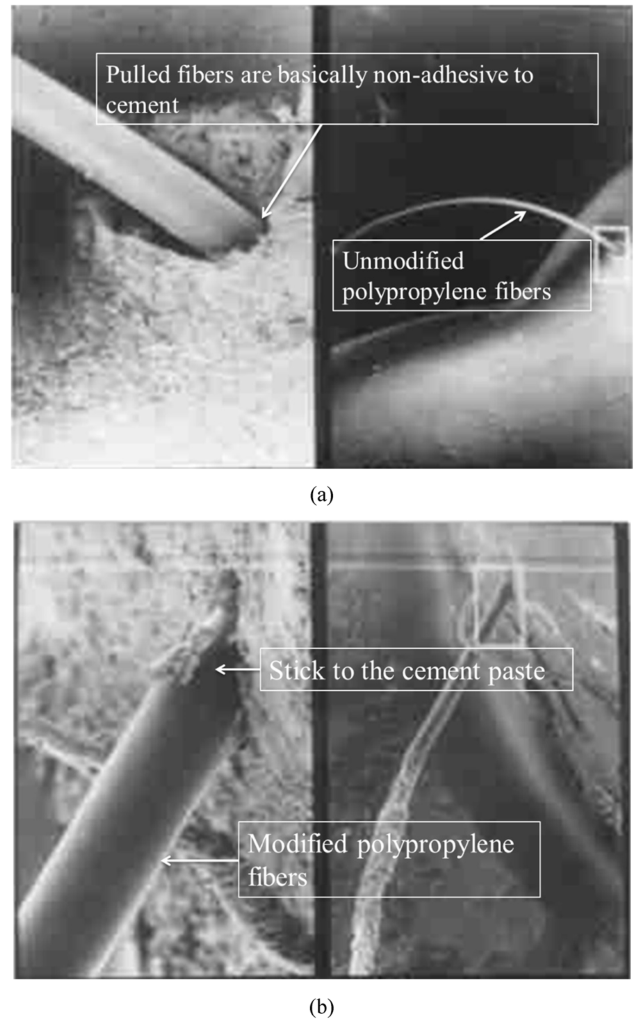

Figure 10: The bonding between (a) unmodified and (b) modified PP fibers and cement [55].

the micro-reinforcement of cracks in concrete during the hardening stage of cement due to their high elastic modulus, which better transfers the force applied to the concrete matrix, effectively limited the formation of internal cracks in the concrete, and prevented the further expansion of the cracks. Shi and Xie [59] also stated that when steel fibers were evenly distributed inside the concrete, they considerably improved the ability of controlling the development of internal cracks in the concrete and thus enhanced the abrasion resistance of concrete due to their strong toughness and flexural tensile strength. In addition, different fibers with a low elastic modulus, such as polyethylene fibers, steel fibers *etc.*, generally increase the compressive strength of concrete considerably. Ju *et al.* [60] compared the effect of different types of fibers on the abrasion resistance of concrete and showed that the unit water consumption of concrete mixed with steel fibers was relatively higher than that of the concrete mixed with other fibers under a similar slump and air content. Nevertheless, steel fibers still caused the most significant increase in the compressive strength of concrete and enhanced its abrasion resistance markedly. Besides, Liu [61] stated that a minimum dosage of steel fibers in concrete was required to form a network structure. In fact, below this optimum content of steel fibers, the strength of the concrete cannot increase, and a weak interlayer is formed inside the concrete, which creates a peeling layer at the fiber–cement matrix interface, making it easier for the concrete to separate under the action of abrasion, thus, the performance of all aspects of the concrete declines. Abid *et al.* [62] also investigated the abrasion resistance of C30 concrete containing three different amounts of steel fibers and compared the results with the data on the abrasion resistance of C40 and C50 concrete (Figure 11). Their results showed that steel fibers effectively promoted the abrasion resistance of the concrete, and the abrasion resistance improved as the steel fiber content of the concrete increased, the performance of the C30 concrete reached that of the C40 concrete but was still lower than that of the C50 concrete. It was also observed that the reinforcing effect of steel fibers had a similar increasing tendency at different curing periods.

It can be concluded that when steel fibers are uniformly distributed in concrete, they can alleviate and weaken the intense stress concentration generated by defects such as micro-cracks and pores in concrete formed under the action of high-speed sand-containing water flows. Moreover, similar to PP fibers, they can reduce the expansion of cracks, improve the toughness of concrete, and enhance its abrasion resistance, and it is improves the abrasion resistance of concrete. However, there are certain distinctions between these two types of fibers in enhancing the abrasion resistance of concrete. By observing the surface of the concrete structure damaged by a high-speed sandy water flow, Wu [63] reported that the cementitious material on the concrete surface peeled off when the ultimate tensile strength of concrete was lower than the concentrated tensile stress. Since the tensile strength of steel fibers is much higher than that of concrete and the elastic modulus of steel-fiber-reinforced concrete increases with the fiber content, steel fibers can effectively control the mass loss of concrete to mainly bear the load after cracking, which enhances the abrasion resistance of the concrete. Nevertheless, due to their low modulus of elasticity, PP fibers cannot play a role in strengthening the concrete,

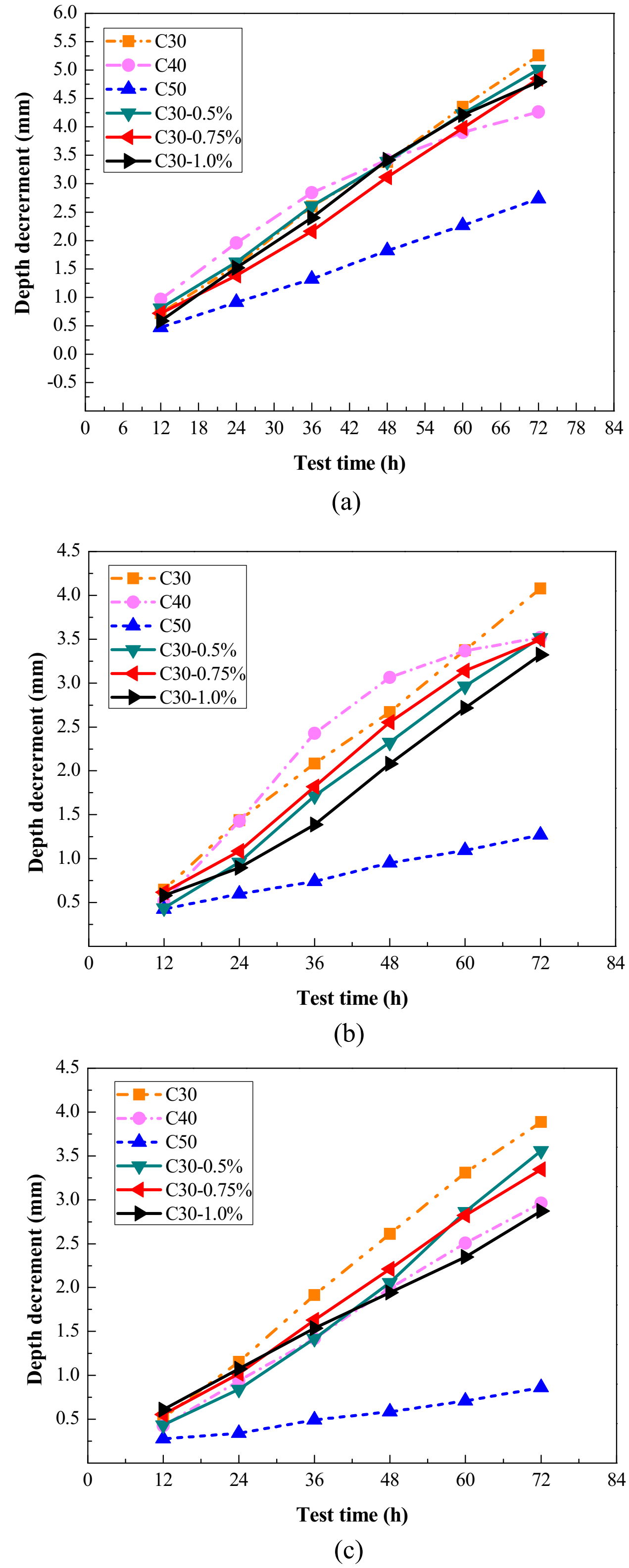

Figure 11: Different concretes in the depth decrement at: (a) 7 days, (b) 28 days, and (c) 90 days [62].

similar findings can also be found in the studies of Liu [61] and Hu *et al.* [64]; however, according to Liu [61], during abrasion damage to concrete, steel fibers are generally removed from the surface of the specimen, as shown in Figure 12. Therefore, the impact of steel fibers on the abrasion resistance of concrete is often weaker than PP and PP fibers.

In other words, steel fiber due to its high elastic modulus can significantly improve the strength of concrete; however, to the ductility and toughness of concrete, the enhancement was relatively insignificant when compared to the use of lower elastic modulus fibers like PP fiber. And combined with the higher cost, therefore, for the modified abrasion resistance of hydraulic concrete, steel fibers may not be the best choice to apply in practical engineering.

2.3.5 Special aggregate

Because the internal aggregate can continue to endure the abrasive damage after the cement surface of concrete was abraded by high-speed sand-containing water flow, the high-strength aggregate used can eminently enhance the abrasion resistance of concrete.

