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Performance Evaluation of Additives to Make Abrasion Resistant Concrete: A Review

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Abstract: ***One of the most common forms of deterioration of concrete structures is by surface abrasion. Abrasion primarily depends upon the resistance level of materials, mix composition, strength gain and construction practices. Such deteriorations endanger the structural safety and increase the cost of repair and maintenance. In order to minimize the maintenance problems and to increase the serviceability of the structures, it is important that the structure should be resistant to abrasion. Understanding the physics of abrasion is critical for reducing its negative effects on concrete because abrasion is a typical degradation mechanism for concrete. An effort has been spent to identify the factors affecting abrasion of concrete structures and a review on different additives that can be added to achieve abrasion-resistant concrete is carried out. This paper reviews the research work carried out in the area of surface abrasion with works focusing within the last decade.***
Keywords: Abrasion Resistance, Additives, Concrete Abrasion, Degradation, Durability, Serviceability.

I. INTRODUCTION

Concrete is the basic and widely used constituent in any construction works. Concrete's ongoing popularity stems from the fact that it is not only economic, but also extremely strong and long-lasting. Concrete outlasts wood, asphalt, and other building materials by decades and even strengthens over time. Concrete is a highly adaptable material that is used to build structures such as buildings, bridges, dams, tunnels, pavements, runways, and highways. In contrast to steel or timber buildings, where weathering is unavoidable, concrete structures do not require coating or painting for regular applications as weather protection. Despite of all the advantages possessed by concrete, it can also have deteriorations in long term. The potential causes of concrete failures include chemical reactions, shrinkage, weathering, and abrasion/erosion. Out of these, abrasion damages are predominant on hydraulic structures such as dams, culverts, spillways, concrete pavements, bridge structures, concrete sleepers, etc. Understanding the causes of concrete damage is critical in the rehabilitation and repair works. Abrasion on concrete structures may be due to wear on concrete floors due to human and vehicle traffic or due to abrasive materials in water like debris affecting the hydraulic structures [1,2]. Abrasion, as defined by ASTM, is the physical wear due to hard particles rubbing against and moving along a solid interface [3]. Abrasion depends upon the resistance level of the materials, mix composition, strength gain, and construction practices. The wearing resistance of concrete is closely related to compressive strength at the wearing surface.

Abrasion resistance is deeply connected with the bond of the cement paste with the coarse aggregates. When concrete buildings are abraded, the surface becomes smooth. Abrasion is indicated by lengthy, shallow grooves on a concrete surface and spalling along monolith joints. Fig.1 illustrates the process of abrasion in concrete structures when subjected to prolonged external forces. First, the concrete near the mortar's surface progressively wears away, exposing the coarse aggregate. Following that, the impact of aqueous particles causes the fractured coarse aggregate to generate microscopic gaps at the paste-aggregate interface. After repeated collisions, voids form, which are then absorbed by the concrete. The size of the coarse aggregate, the type of sand utilized, and the momentum of the revolving water jet all have a significant impact on void formation.

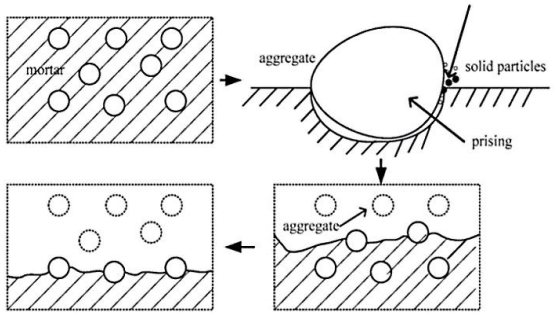

Fig. 1 Schematic Representation of Abrasion Process in Concrete Structures [4]

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The abrasion rate depends on the hardness, shape, size, and quantity of the waterborne particle; the speed of the water jet; and concrete quality [4]. Although good-quality concrete can withstand the impact of high flow velocity of jet and has almost no damage, the concrete cannot withstand the abrasion effect of scraps grinding or repeated impact on the surface for a long time. Abrasion can totally wear away concrete from structural components in the worst-case scenario. Abrasion resistance is thus described as a surface's ability to resist being worn away by rubbing or friction [5]. Establishment of quantitative relationships between the factors and abrasion resistance would be of practical value. This paper identifies and discuss the major factors affecting abrasion and how incorporation of various additives improves the abrasion resistance of concrete structures. The degree up to which these additives can enhance the abrasion resistance is also studied in this paper.