According to Liu *et al.* [65], the anti-abrasion properties of each constituent of concrete, especially the coarse aggregate, can significantly impact the overall abrasion resistance of concrete. In general, the more rigid the aggregate was, the stronger its bonding with the cement matrix became, and thus the more substantial the abrasion resistance of concrete was. The data on the concrete exposed to high-speed sandy water abrasion for a long time indicated that the particle size of coarse aggregate

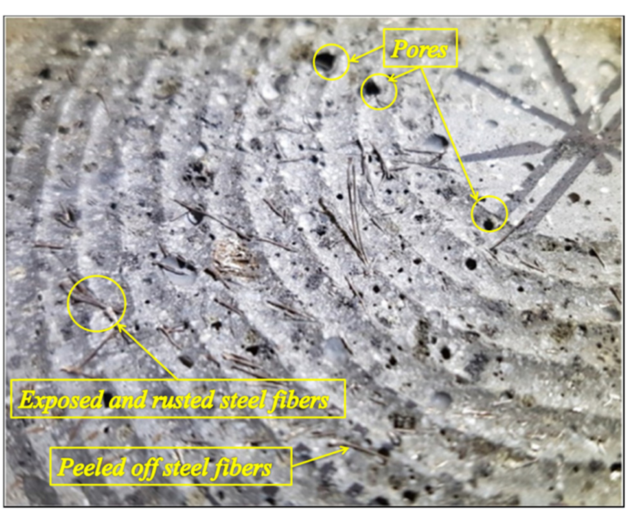

Figure 12: The exposed steel fibers due to the mass loss from the surface of steel-fiber-reinforced concrete [61].

influences the formation of pores in the concrete damaged by abrasion, and the mechanism for the direct bonding between coarse aggregate and mortar plays a vital role in the abrasion resistance of concrete. Li and Yang [66] also demonstrated that the selection of coarse aggregate markedly impacted the abrasion resistance of concrete and recommended that gravel be chosen instead of pebbles as the coarse aggregate as much as possible for abrasion-resistant concrete. The fundamental reason for this recommendation is that the mechanical characteristics of pebbles and crushed stones vastly differ, under high-speed sand-containing water scouring, the weak particles of pebbles made the concrete surface uneven and formed other deficiencies. Moreover, the strength of the bonding of pebbles with cement is inferior to that of crushed stones with cement. As a result, the resistance of pebble aggregate to the abrasion damage from high-speed sand-containing water flows is weaker than that of the crushed stone, so the improvement in the abrasion resistance of the concrete containing pebble aggregate is relatively limited.

At present, the Los Angeles abrasion test is standard and reliable for determining the wear loss of aggregate. Considering the limitations of the existing tests, Mohajerani *et al.* [67] studied using modified compaction to replace the Los Angeles wear test. Esra and Kursat [68] also established a prediction of the wear resistance of coarse aggregate and proposed a convenient way to measure the wear resistance of coarse aggregate, making it easier to decide on using coarse aggregate to improve the abrasion resistance of concrete. However, geographical variables limit employing special aggregate in practical engineering, so while they have an excellent anti-abrasion function, they still have several limitations in large-scale applications.

2.3.6 Other materials

Many other materials have been employed to enhance the abrasion resistance of concrete in addition to the widely used silica fume, fibers, and coarse aggregate. For example, Gurpreet and Rafat [69] incorporated waste foundry sand with a particle size of 150–600 μm in concrete as fine sand and found that the formation of a dense matrix helped improve the abrasion resistance of concrete, and the abrasion resistance of concrete improved with the increase in the waste foundry sand content, regardless of the curing period; Thomas *et al.* [70] analyzed the influence of substituting waste tire rubber particles for part of fine aggregate on the abrasion resistance of ordinary and high-strength concrete. They found that the weak bonding between the cement paste and the rubber particles did not affect the abrasion resistance of the resultant concrete, so the rubber particles could enhance the abrasion resistance of concrete. Xie and Lou [71] investigated the abrasion resistance of the concrete reinforced with rubber particles, and found that the content of the rubber particles was the most crucial factor affecting the abrasion resistance of concrete. They reported that the best improvement in the abrasion resistance of concrete was achieved at 15% of rubber particles, while a rubber particle content of 30% reduced the abrasion resistance of the concrete. Feng *et al.* [72] also proposed using controlled permeability formwork liner construction technology to pour concrete. It markedly enhanced the abrasion resistance of concrete and was applied to the overflow parts such as drain grooves and gate piers that require high abrasion resistance.

Even enhancing the abrasion resistance of concrete by adding different materials is considerable, but there are some drawbacks to limiting its application, such as the selection of different materials, the comparison to traditional materials, and lack of more systematic research. As a result, further research is required to conduct for the application of these additives.

3 Concrete abrasion resistance research in the future

In order to increase the service life of a hydraulic structure and to retain it for as long as possible in a safe and reliable condition, the hydraulic concrete must have high mechanical resistance. Therefore, numerous studies on the abrasion resistance of concrete have been carried out. The resistance of concrete to abrasion is influenced by variables such as strength, aggregate properties, surface finish, and type of hardeners or toppings. In general, parameters such as cementitious materials content, water to cementitious materials ratio, air content, type of finish, and curing are known to affect the characteristics of the concrete surface layer, including abrasion. However, to develop concrete with high abrasion resistance, the use of higher anti-abrasion concrete materials in hydraulic structures will be the most effective and widely used way to make sure the safe operation of hydraulic structures. The concrete cooperated with materials to improve the abrasion resistance, using more suitable materials will be the future development of research on higher hydraulic structure concrete's abrasion resistance.

3.1 Concrete composed of silica fume and fibers

The combination of silica fume and fiber brings significant reinforcement to concrete specimens. Good mechanical response, abrasion resistance, and satisfactory volume stability of the concrete can be achieved by the proper combination of silica fume and fiber. From the research works of Hasan-Nattaj and Nematzadeh [73], Susanto *et al.* [74], and Xue and Lou [75], it can be inferred that the cracks were caused by the defects of the early hydration heat release and considerable plastic shrinkage of silica fume concrete, the stress concentration at the tip of cracks inside the concrete was reduced due to the "bridging" effect of fibers in concrete. Thus, adding fibers can effectively inhibit the early crack development of silica fume concrete. Moreover, the silica fume fills the pores of the matrix of the fiber-reinforced concrete and produces more hydrated calcium silicate gel, which can dramatically enhance the strength and compactness of the concrete, allowing the concrete to resist the damage from high-speed sand-laden water flows. Thus, the abrasion resistance of concrete improves as well [62].

As shown in Figure 13, Xue and Lou [75] changed the fiber content of silica fume concrete to examine the influence of fiber content on the abrasion resistance of concrete. It can be concluded that the abrasion resistance of silica fume concrete modified by fibers has remarkably improved, but when fiber content higher than 0.9% has no significant lifting effect on the abrasion resistance of concrete. Wang *et al.* [76] have also experimented on the ordinary concrete, fiber-reinforced concrete, concrete incorporating silica fume, and concrete modified by fibers and silica fume to study the abrasion resistance of concrete at different water-to-binder ratios. Figure 14 demonstrates that the water-to-binder ratio has the most dominant influence on the abrasion resistance of concrete and adding silica fume and fibers to concrete enhance its abrasion resistance at the same water-to-binder ratio.

The recent research on the abrasion resistance of concrete containing fibers and silica fume has primarily focused on the ratio of the materials and the selection of the type of materials. Wang *et al.* [77] and Ryu *et al.* [78] carried out corresponding studies on the influence of mixed fibers on the mechanical properties of silica fume concrete. It is easy to establish that, compared to the case of using one kind of fiber, the synergistic effect of mixing fibers can better inhibit the expansion of cracks inside the concrete when the concrete is subjected to external forces.

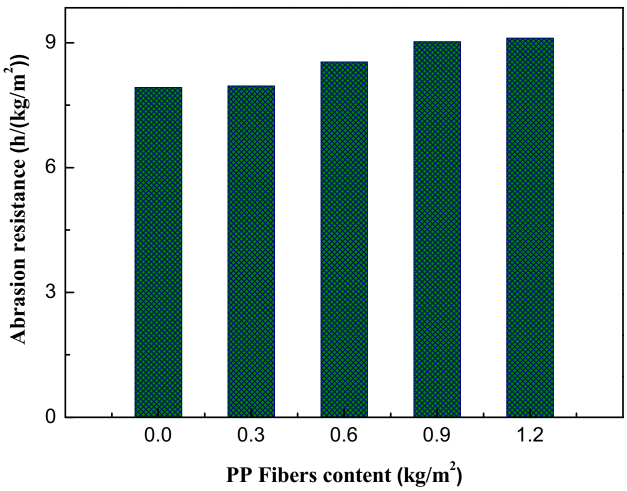

Figure 13: The effect of fiber content on the abrasion resistance of silica fume concrete [75].

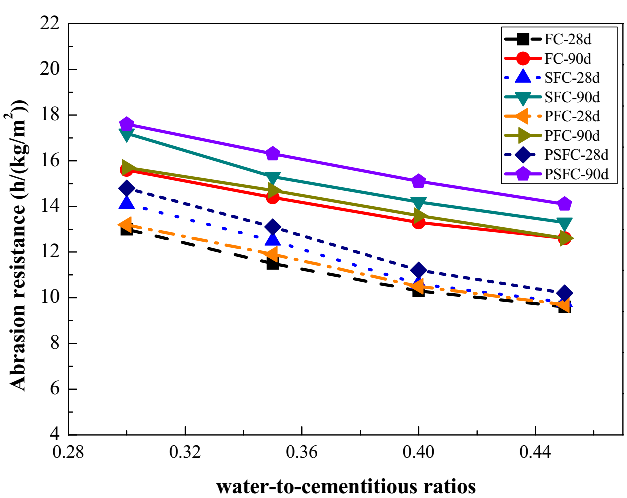

Figure 14: The effect of water-to-binder ratio on the concrete abrasion resistance [76].

Further, fibers of different lengths or thicknesses can diminish the stress concentration inside the concrete in different ways, and the improvement in the abrasion resistance of concrete is evident. Tavakoli *et al.* [79] investigated the impact of the shape of fibers on the abrasion resistance of concrete. They found that fibers with multiple anchor points had a better restraining effect on the cracks due to the wavy shape at both ends, the adhesion between the fibers and the matrix was great, and they had a better effect on improving the abrasion resistance of concrete when compared to other fibers with different shapes of the same type. Yoo *et al.* [80] studied the effect of the fiber content on the performance of silica fume concrete. Generally, with an increase in the fiber content of concrete, its mechanical properties improved. However, adding fibers more than their optimal content reduces their bonding with the concrete matrix because of their uneven dispersion and thus agglomeration in concrete. Hence, the role of fibers cannot be fully exerted, and the abrasion resistance of concrete declines. But, in summary, there was an increase in abrasion resistance of silica fume concrete mixtures due to the inclusion of fibers

3.2 Concrete reinforced with nanoparticles

With the development of nanotechnology and the decrease in nanomaterials production cost, more and more scholars have applied nanomaterials to concrete, making the concrete obtain very special strength manifestation and mechanism properties [81]. The materials, mainly including a wide range of organic, inorganic, metallic, and nonmetallic materials, are used in the transition region between macroscopic matter and atomic clusters, is the hot topic of research in materials science today and has been hailed by scientists as “the most promising material in 21st century” [82,83]. Compared to the traditional materials, nanomaterials have many brand new physicochemical properties, such as surface effects, bulk effects, quantum size effects, macroscopic quantum tunneling effects, interaction effects, and so on. And that makes nanomaterials compared to conventional granular materials better enhance the properties of the concrete.

The addition of nanomaterials into cementitious materials not only filled its voids, but also promoted the cement hydration and modified the interfacial microstructure of cement stone and aggregate, resulting in the strength, impermeability, and durability of cementitious materials gaining improvement. Besides, incorporating with some special nanomaterials will also make the cementitious materials have the property of photocatalytic effect and electromagnetic shielding effect. For example, nano-SiO_2 and nano-$CaCO_3$ will modify the concrete microstructure and enhance the concrete's mechanism performance. But concrete mixed with nano-TiO_2 is capable of decomposing SO_2, NO_x, and other harmful polluting gases emitted from motor vehicles, to purify the air [84–87]. Meanwhile, strong electrical conductivity and sensing capacity will appear with nano metal oxides, which are called smart cement-based materials. It can be used for long-term monitoring of civil engineering structures facilitate, like the concrete structures cracking and record the damage situation, even can knows the weight and speed of vehicles, *etc.*, which is meaningful in practical engineering on preventing the cracking and damage of concrete in timely, and to prevent major unexpected accidents [88,89]. Besides, Golewski and Szostak [90] used a specifically formulated chemical nano-admixture, which were in the form of seeds of the C–S–H phase, to replace FA as a Portland cement replacement in concrete, and the results show that calcium silicate hydrate seeds cause an increase in mechanical features of composites with cement matrix, and nano-admixture used will accelerate the strength growth in concretes [91]. On the basis of the heat of hydration test, much higher hydration heat was found in mixtures modified with the nano-admixture [92]. And it can be found that the nano-admixture in the form of the active CSH seeds is a modern and innovative form of accelerating the curing of concretes at a very early age, leading to the formation of a more homogenized and compact cement matrix structure [93].

3.2.1 Nano-silica

Focused on the research of added nanomaterials in concrete to improve its abrasion resistance, nano-SiO_2 particles are the widely used materials at present. As an inorganic chemical material, nano-SiO_2 is non-toxic, pollution-free, and tasteless, with a spherical, flocculent, and reticulated quasiparticle microstructure and insoluble in water [94]. Referring to the practicalities of using silica fume to enhance the concrete abrasion resistance, Nano-SiO_2 benefits from the higher specific surface area, and smaller particle size has better reinforcement in abrasion resistance of concrete. Golewski [95] modified siliceous FA, silica fume, and nano-silica in ordinary Portland cement, and it was found that the modified concrete was characterized by a well-developed structure and had high values of mechanical parameters, besides, it also showed a significant reduction in CO_2 emissions.

The modification effects of nano-SiO_2 in concrete can be concluded as:

1) Accelerate pozzolanic reaction. In the early stage of the concrete curing period, nano-SiO_2 will react with calcium hydroxide in hydration products to produce more calcium silicate hydrate gel, which with higher specific surface area and stronger gluing capacity, increases the degree of polymerization of C–S–H gel and orderliness of the structure, resulting in improved density of concrete and enhanced bonding between the cementitious paste and aggregates [96–98].
2) Crystal nucleus effect. Due to the high specific surface area, the nano-SiO_2 will be as the hydrate seed to facilitaing hydration, and the hydration will be carried out by encompassed with nano-SiO_2, the C–S–H gel grows on the surface of nano-silica, therefore, more outstanding optimization of the internal microstructure and microscopic defects of concrete can be seen [99,100].
3) Filling effect. Enhance the density of matrix, and reduce the porosity [101].

The research on using nano-SiO_2 in concrete to enhance its abrasion resistance is inadequate currently. The influence of SiO_2 nanoparticles in concrete is similar to the silica fume, but with a more outstanding performance. Therefore, in order to meet the demand for higher abrasion resistance of concrete in hydraulic structures, adding nano-SiO_2 in concrete to replace silica fume, to analyze the mechanism of nano-SiO_2 materials to improve the concrete abrasion resistance, is a new research direction for higher abrasion resistance new concrete materials. In the research conducted by Jo *et al.* [102], they monitored the amount of calcium hydroxide to determine the extent of the pozzolanic hydration, and found that the addition of nano-SiO_2 accelerated the early hydration process of concrete, and was also far more effective than the application of silica fume. Besides, Hou *et al.* [103], through the SEM micrograph of cement mortar mixed with 1.5% nano-SiO_2 at 7 days, found that the microstructure of cementitious materials at this period was neatly distributed and dense. Meanwhile, due to the reaction between nano-SiO_2 and $Ca(OH)_2$, a large amount of hydration heat will be released, which will promote the hydration reaction process, resulting in a restricted content of $Ca(OH)_2$ crystals, and has a great enhancement for the early concrete strength [103,104]. As can be seen in Figure 15, concrete added with 5% nano-SiO_2 particles has a smoother microstructure surface, denser matrix, and higher integrality when compared to the normal concrete [105], which represents a higher abrasion resistance. In the relatively later stage of concrete curing, because of the larger specific surface area of nano-SiO_2, the surface adsorption of water is larger, making the cement's continued hydration less effective in the later stage. Under the situation of huge content of nano-SiO_2, it will even decrease the concrete strength. In general, the incorporation of nano-SiO_2 has a significant enhancement on the concrete's early strength [106]. Although the growth rate of early self-shrinkage strain in concrete is higher with increase in the nano-SiO_2 content [107,108], and increases in the amount of water used in concrete will prominently improve the strength of concrete even with a small dosage of nano-SiO_2 [109].

The research on incorporating nano-SiO_2 into concrete to enhance its abrasion resistance was mainly focused on

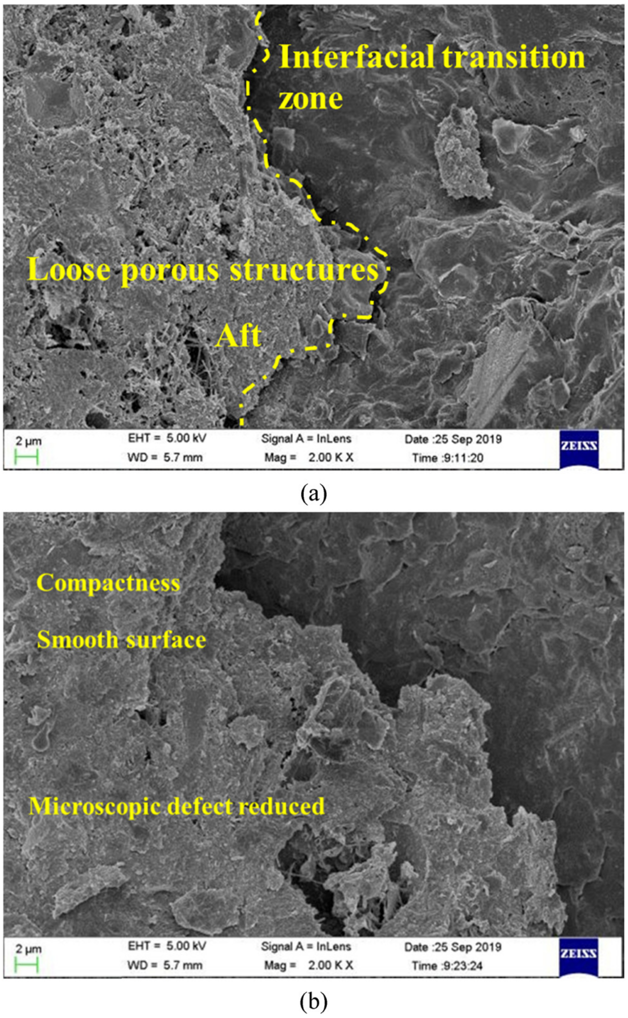

Figure 15: The transition zone: (a) normal concrete and (b) concrete modified with 5% nano-SiO_2 [105].