II. FACTORS AFFECTING ABRASION IN CONCRETE STRUCTURES

Several factors govern the abrasion on concrete structures like water-cement (w/c) ratio, aggregates, compressive strength, etc. Knowing the effect of each parameter in abrasion is crucial for understanding the performance of abrasion-resistant concrete

A. Aggregates

Kilic et al. (2008) attempted to evaluate the effect of aggregates on concrete abrasion resistance. He investigated the effect of aggregate type on the strength and abrasion resistance of high strength silica fume concrete. To make high strength concrete containing silica fume, five different aggregate types (gabbro, basalt, quartzite, limestone, and sandstone) were employed. The percent abrasion loss data indicated that, in general, a relationship existed between concrete compressive strength and abrasion. Concrete abrasion decreases as concrete strength increases. Among the five aggregates, gabbro demonstrated the greatest compressive strength and abrasion resistance, while sandstone demonstrated the least compressive strength and abrasion resistance.

Liu et al. (2006) studied the effect of aggregate size in the process of abrasion. For the testing program, three maximum aggregate sizes of 5, 13 and 25 mm were incorporated into the concrete mixes with low and high compressive strengths (approximately 25 and 90 MPa, respectively). It was observed that maximum aggregate size increased abrasion resistance in low-strength concretes. Larger aggregates, according to the researchers, reduced the percentage of surface area for the weaker cement paste to cover, resulting in a better bond and a lower number of aggregates removed by abrasive processes. When low-strength concrete was subjected to abrasive attack, larger particles took more energy to remove. There was no such relationship in high strength concrete.

Dhir et al. (1991) also carried out a test program that investigated the effect of maximum aggregate size on abrasion resistance. Maximum aggregate sizes of 5, 10, 20, and 40 mm were evaluated, with compression strength being constant for each. Their test results revealed that when the coarse aggregate size was increased, the abrasion depth reduced. According to the study, the 40 mm aggregate sample was subjected to more severe dynamic loading, resulting in larger abrasive losses than the 10- and 20-mm aggregates.

Evangelista and de Brito (2007) investigated the abrasion resistance of concrete incorporating fine recycled concrete aggregate and compared their results with concrete including natural or virgin fines. Their test results showed that the abrasion resistance of concrete improved with a 5% and 30% reduction in abrasion loss for the 30% and 100% substitution of normal fines, respectively. According to the scientists, this was owing to a stronger bond between the cement paste and the coarse aggregate. Konin and Kouadio (2012) also tried to investigated the abrasion resistance of concrete where the coarse aggregate was either entirely recycled concrete or natural. The results show that recycled aggregate concrete outperformed natural aggregate concrete in terms of abrasion resistance. The researcher indicated that the better link between the aggregate and the cement matrix was the key cause for the improved abrasion resistance of recycled aggregate concrete.

Pedro et al. (2017) tested concrete specimens with and without recycled aggregates (RA) and found that the use of RA had no effect on abrasion resistance, with thickness losses of around 3.5 and 4.5 mm for coarse RA and both coarse and fine RA mixes, respectively. The study by Kumar et al. (2017) suggests that incorporation of recycled aggregates can reduces the abrasion resistance by 18%–22%. It was observed that abrasion reduction is higher for mixes with fine RA.

B. W/C Ratio

Yu-Wen Liu et.al (2006) studied the effect of w/c ratio on abrasion of concrete structures. Four w/c ratios of 0.50, 0.36, 0.32, 0.28 were selected to make concretes that are commonly used in hydraulic structure construction. Test results shows that the surface of concrete slab made with w/c=0.36 after 3 hrs of water-jet testing suffered minute abrasion compared with the surrounding mortar whereas, the surface of a tested slab made with a w/c ratio of 0.28 appears to be quite smooth. This difference is explained by the w/c ratio principle that claims a higher strength for concrete made with a lower w/c ratio.

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In this case, the mortar strength is comparable to that of the coarse aggregate. A conclusion can be drawn from the test results that concrete abrasion resistance is in inversely proportional to the w/c ratio used. Concrete with a low w/c ratio develops less porosity, higher strength and a stronger interfacial bond in the hardened mortar and thus enhances the overall concrete abrasion erosion resistance performance. This result was in agreement with the findings of Laplante et.al (1991) which depict the fact that concrete abrasion resistance decreases as W/C increases.