the content of nano-SiO_2 in concrete at present. Similar to the use of silica fume, it's not increase the content of SiO_2 nanoparticles in concrete will have a better improvement effect in concrete. It's mainly because the slump of concrete will significantly decrease as the added with nano-SiO_2, and also the SiO_2 nanoparticles evenly dispersed inside concrete were difficult. So, combined with different experiment conditions and materials, a degree of disagreement exists in the suggestion for the optimum dosage of nano-SiO_2 in concrete. Li [110], by controlling the content of nanomaterials, found that the addition of nano-SiO_2 will significantly increase the concrete's early strength and durability, but the final strength's change is not obvious, and recommended that the optimal dosage of nano-SiO_2 should not be over 3% in concrete, otherwise it will have a negative impact on the concrete fluidity and workability. Huang *et al.* [111] studied high-content FA concrete compounded with nano-SiO_2 and PVA fibers (polyvinyl alcohol fibers), and the results suggested that the dosage of nano-SiO_2 should be between 0.5 and 1.5%, the larger content leading to an excessive reduction in the fluidity of the concrete, which is detrimental to the dispersion of fibers and affects the strength of concrete. Li *et al.* [112] stated that the enhancement of concrete strength in the situation of 4% content of nano-silica is already weaker than the 3% situation, just because the limitations of dispersion method. But Xu [13] studied the C30 concrete and found that the content of nano-SiO_2 reached 7%, and the strength of the concrete would still increase with the extent of nanomaterials. However, for C60 concrete, the strength of the concrete already decreased with the nano-SiO_2 at 3%. Figure 16 demonstrated that concrete abrasion resistance will be remarkably enhanced when nano-SiO_2 and PP fibers were reinforced, and the abrasion resistance of concrete decreased with the increase in the content of nanoparticles [113]. Rahmanzadeh *et al.* [114] kept the content of nano-silica at 5%, changed the water–cement ratio, and studied its abrasion resistance, the results showed that the abrasion resistance of concrete decreased with the increase in the water–cement ratio, but due to the influence of nano-SiO_2, the abrasion resistance will still be enhanced, as shown in Figure 17. Besides, Alireza [115] found that the difference in the average size of nano-SiO_2 will result in different content suggestions, when the size of nano-SiO_2 is 15 nm, the cement replacement is suggested at 1.0%, but when the size is 80 nm, the best content in concrete will be 1.5%.

At the same time, cooperating nanomaterials with other mineral admixtures were also a popular research

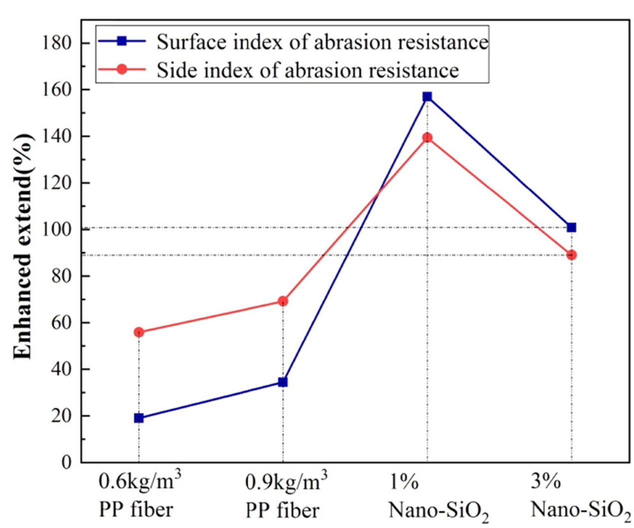

Figure 16: The effect of different materials on the concrete abrasion resistance [113].

direction for improving the concrete property. For example, Ji *et al.* [116] studied the concrete mechanical properties by adding FA and nano-SiO_2, and found that the 7 days and 28 days compressive and flexural strengths could be significantly improved with 0.5% nano-SiO_2. Zhang *et al.* [117] added nano-SiO_2 to concrete mixed with 50% FA or slag, and results showed that when the nano-SiO_2 was mixed at 1%, the concrete setting time was significantly reduced. Sun *et al.* [118] stated that high content FA concrete, like incorporating 2% nano-SiO_2 in 40% FA concrete, would result in the optimum early mechanical properties of concrete; Musa *et al.* [119] used the Box–Behnken design method to test the concrete mixed with nano-silica and crumb rubber, the results showed that the abrasion resistance of concrete decreased with an increase in crumb rubber, and enhanced with an increase in the addition of nano-silica; Nazari and Riahi [120] found that Portland cement partially replaced with SiO_2 and Al_2O_3 nanoparticles will enhance the concrete abrasion resistance, and increase in the nanoparticles content have found to increase the abrasion resistance of concrete which was cured in water and saturated limewater. Similar study has been applied by Shadi and Ali [121] where Portland cement was partially replaced up to 2.0 wt% with SiO_2 and CuO nanoparticles, and it was found that concrete mixed with SiO_2 nanoparticles has a better enhancement than CuO nanoparticles, as can be seen in Figure 18. However, completely different results can be seen in Figure 19, Gupta and Kumar [122] through experiments found that added coir fiber and nano-SiO_2 will decrease the concrete abrasion resistance, but the increase in the content of nano-SiO_2 from 2 to 3% will compensate for the loss in weight, thereby indicating that nano-silica really can fill the voids and make the concrete more homogeneous.

Although modifying the abrasion resistance of hydraulic concrete with nanoparticle materials was effective and outstanding, the influence of many factors such as curing medium, age of curing, water to cement ratio, aggregate type, nanoparticles content, *etc.*, on the abrasion resistance of concrete incorporating nanoparticles remain unknown. Therefore, the study about nano-SiO_2 used in concrete still needs to pay more attention on it, to obtain higher anti-abrasion concrete new material in the future.

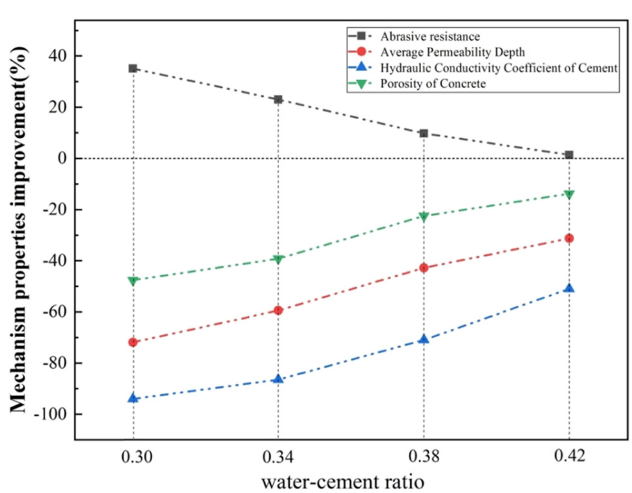

Figure 17: Different mechanical properties change compared to concrete W/C ratio at 0.46 [114].

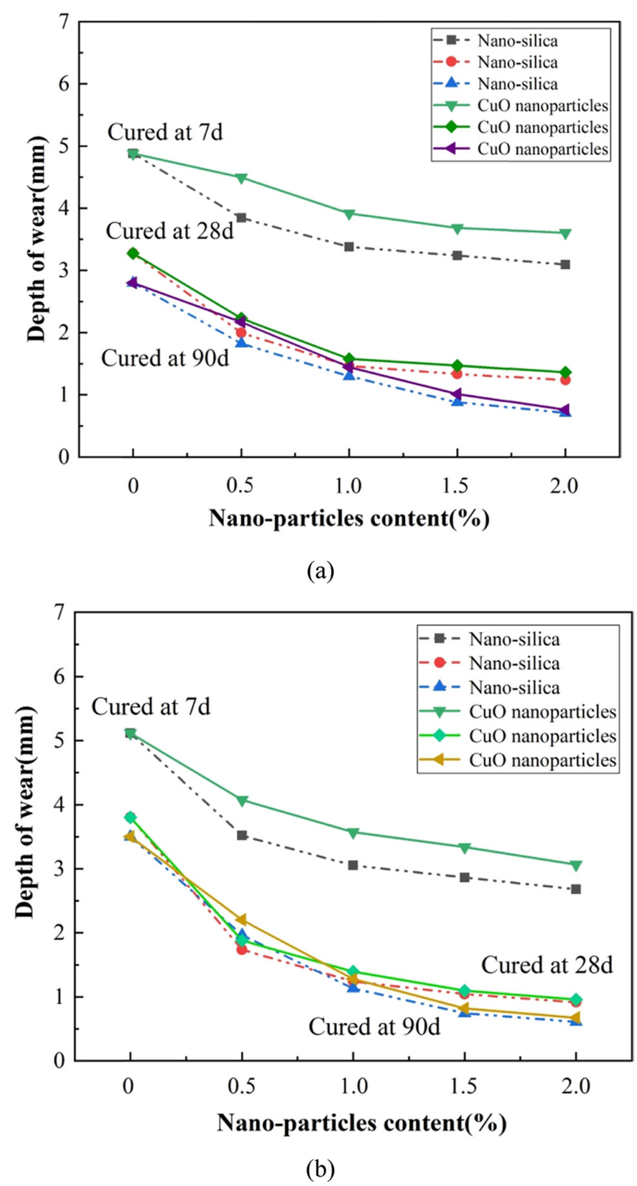

Figure 18: Abrasion resistance of concrete cured in (a) water and (b) saturated limewater [121].