The effect of water-cement ratio on abrasion was also studied by Rahmani et al. (2018). The test results show that by lowering the water-cement ratio, the abrasion resistance of nano silica concrete enhanced. The abrasion resistance of concrete was increased by 42 % by lowering the water-cement ratio from 0.46 to 0.30 in nano silica concrete sample. The abrasion resistance of the mortar phase decreases as the water-cement ratio increases, and the abrasion resistance of concrete approaches the abrasion resistance of aggregates. In a similar study carried out by Ghasemipor et al (2018) on varying w/c ratio to identify its influence on abrasion, it was observed that the depth of abrasion increases as the water-cement ratio increases, but the abrasion resistance of the concrete diminishes. The gradient of the depth of abrasion curve was found to gradually decrease as the water-cement ratio is increased from 0.35 to 0.55. This issue is related to the two-phased nature of concrete in abrasion, which means that when the water-cement ratio increases, the abrasion strength of the mortar phase decreases, but the abrasion strength of concrete tends to be the same as the abrasion strength of aggregates.

C. Compressive Strength

Laplante et.al (2006) evaluated the effect of compressive strength on abrasion of concrete. Four air-entrained concretes with W/C = 0.48 were used. The two coarse aggregates used were a “strong" granite gravel and a "soft" limestone. In both mixes, silica fume replaced cement on a volume basis corresponding to 7.5% by mass. The results indicated that the two concretes without silica fume had similar compressive strengths, as did the two silica-fume concretes, indicating that aggregates only slightly affect compressive strength at the same W/C used. Nevertheless, the silica-fume concretes yielded much higher compressive strengths than those without. It was also noticed that the use of silica fume in concrete decreases somewhat the depth of wear.

The study carried out by Ghafoori et al (2019) projects that the use of Type V cement in the mixture can result in a 23% lower abrasion depth at 28 days, whereas concrete containing Type III cement produced a 16% lower abrasion depth at 28 days. A significant improvement was observed in abrasion resistance for the Calcium Sulfoaluminate (CSA) cement concrete mixture with 44% lower abrasion depth at 28 days testing in comparison with 24 hours testing. It was inferred from the study that increases in the compressive strength can considerably reduce depth of wear. The study by Adewuyi et al. (2017) also stated that concrete's compressive strength had a substantial influence on its abrasion resistance, which improved with age for all concrete compositions.

D. Curing

Kevern et.al (2009) studied the combinations of four different pervious concrete mixtures cured using six common curing methods. The types of curing evaluated were air curing, moist curing under plastic for 7 and 28 days, soybean oil curing, white pigment curing, and curing with non-film evaporation retardant. Fig. 2 shows the result of abrasion loss for various curing regimes.

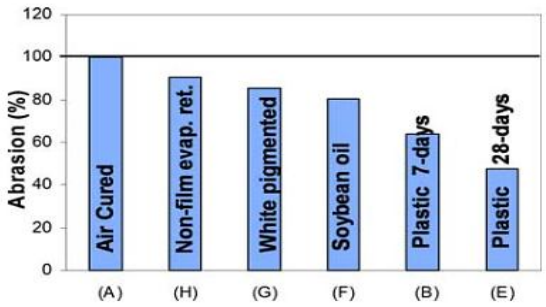

Fig. 2 Effect of curing regime on concrete [16]

The results shows that the mixtures cured under plastic had the best abrasion resistance. Of the surface-applied treatments, the soybean oil emulsion (F) had the best abrasion index, followed by the standard white pigment (G) and non-film-forming evaporation retardant (H). The moist cured specimens performed the best with the least abrasive losses, where the moisture trapped by the plastic sheet helped to densify the concrete surface. The air cured specimens experienced the most abrasive losses from the concrete surface.

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Adewuyi et al. (2017) studied the effect of curing age on abrasion resistance of concrete. 7, 28, 42, 56 and 70 day curing was applied and it was observed that in all the cases, wear depth decreased with curing age of concrete. It was also found from the investigation that cement content and cement-total aggregate ratio (CTAR) have similar influence on abrasion resistance.

R.K Dhir et.al (1991) tested four series of concrete mixes after the specimens were cured until the age of 28 days. He made use of five types of curing mechanism, namely water ponding at 20°C to 4 days, wet hessian at 20°C to 4 days, resin-spirit-based curing membrane on top surface, wax-water-based curing membrane on top surface and air curing at 20°C. The results of the specimens subjected to simulated in situ curing methods suggests that water ponding method can only be effective when correctly applied, which can be difficult in practice. Curing with wet hessian, normally covered with polythene sheeting, requires less attention, and can provide a relatively more consistent curing. The two curing membranes were found to give similarly improved abrasion resistance. From the limited results obtained from the study, and considering the practical application it may be tentatively concluded that wet hessian or the application of resin- spirit-based curing membranes are the most practical and effective methods for curing in situ slabs.