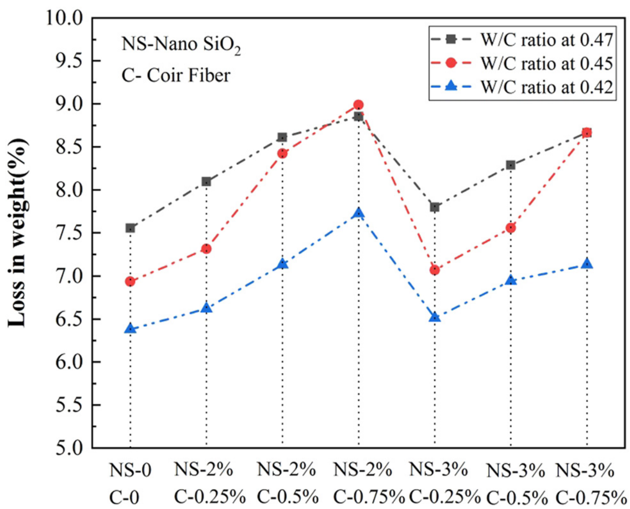

Figure 19: Abrasion resistance of concrete for different W/C ratio after 28 days [122].

3.2.2 Other nanoparticles

Because the main cement hydration product C–S–H gel belongs to the nanoscale, so aside from the wide application of nano-SiO_2 mixed in concrete, many other nanoparticles have also been used in concrete to improve its abrasion resistance.

For example, Tian *et al.* [123] studied the different contents of nano-$CaCO_3$ influence on concrete abrasion resistance, the results showed that nano-$CaCO_3$ mixed with concrete will promote the cement hydration, reinforce the concrete microstructure, and improve the concrete density. Therefore, the abrasion resistance can be enhanced effectively. There is approximately 6 times increase in concrete abrasion resistance compared to normal concrete when the Nano-$CaCO_3$ content is at 1.5%. Besides, due to adding a little fraction of graphene oxide (GO) can improve the transport properties, enhance Young's modulus, and increase the mechanical properties. So, researchers have been interested in the application of GO to enhance concrete abrasion resistance. Du *et al.* [124] found that the addition of GO (up to 0.1% by weight of cement) can enhance the concrete abrasion resistance by accelerating the hydration of cement and providing nucleation sites for hydration, facilitating the cement clinker consumption, and producing more hydration products. Du *et al.* [125] also points out that the surface abrasion resistance of high-volume fly ash (HVFA) mixtures will be modified by GO, and the micro-hardness, scratch surface roughness, and scratch hardness of the HVFA mixture first improved and then deteriorated with the increase in GO content. The suggestions on GO content in HVFA mixtures is 0.05 wt%. Li and Gao [126] also studied the impact of nano-MgO and nano-Al_2O_3 on concrete abrasion resistance, and through experiments found that nano-MgO was a benefit to the abrasion resistance of ultra-high performance concrete, but nano-Al_2O_3 will inhibit the cement hydration, thus there was no obvious influence on concrete abrasion resistance.

Meanwhile, many scholars have applied nanoparticles to protective covering to enhance its abrasion resistance. The addition of nanomaterials is one of the most effective ways to reduce the abrasive damage, aside from improving the abrasion resistance, it will also make materials acquire some new properties like corrosion protection, electrical conductivity, self-cleaning, and photocatalytic properties [127]. For example, Xu and Cai [128] used the combined ultrasonic cavitation and high-speed dispersion, and with the help of dispersant uniformly dispersed nano-Al_2O_3/ZrO_2 in epoxy resin. They found that the new coating has excellent abrasion resistance, salt spray resistance, and anti-aging properties, at the same time, the bonding strength between the coating and concrete will be remarkably improved due to the high surface activation energy of nanoparticles.

In summary, thanks to the outstanding performance of nanoparticles, concrete will be effectively enhanced when mixed with nanoparticles, therefore, more and more research has been applied in this field to study the mechanism of nanoparticle reinforcement. However, the research on concrete abrasion resistance modified with nanoparticles is still in the preliminary stage, still more efforts are needed to study the influence of nanoparticles on concrete abrasion resistance.

4 Prospects

In summary, although relevant works have attempted to increase the abrasion resistance of hydraulic concrete, the existing research in this field still has the following insufficient improvement. Based on this, this work recommends some future directions for enhancing the abrasion resistance of hydraulic concrete.

- The abrasion resistance of concrete materials is insufficient. As the design heads and water flow rate of water conservancy engineering structures keep rising, there are also stricter requirements for in-service hydraulic structure concrete to resist abrasion damage. Therefore, additional studies are needed to develop abrasion-resistant concrete that can fulfill more stringent engineering requirements. Nanoparticles will be an

appropriate material for improved abrasion resistance of hydraulic concrete, but few studies have been conducted on nanoparticles-modified abrasion resistance of concrete, besides, the dispersion of nanoparticles in concrete and the promoting of application in actual engineering still needs to be further studied. Besides, the use of supplementary cementitious material such as metakaolin in concrete will also be a considerable enhancement direction for abrasion resistance of hydraulic concrete. Because it reacts with calcium hydroxide forming C–S–H gel, and also makes refinement in pore structure which is similar to the use of silica fume. But the difference will be the delay and dilution effect of pozzolan will lead to loss of strength at early ages. And most importantly, modified metakaolin in concrete showed a reduction in the early age strength but at subsequent ages, significant improvement in strength results was noticed, and this will be the most interesting performance for hydraulic concrete. Ashish and Verma [129] stated that the increase in CH consumption is due to highly reactive Si/Al in the metakaolin, and the higher the replacement levels, the more the conversion of CH to C–S–H will be. Meanwhile, the utilization of industrial waste is a major problem worldwide, like waste foundry sand (WFS). Researchers incorporate WFS in replacement to natural sand in concrete, and the results showed that with the increase in WFS content, compressive strength tends to decrease at an early age. However, at later ages, an increase in compressive strength can be observed. So, the fineness of WFS relative to fine aggregate and the formation of C–S–H gel leads to the densification and better bonding of concrete [130]. Therefore, paying more attention to the materials which enhance concrete strength at later ages more prominently will be more meaningful for improving the hydraulic concrete abrasion resistance, and the selection and proportion of materials, the combination of different materials, or the development of new materials, will all be the potential research direction.
- The factors influencing the abrasion resistance of concrete are not comprehensively considered. Current research on the abrasion resistance of concrete mainly focuses on the single-factor influence and only considers which material has the most significant impact on the abrasion resistance of concrete. However, there are few studies on the abrasion resistance of concrete under the combined effect of multiple environmental factors, such as freezing and thawing, acid, alkali, and salt erosion, and temperature change, or the expected impacts of two or more influencing factors. The investigation into the abrasion resistance of concrete under the combined action of numerous failure mechanisms is insufficient. Therefore, further research is needed to establish the relationship between the abrasion resistance of concrete and these factors.
- Research on the abrasion resistance of concrete is overly related to its compressive strength. Generally speaking, the abrasion resistance of concrete is mainly related to the compressive strength, but not all concrete admixes used to improve its strength result in higher abrasion resistance, blindly reducing the water-to-cement ratio of concrete cannot improve the abrasion resistance of concrete [131]. The abrasion resistance of concrete depends not only on its structural forms, such as the strength of the bond between the aggregate and cement mortar, but also on the proportion of the cement [132]. Therefore, when the water-to-cement ratio of concrete is too low, the excessively viscous cement paste increases the compressive strength of the concrete due to the excessive content of the cement paste, but the abrasion resistance of concrete diminishes due to the relatively tiny amount of aggregates. However, the current works on the abrasion resistance of concrete have mainly been carried out based on the research on its compressive strength. The reliance on the compressive strength of concrete is excessive, and more systematic research on abrasion resistance itself is still lacking. The structural mechanisms, material properties like strength or toughness of concrete, and the concrete material parameters, such as water-to-cement ratio, aggregate, and cement properties which will impact the abrasion resistance of concrete most significantly, still need to be further investigated.

5 Conclusion

This study provides a general overview of the different existing approaches for enhancing abrasion resistance of hydraulic concrete published in standards and scientific documents and discusses major areas holding significant potential to improve current practices. The information is presented as a practical guide to assist understand the mechanism of concrete abrasion, enhanced methods, and widely applied or potential materials of anti-abrasion concrete that facilitate the development of higher anti-abrasion concrete materials. From this work, the following outlines can be concluded:
- At present, the abrasion resistance of hydraulic concrete is mainly enhanced using the following three

aspects: (1) changing the river flow pattern during the abrasion process to weaken the cavitation damage; (2) using more abrasion-resistant and well-connected repairing materials on the damaged structure to continue to endure the abrasion process; and (3) employing various materials to improve the abrasion resistance of concrete to directly resist the damage influence.

- The following four ways primarily improve the abrasion resistance of concrete when using different abrasion-resistant materials in concrete: (1) reducing the content of calcium hydroxide crystals and increasing the calcium silicate hydrate gels in concrete; (2) reducing the concrete porosity and increasing the strength of the cement paste; (3) using materials with superior hardness or abrasion resistance after the surface layer of concrete was washed and peeled off to resist the impact of abrasion damage; and (4) restricting the development of cracks inside the concrete during the process of abrasion damage to alleviate further damage to concrete, improve the brittleness of the concrete, and ease cracks and other defects so that the concrete maintains continuity, delaying the abrasion damage to concrete.
- The current experimental studies focus on the abrasion effects that are associated with the composite properties of concrete. Several strategies are known to improve the concrete resistance to abrasions, such as the increase in concrete compressive strength, the enhancement of coarse aggregate content and hardness, or the addition of reinforcing fibers and silica fume to the concrete. Nevertheless, abrasion resistance is not a bulk property such as strength but rather is a surface property that depends primarily on surface layer characteristics; therefore, future research should pay more attention to the abrasion itself to obtain the higher abrasion resistance of hydraulic concrete.
- The current abrasion-resistant concrete material shows insufficient abrasion resistance and utilizing more appropriate materials in concrete to improve its abrasion resistance was still the most effective way. Concrete modified with nanoparticles will enhance its abrasion resistance effectively, similar to the enhanced mechanism of silica fume but much better effectively and with many new properties, which show that modified concrete abrasion resistance with nanoparticles was a reliable method. However, the research on nanoparticles incorporated to improve concrete abrasion resistance still stays in the preliminary stage, the enhancement mechanism, optimum dosage, and the synergistic effect with other reinforcing materials still need more research. Besides, the reaction between abrasion resistance with other special properties such as self healing and self-sensing of nano-particles concrete, still need further research about it.
- Modified abrasion resistance of concrete with nanoparticles was effective. Based on the present research we can figure that nano-silica with an ideal effect on the compactness of concrete can replace the application of silica fume to enhance its abrasion resistance. However, the suggested dosage, particle size distribution, and combination with other enhancing materials still need further research. Besides, the even dispersion of nanoparticles in concrete and promoting the application in reality engineering will be the barriers to development. Meanwhile, when increasing the abrasion resistance of concrete, enhancing its strength and durability together is also the requirement for the higher anti-abrasion concrete materials development.

Funding information: The authors would like to acknowledge the financial support of the National Natural Science Foundation of China (Nos. U2040224 and 51879244).

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

References

[1] Wang JG. Research on damage and prevention measures of hydraulic buildings. MA thesis. Sichuan University. 2002.
[2] Zhang L. Discussion on the design of anti-abrasion and anti-corrosion of hydraulic drainage structure. Hydraulic hydropower Eng Des. 2011;30(1):44–7.
[3] Hu HX. Experimental study on anti-abrasion concrete of hydropower stations in the Upper Yellow River. Yellow River. 2020;42(10):142–7.
[4] Liu XF, Wang DW, Ji ZW, Zhao X. Variation and influence factors of the tail channel geometries in the Yellow River Estuary. J Sediment Res. 2020;45(5):42–7.
[5] Zhang T. Experimental study on high-performance concrete with resistance to abrasion from bed load sediment. MA thesis. Xinjiang Agricultural University; 2015.
[6] Yang L, Fang YW, Tang K, Wang WM, Effects of fly ash content on the mechanical properties and abrasion resistance of manufactured sand concrete. 2019;5:85–8 + 95.
[7] Xie Y, Yu B, Wu XM, Fan YM. Influence of mineral admixture on concrete abrasion resistance. Adv Mater Res. 2010;168–170:78–81.

[8] Kang JF. The abrasion-resistance investigation of rubberized concrete. J Wuhan Univ Technol (Mater Sci Ed). 2012;27(6):1144–8.
[9] Yu W, Liu YY, Lin SW. Abrasion behavior of steel-fiber-reinforced concrete in hydraulic structures. Appl Sci. 2020;10(5562):5562. doi: 10.3390/app10165562.
[10] Dong Y, Yang HQ, Xiao KT, Zhou SH, Wang L. Effect of aggregate on performance of abrasion resistance concrete. Concrete. 2013;12:82–6. doi: 10.3969/j.issn.1002-3550.2013.12.022.
[11] Zhang SY. Testing research on doped nano-silica steel fiber reinforced concrete. MA thesis. Zhengzhou University; 2010.
[12] Song XJ. Application of Nano-materials in new style concrete materials. J Anhui Jianzhu Univ. 2007;4:22–4.
[13] Xu QL. The effects of nano-SiO2 on the performance of cement-based materials and the study of the mechanism. MA thesis. Zhejiang University; 2013.
[14] Gao X, Cai Y, Ding J. Influencing factors of abrasion of hydraulic concrete based on underwater method. J Hydroelectric Eng. 2011;30(2):67–71.
[15] Hao NF. Study on evaluation method of abrasion resistance of hydraulic concrete. MA thesis. Northwest A&F University; 2012.
[16] Feng L, Jiang YL, Tang HQ, Wen T, Li FH. Research progress on erosion protection of hydraulic concrete. Sichuan Build Mater. 2022;48(1):1–3.
[17] Song ZC. Cause analysis and remedial measures for scouring damage of flushing bottom hole of a hydropower station. Yunnan Water Power. 2022;38(1):252–3.
[18] Grdic ZJ, Curcic GAT, Ristic NS, Despotovic IM. Abrasion resistance of concrete micro-reinforced with polypropylene fibers. Constr Build Mater. 2011;27(1):305–12. doi: 10.1016/j.conbuildmat.2011.07.044.
[19] Tian JT, Jiang FT. Development of abrasion-resistance apparatus against high-speed flow and study of abrasion resistance mechanism. J China Inst Water Resour Hydropower Res. 2006;2:123–7.
[20] Zarrabi N, Moghim MN, Eftekhar MR. Effect of hydraulic parameters on abrasion erosion of fiber reinforced concrete in hydraulic structures. Constr Build Mater. 2021;267:120966. doi: 10.1016/j.conbuildmat.2020.120966.
[21] He Y, Qian W, Zhang Y, Cai Y, Wang X. Research on thermal effect in cavitation process of hydraulic concrete. Concrete. 2017;10:24–8. doi: 10.1088/1755-1315/252/2/022008.
[22] Wang HQ, Zhang GB. Mechanism of abrasion and cavitation damage of hydraulic structures and their prevention measures. Yunnan Water Power. 2008;2:89–92.
[23] Xiu SH, Chen GS, Chen ZW. Research on anti-cavitation and anti-abrasion of hydraulic concrete structures. Water Conservancy Hydropower Constr. 2003;3:39–41.
[24] Mai SF, Fang WS, Li JW. Study and application of “sea island structure” epoxy resin “alloy” materials resistant to erosion and abrasion. Constr Technol. 2005;4:36–9. doi: 10.3969/j.issn.1002-8498.2005.04.013.
[25] Sun ZH, Zhu DK, Wang JP, Cai CY, Fang WS. Protective experiment on abrasion resistance of overflow surface concrete of Fuchunjiang Hydropower Station. Water conservancy hydropower Technol. 2013;44(9):90–2 + 99.
[26] Wang L, Zhang JW, Ba T, Ben XP. Abrasion and cavitation resistance of desilting tunnel in high-speed water flow zone of Xiaolangdi. China Water Resour. 2015;10:22–4 + 33.
[27] Mehta A, Deepankar KA. Silica fume and waste glass in cement concrete production: a review. J Build Eng. 2020-05;29:100888. doi: 10.1016/j.jobe.2019.100888.
[28] Ashish DK, Verma SK. Effect on permeability of concrete made with successive recycled aggregate and silica fume. Urbanization Chall Emerg Economies: Resil Sustainability Infrastruct. 2018;12:196–205. doi: 10.1061/9780784482032.021.
[29] Santanu B, Bratish S. Optimum silica fume content and its mode of action on concrete. Mater J. 2003;100:5.
[30] Yogendran V, Langan BW, Ward MA. Hydration of cement and silica fume paste. 1991;21(5):691–708.
[31] Gao H, Zeng L. Mix parameter design and crack resistance of abrasion resistant concrete with fly ash and silica power. China Rural Water Conservancy Hydropower. 2017;9:164–8 + 172.
[32] Wu JH, Li ZH, Zhang C. Effects of silica fume content on interfacial bond strength between cement based grouting material and old concrete. Bull Chin Ceram Soc. 2018;37(12):3989–95.
[33] Tuer-hong·TUEr-di’, Zeng, L. HF fly ash and silica fume concrete abrasion resistance test. China Rural Water Conservancy Hydropower. 2012;10:111–3 + 116.
[34] Ma SJ. Application of high-performance concrete (HPC) with silica in hydropower engineering. China Rural Water Conservancy Hydropower. 2004;11:71–3.
[35] Liu SH, Fang KH. Influence of fly ash on crack resistance of hydraulic concrete. J Hydroelectric Eng. 2005;2:73–6.
[36] Gil D, Golewski G. Potential of siliceous fly ash and silica fume as a substitute for binder in cementitious concretes. E3S Web Conf. 2018;Vol.49:30. doi: 10.1051/e3sconf/20184900030.
[37] de Gutiérrez RM, Díaz LN, Delvasto S. Effect of pozzolans on the performance of fiber-reinforced mortars. Cem Concr Compos. 2004;27(5):593–8. doi: 10.1016/j.cemconcomp.2004.09.010.
[38] Naik TR, Singh SS, Ramme BW. Effect of source of fly ash on abrasion resistance of concrete. J Mater Civ Eng. 2002;14(5):417–26. doi: 10.1061/(ASCE)0899-1561(2002)14:5(417).
[39] Ma SJ, Zhang HL, Dong P. The confecting technique of high-performance concrete with additives of powder and ash. China Rural Water Conservancy Hydropower. 2005;4:64–7 + 69. doi: 10.3969/j.issn.1007-2284.2005.04.024.
[40] Ashish D, Verma S. Determination of optimum mixture design method for self-compacting concrete: Validation of method with experimental results. Constr Build Mater. 2019-08-30;217:664–78. doi: 10.1016/j.conbuildmat.2019.05.034.
[41] Ding L. Optimization of mixing for silica fume concretesb; MA thesis. Northeast Forestry University. 2007.
[42] Li SX, Hu Q, Sun ZB. Study on confect technic of C60~C80 high strength abrasion-erosion resistance concrete. Concrete. 2011;12:133–5. doi: 10.3969/j.issn.1002-3550.2011.12.042.
[43] Deng ZZ, Yang H,Q, Xiao KT. Performance test of abrasion-resistant concrete with fiber. Concrete. 2017;4:8–10 + 14.