E. Concrete Cracks

Liu et.al (2011) studied the effect of surface cracks in abrasion. He evaluated the resistance of concrete specimens with abrasion in three crack patterns (0°, 45° and 90°), four surface crack widths (0.5, 1, 2 and 3 mm) and two silica fume (5% and 10%) contents. During the abrasion test, it was observed that the rough surface of concrete increased as the crack width increased. For concrete surfaces containing 90° cracks, the abrasive resistance decreased as the crack width increased. When the crack width is greater than 1 mm, scratching action increased the abrasion loss. It can be seen that the abrasive loss at a 90° crack is higher than for a 0° or a 45° crack for specimens with the same crack width and length. This may be explained by the fact that the abrading cutter more easily enters the 90° cracks than either the 0° or 4^{5o} cracks due to the greater contact length between abrading cutter and cracks, producing quite serious scrapes. The abrasion resistance of the concrete specimens containing 0°, 45°, and 90° crack at 0.5 and 1.0mm widths exhibit decrease of about 59-98%, 59-108% and 66-125 %, respectively, as compared to the without crack specimen.

The study by Abdelbary et al (2014) also confirms the fact that imposed cracks marked perpendicular ($\theta = 90°$) to the sliding direction can wear more, whereas parallel cracks ($\theta = 0°$) show a much smaller effect. It is also noted that the effect of cracks on abrasion also depends on the nature of loading. When the specimen is subjected to dynamic load, wear rates grow rapidly, although continuous loading has minimal effect on them.

Liu et al. (2007) studied the effect of crack width and crack orientation. Fig. 3 shows the crack orientations considered in the present study. The results claim that for water flow impinging directly on the fracture, the abrasion rate increases marginally with crack width greater than 1 mm. When the water flow impinges above the crack, the abrasion rates increase as the crack width increases. A crack width of 3 mm, in particular, has the greatest rise in abrasion rate. When waterborne sand flow impinged above the surface crack, the abrasion rate rose by almost 16%, 21%, and 38%, respectively, as crack width increased from 0 to 1, 2, and 3 mm. The results of the abrasion resistance test of concrete specimens with surface cracks at an angle of 0°, 45°, and 90° illustrates that in the event of a water-jet impinging directly on the fracture, a larger angle increases the abrasion rate dramatically. When the angle of the water-jet impinging directly on the crack was increased from 0 to 45 and 90 degrees, the abrasion rate increased by 8% and 20%, respectively.

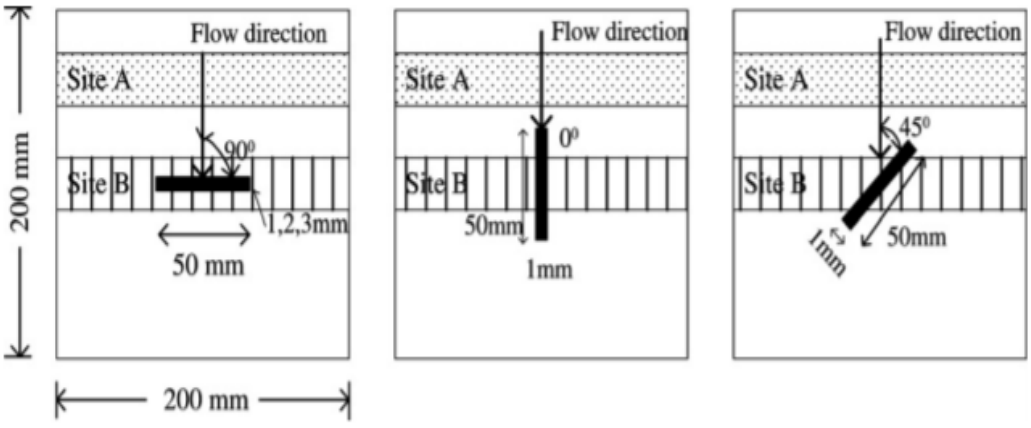

Fig. 3 Crack orientation on concrete surface [36]

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III.EFFECT OF ADDITIVES ON ABRASION RESISTANCE

A. Fly Ash

Tarun R. Naik et.al (1994) investigated the feasibility of high-volume fly ash concrete for abrasion resistance. Concrete mixtures were proportioned to have two levels of cement replacements (50% and 70%) with an ASTM Class C fly ash. The accelerated test method used in this work produced higher amounts of abrasion relative to the ASTM C-944 test method. As expected, depth of wear increased with time of abrasion. Up to 55 minutes of abrasion time during the accelerated testing, the reference mixture containing no fly ash and 50% cement replacement exhibited abrasion depth less than 3 mm. However, when time of abrasion increased to 60 minutes, the fly ash concrete mixtures with 50% and 70% cement replacement showed depth of wear greater than 3 mm.