[44] Liu WD, Wang YM. Resistances of impact and abrasion for polypropylene fiber concrete. Concrete. 2005;1:43–5.
[45] Lu AQ, Li KL, Zhu YR, Hu ZN. Experimental study on the impact and abrasion resistance of polypropylene fiber concrete. Water conservancy hydropower Technol. 2002;4:37–9.
[46] Sukhoon P, Selamu YA, Hyeong-Ki K. Abrasion resistance of ultrahigh performance concrete incorporating coarser aggregate. Constr Build Mater. 218;165:11–6. doi: 10.1016/j.conbuildmat.2018.01.036.
[47] Xie XM, Yu QS, Hu L. Experimental research on the shock and wearing resistant concrete blended with polypropylene fiber. J Chongqing Jianzhu Univ. 2008;3:134–7 + 142. doi: 10.3969/j.issn.1674-4764.2008.03.031.
[48] Nihat K. Abrasion resistance and fracture energy of concretes with basalt fiber. Constr Build Mater. 2014;50:95–101. doi: 10.1016/j.conbuildmat.2013.09.040.
[49] Cheng TC, Cheng A, Huang R, LIN WT. Abrasion properties of steel fiber reinforced silica fume concrete according to Los Angeles and water abrasion tests. Mater Science/Medziagotyra. 2014;20(4):498–502. doi: 10.5755/j01.ms.20.4.6460.
[50] Omoding N, Cunningham LS, Lane-Serff GF. Influence of basalt micro-fibers on the abrasion resistance of concrete in hydraulic structures. Mater Struct. 2021;54(2):65. doi: 10.1617/s11527-021-01650-9.
[51] Atis CD, Karahan O, Ari K, Celik Sola Ö, Bilim C. Relation between Strength Properties (Flexural and Compressive) and Abrasion Resistance of Fiber (Steel and Polypropylene)-Reinforced Fly Ash Concrete. J Mater Civ Eng. 2009;21(8):402–8. doi: 10.1061/(ASCE)0899-1561(2009)21:8(402).
[52] Horszczaruk E. Abrasion resistance of high-performance hydraulic concrete with polypropylene fibers. Tribologia. 2012;1:63–72.
[53] Andrzej M, Brandt. Fiber-reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Composite Struct. 2008;86(1):3–9. doi: 10.1016/j.compstruct.2008.03.006 CODEN: COMSE2.
[54] Vahid A, Togay O. Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. Constr Build Mater. 2015;94:73–82. doi: 10.1016/j.conbuildmat.2015.06.051.
[55] Sheng ST, Fang KH. Application of polypropylene fiber in the high-performance hydraulic concrete. Concrete. 2003;11:51–3 + 59.
[56] Liao XT, He Y, Yang XG, Wang YM. Interfacial behavior of PP fiber reinforced cement composite(II)-SEM observation and morphological study on fracture surface. J Build Mater. 2000;1:71–4.
[57] Shi L. Influence of modified polypropylene fiber on the mechanical properties of concrete. Coal Sci Technol Mag. 2014;3:39–41.
[58] Ji T, Ji GJ, Wang SJ, Liu Y. Influence of polyvinyl alcohol fiber on properties of hydraulic abrasion resistance concrete. J Southeast Univ (Nat Sci Ed). 2010;40(S2):192–6.
[59] Shi ZW, Xie F. Experimental research on abrasion resistance of steel fiber-reinforced concrete based on response surface method. J Highw Transportation Res Dev (Engl Edition). 2016;10(2):16–20. doi: 10.1061/JHTRCQ.0000496.
[60] Ju GD, Shi Y, Li JZ. Comparative study on influence of different fibers to performance of abrasion resistance concrete. Yangtze River. 2010;41(21):21–3.
[61] Liu RL. Research on abrasion resistance of steel fiber concrete in hydropower engineering. Water conservancy Technical Superv. 2020;5:123–5 + 222.
[62] Abid SR, Hilo AN, Ayoob NS, Daek YH. Underwater abrasion of steel fiber-reinforced self-compacting concrete. Case Stud Constr Mater. 2019;11:11. doi: 10.1016/j.cscm.2019.e00299.
[63] Wu P. Effect of steel fiber and PVA fiber on mechanical and abrasion resistance performance of ultrahigh-performance concrete. MA thesis. Hubei University of Technology; 2019.
[64] Hu JS, Yang XM, Zhou ZS, Tang DG. Experimental study on tenacity increase characteristics of steel fiber reinforced concrete and polypropylene fiber reinforced concrete under impact load. J Build Struct. 2005;2:101–5.
[65] Liu Y-W, Yen T, Hsu. T-H. Abrasion erosion of concrete by water-borne sand. Cem Concr Res. 2005;36(10):1814–20. doi: 10.1016/j.cemconres.2005.03.018 CODEN: CCNRAI.
[66] Li GW, Yang YH. Testing & study of Xiluodu hydroelectric power station scour & wear resisting concrete properties. Hydropower Stn Des. 2004;3:92–7. doi: 10.3969/j.issn.1003-9805.2004.03.025.
[67] Mohajerani A, Nguyen BT, Tanriverdi Y, Chandrawanka K. A new practical method for determining the LA abrasion value for aggregates. Soils Found. 2017;57(5):840–8. doi: 10.1016/j.sandf.2017.08.013.
[68] Esra TT, Kursat EA. A preliminary estimation method of Los Angeles abrasion value of concrete aggregates. Constr Build Mater. 2019;222:437–46. doi: 10.1016/j.conbuildmat.2019.06.176.
[69] Gurpreet S, Rafat S. Abrasion resistance and strength properties of concrete containing waste foundry sand (WFS). Constr Build Mater. 2011;28(1):421–6. doi: 10.1016/j.conbuildmat.2011.08.087.
[70] Thomas BS, Kumar S, Mehra P, Gupta RC, Joseph M, Csetenyi LJ. Abrasion resistance of sustainable green concrete containing waste tire rubber particles. Constr Build Mater. 2016;124:906–9. doi: 10.1016/j.conbuildmat.2016.07.110.
[71] Xie L, Lou ZK. Research on property of abrasion resistance of rubber-filled concrete. J Water Resour Water Eng. 2014;25(2):188–91.
[72] Feng X, Jin JX, Tian ZH. Construction technology of permeable formwork for anti-abrasion hydraulic concrete [C]. The 3rd National Symposium on Safety and Disease Treatment Technology of Hydraulic Sluice Structures. 2011.
[73] Farid HN, Mahdi N. The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica. Constr Build Mater. 2017;137:557–72. doi: 10.1016/j.conbuildmat.2017.01.078.
[74] Susanto T, Vahid A, Claudia PO. Flexural behavior and durability properties of high-performance hybrid-fiber-reinforced concrete. Constr Build Mater. 2018;182:504–15. doi: 10.1016/j.conbuildmat.2018.06.158.
[75] Xue Y, Lou ZK. Research on the influence of polypropylene fiber on the performance of silica fume concrete. Yellow River. 2010;32(9):130–1.
[76] Wang L, Zhou SH, Shi Y, Tang SW, Chen E. Effect of silica fume and PVA fiber on the abrasion resistance and volume stability

of concrete. Compos Part B. 2017;130:28–37. doi: 10.1016/j.compositesb.2017.07.058.
[77] Wang HC, Zhang LL, Gao SL, Gu SW, Chen Q. Experimental study on influence of PVA fiber on mechanical properties of engineered cementitious composites. Concrete. 2013;4:4–7 + 14. doi: 10.3969/j.issn.1002-3550.2013.04.002.
[78] Ryu GS, Kang ST, Park JJ, Koh KT, Kim SW. Mechanical behavior of UHPC (ultrahigh-performance concrete) according to hybrid use of steel fibers. Adv Mater Res. 2011;1334:453–7.
[79] Tavakoli HR, Jalali P, Mahmoudi S. Experimental evaluation of the effects of adding steel fiber on the post-cyclic behavior of reinforced self-compacting concrete beams. J Build Eng. 2019;25:25. doi: 10.1016/j.jobe.2019.100771.
[80] Yoo D-Y, Lee J-H, Yoon. Y-S. Effect of fiber content on mechanical and fracture properties of ultrahigh performance fiber reinforced cementitious composites. Composite Struct. 2013;106:742–53.
[81] Sanchez F, Sobolev K. Nanotechnology in concrete–A review. Constr Build Mater. 2010;24(11):2060–71.
[82] Zhang LD, Mou JM. Nano-material science. Shenyang: Liaoning Science and Technology Press; 1994.
[83] Yang DS, Feng R. Materials nova-nanomaterials. Changsha: Hunan Science and Technology Press; 1997.
[84] Zhu Y, Lei YY. Nano TiO_2 – a new inorganic antibacterial agent. Mod Chem Ind. 1999;8:46–8.
[85] Ren X,T, Zeng LK. Titanium dioxide and environmentally friendly building materials. N Build Mater. 2000;7:36–7.
[86] Tang M, Chen Y. Discussion high functional concrete material. Concrete. 2001;3:14–8.
[87] Xu XC. Research and development of concrete containing photocatalyst. J Hubei Eng Univ. 2001;6:53–5.
[88] Yao W, Wu KR. Research status and development trend of intelligent concrete. N Build Mater. 2000;10:22–4.
[89] Wu SG, Huang YC. Experimental research on intelligent concrete. J Harbin Univ Civ Eng Architecture. 2001;2:128–9.
[90] Golewski G, Szostak B. Application of the C-S-H phase nucleating agents to improve the performance of sustainable concrete composites containing fly ash for use in the precast concrete industry. Materials. 2021-11-01;14(21):6514. doi: 10.3390/ma14216514. PMID: 34772036.
[91] Szostak B, Golewski G. Effect of nano admixture of CSH on selected strength parameters of concrete including fly ash. Mater Sci Eng. 2018-09-01;416(1):12105. doi: 10.1088/1757-899X/416/1/012105
[92] Szostak B, Golewski G. Rheology of cement pastes with siliceous fly ash and the CSH nano-admixture. Materials. 2021-07-01;14(13):3640. doi: 10.3390/ma14133640 PMID: 34209995.
[93] Golewski GL, Bartosz S. Strengthening the very early-age structure of cementitious composites with coal fly ash *via* incorporating a novel nano admixture based on C-S-H phase activators. Constr Build Mater. 2021-12-20;312:125426. doi: 10.1016/j.conbuildmat.2021.125426.
[94] Jiang XY, Li X. Progress in application and preparation of nano-silica microspheres. Bull Chin Ceram Soc. 2011;30(3):577–82.
[95] Golewski G. Green concrete based on quaternary binders with significant reduce of CO_2 emissions. Energ (Basel). 2021-08-01;14(15):4558. doi: 10.3390/en14154558.
[96] Wang L, He Z, Yang HQ, Cai XH. Study on the microstructural mechanism to improve the abrasion resistance of concrete by adding silica fume. J Hydraulic Eng. 2013;44(1):111–8.
[97] Chen H, Chen Q, Xu Y, Lawi AS. Effects of silica fume and fly ash on properties of mortar reinforced with recycled-polypropylene. Constr Build Mater. 2022;316:125887. doi: 10.1016/j.conbuildmat.2021.125887.
[98] Yang JZ, Wang JY, Zhang LY. Experimental study on abrasion resistance of silica powder high performance concrete. Yellow River. 2009;31(6):102–3.
[99] Xu J, Wang XZ. Effect of nano-silica modification on interfacial transition zone in concrete and its multiscale modelling. J Chin Ceram Soc. 2018;46(8):1053–8. doi: 10.14062/j.issn.0454-5648.2018.08.02.
[100] Kawashima S, Hou P, Corr DJ, Shah SP. Modification of cement-based materials with nanoparticles. Cem Concr Compos. 2013;36:8–15. doi: 10.1016/j.cemconcomp.2012.06.012.
[101] Liu C, He X, Deng X, Wu Y, Zheng Z, Liu J, et al. Application of nanomaterials in ultra-high performance concrete: A review. Nanotechnol Rev. 2020;9(1):1427–44. doi: 10.1515/ntrev-2020-0107.
[102] Jo BW, Kim CH, Tae G, Park JB. Characteristics of cement mortar with nano-SiO_2 particles. Constr Build Mater. 2005;21(6):1351–5. doi: 10.1016/j.conbuildmat.2005.12.020.
[103] Hou XB, Huang D, Wang W. Recent progress on high performance concrete with nano-SiO_2 particles. Concrete. 2013;3:5–9. doi: 10.3969/j.issn.1002-3550.2013.03.002.
[104] Chen RS, Ye Q. Research on the comparison of properties of hardened cement paste between nano-SiO_2 and silica fume added. Concrete. 2002;1:7–10.
[105] Tian J. Experimental study on influence mechanism of nanoparticles on abrasion resistance of high performance cement-based composites. Hubei University of Technology; 2020. doi: 10.27131/d.cnki.ghugc.2020.000164.
[106] Ye Q, Zhang ZN, Kong DY, Chen RS, Ma CC. Comparison of properties of high strength concrete with Nano-SiO_2 and silica fume added. J Build Mater. 2003;4:381–5.
[107] Guo BL, Zuo F, Wang BM. Experimental study on autogenous shrinkage of high strength concrete with Nano-SiO_2. Highway. 2006;10:175–80.
[108] An MZ, Zhu JQ, Qin WZ. Autogenous shrinkage of high performance concrete. J Build Mater. 2001;2:159–66.
[109] Stefanidou M, Papayianni I. Influence of nano-SiO_2 on the Portland cement pastes. Compos Part B. 2012;43(6):2706–10. doi: 10.1016/j.compositesb.2011.12.015.
[110] Li GH. Effect of Nano-materials on durability of concrete. MA thesis. Southwest Jiaotong University; 2006.
[111] Huang JJ, Li DD, Wu M, Li GY. Bending fracture toughness of nano-SiO_2/PVA fiber modified high-volume fly ash concrete. J Shantou University(Natural Sci Ed). 2018;33(4):71–80.
[112] Li ZD, Meng D, Wang ZP, Wu XM, Huang X. Analysis on macroscopic property and micrococoscopic control mechanism of nano-SiO_2 modified concrete. Bull Chin Ceram Soc. 2020;39(7):2145–53. doi: 10.16552/j.cnki.issn1001-1625.2020.07.018.
[113] Li H, Zhang MH, Ou JP. Abrasion resistance of concrete containing nano-particles for pavement. Wear.

2006;260:1262–6. doi: 10.1016/j.wear.2005.08.006 CODEN: WEARAH.

[114] Rahmanzadeh B, Rahmani K, Piroti S. Experimental study of the effect of water–cement ratio on compressive strength, abrasion resistance, porosity and permeability of nano silica concrete (Article). Frattura ed Integrita Strutturale. 2018;12(44):16–24. doi: 10.3221/IGF-ESIS.44.02.

[115] Naji Givi A, Abdul Rashid S, Aziz FNA, Salleh MAM. Experimental investigation of the size effects of SiO_2 nanoparticles on the mechanical properties of binary blended concrete. Compos Part B. 2010;41(8):673–7. doi: 10.1016/j.compositesb.2010.08.003.

[116] Ji T, Huang YZ, Zheng ZQ. Primary investigation of physics and mechanics properties of nano-concrete. Concrete. 2003;3:13–4 + 48. doi: 10.3969/j.issn.1002-3550.2003.03.003.

[117] Zhang MH, Islam J, Peethamparan S. Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag. Cem Concr Compos. 2012;34(5):650–62. doi: 10.1016/j.cemconcomp.2012.02.005.

[118] Sun J, Shen X, Tan G, Tanner JE. Modification effects of nano-SiO_2 on early compressive strength and hydration characteristics of high-volume fly ash concrete. J Mater Civ Eng. 2019;31(6):04019057. doi: 10.1061/(ASCE)MT.1943-5533.0002665.

[119] Musa A, Bashar SM, Nasir S. Abrasion resistance of nano silica modified roller compacted rubbercrete: cantabro loss method and response surface methodology approach. IOP Conf Series: Earth Environ Sci. 2018;140:012119. doi: 10.1088/1755-1315/140/1/012119.

[120] Nazari A, Riahi S. Abrasion resistance of concrete containing SiO_2 and Al_2O_3 nanoparticles in different curing media. Energy Build. 2011;43(10):2939–46. doi: 10.1016/j.enbuild.2019.05.037.

[121] Shadi R, Ali N. Compressive strength and abrasion resistance of concrete containing SiO_2 and CuO nanoparticles in different curing media. Sci China(Technological Sci). 2011;54(9):2349–57. doi: 10.1007/s11431-011-4463-4.

[122] Gupta M, Kumar M. Effect of nano silica and coir fiber on compressive strength and abrasion resistance of concrete. Constr Build Mater. 2019;226:44–50. doi: 10.1016/j.conbuildmat.2019.07.232.

[123] Tian J, Su J, Wu P, He Z, Cai X. Experimental research on abrasion resistance of concrete mixed with Nano-$CaCO_3$. China Concr Cem Products. 2020;6:9–12. doi: 10.19761/j.1000-4637.2020.06.009.04.

[124] Du S, Tang Z, Zhong J, Ge Y, Shi X. Effect of admixing graphene oxide on abrasion resistance of ordinary portland cement concrete. AIP Adv. 2019;9(10):105110. doi: 10.1063/1.5124388 CODEN: AAIDBI.

[125] Du S, Jiang Y, Zhong J, Ge Y, Shi X. Surface abrasion resistance of high-volume fly ash concrete modified by graphene oxide: Macro and micro-perspectives. Constr Build Mater. 2020;237:117686. doi: 10.1016/j.conbuildmat.2019.117686.

[126] Li SX, Gao XJ. Effect of nano Al_2O_3 and MgO on abrasion resistance and mechanism of ultra-high performance concrete. SurfaceTechnology. 2018;47(10):123–30. doi: 10.16490/j.cnki.issn.1001-3660.2018.10.016.

[127] Wu T, Wen XF, Pi PH, Cheng J, Yang ZR. Progress of nano abrasion resistant composite film. Polym Mater Sci & Eng. 2009;25(7):162–5. doi: 10.16865/j.cnki.1000-7555.2009.07.045.

[128] Xu XF, Cai YB. Study on NANO-Al_2O_3/ZrO_2 wear-resistant coating. N Build Mater. 2011;38(5):63–5. doi: 10.3969/j.issn.1001-702X.2011.05.018.

[129] Ashish D, Verma S. Cementing efficiency of flash and rotary-calcined metakaolin in concrete. J Mater Civ Eng. 2019-12-01;31(12):4019307. doi: 10.1061/(ASCE)MT.1943-5533.0002953.

[130] Ashish D, Verma S. Robustness of self-compacting concrete containing waste foundry sand and metakaolin. A sustainable approach. J Hazard Mater. 2021-01-05;401:123329. doi: 10.1016/j.jhazmat.2020.123329. PMID: 33113711.

[131] Liu DM. Effect of fly ash on the abrasion - erosion resistance of concrete. Concrete. 2010;8:80–1 + 131.

[132] Yang CG. Study of mechanism and character on scour and wear resistance of hydraulic concrete. MA thesis. Northwest Agriculture and Forestry of Science and Technology University; 2006.