Rashad et al. (2014) performed abrasion tests on high-volume fly ash (HVFA) concrete that had fine aggregate (FA) replaced at 10% and 20% GGBFS levels. Their findings revealed that HVFA concrete blended with either silica fume (SF) or equal mixtures of SF and GGBFS had higher abrasion resistance, whereas HVFA blended with GGBFS had poorer abrasion resistance.

The research work carried out by Wang et al. (2021) suggests that when compared to plain cement concrete, the use of 5 % by weight of silica fume and 20 % by weight fly ash increased abrasion resistance, compressive and cracking tensile strengths by roughly 4–9% at all ages evaluated. The positive filler and pozzolanic actions of silica fume and fly ash combine to produce these benefits. The combination of 5% silica fume and 20 % fly ash is appropriate for practical usage in concretes for hydraulic project wearing surfaces. It has also been identified that concrete porosity has a negative relationship with both compressive strength and abrasion resistance. The low early strength of fly ash concrete is closely related to its high porosity at an early age. In contrast, silica fume incorporation could greatly improve the pore structure and decrease porosity, resulting in greater compressive strength and abrasion resistance. Horszczaruk et al. (2017) studied the effects of fluidal fly ash on abrasion resistance of underwater repair concrete. The fly ashes from the fluidal beds were included in 20 %, 30 %, 40 %, and 50 % (of the cement mass) of the concretes under investigation. The fluidal fly ashes are by-products of coal combustion in energy plants with fluidal beds. The abrasion resistance and strength of the tested underwater concretes are affected by the fly ash content. The abrasion resistance of concrete rises with age. The fluidal fly ashes slow the development of concrete strength. The concrete with 30 % (in relation to the cement mass) fluidal fly ashes had the best abrasion resistance. Because of the fluidal fly ashes' high pozzolanic qualities, replacing 30% of the cement with fluidal fly ash results in concrete with better compressive strength, abrasion resistance, and workability, allowing for the proper conduct of repair operations under water. The result of the test suggested that it is not recommended to add more than 30% fly ash to the binder mass. Xu et al. (2020) researched the effect of addition of three supplementary cementitious materials, two class F fly ash (referred to as type I and type II) and one ground granulated blast furnace slag, were utilised as admixtures in this study (5, 15, 25 wt. % and 15, 25, 35 wt. % for single and compound adding, respectively). For all concrete mixtures prepared with additional cementitious materials, increasing replacement content resulted in increasing abrasion value. At 7 days, the abrasion values of mixes containing added cementitious elements were higher than the control and standard values of 3.6 kg per m^2. Meanwhile, at 14 days, the mixes containing type I fly ash had lower abrasion mass loss values than the mixes containing various supplemental cementitious materials and the standard value. However, the mixes containing type I fly ash had superior abrasion resistance than the other mixes, and those containing single slag had higher abrasion values than the others. In summary, the results showed that the initial abrasion values of all mixtures were quite close at 7-day age, but specimens with fly ash were clearly larger than those with slag as the age increased from 14-day to 28-day. In this investigation, it was determined that mixtures including fly ash would improve the abrasion resistance of the concrete surface, however slag had a detrimental effect on the abrasion resistance ability. The abrasion resistance and mechanical properties of concrete containing high-volume fly ash (HVFA) were investigated by Siddique et al. (2010). Sand (fine aggregate) was replaced with 35, 45, and 55% of Class F fly ash by mass. The water to cement ratio and the workability of mixtures were maintained constant at 0.46 and 55 ± 5 mm respectively. In accordance with other studies, it was also observed that the depth of wear increased with increase in abrasion time for all mixtures, and decreased with the increase in age of curing. Fig 4. Shows the depth of wear at 60 min of testing for all concrete mixtures and at all curing ages. It was noticed that the depth of wear decreased with increasing curing time for all concrete mixtures, showing improved abrasion resistance. Furthermore, the presence of increasing levels of fly ash improved abrasion resistance by decreasing the depth of wear as the fly ash concentration increased. The depth of wear for mixtures comprising 35, 45, and 55 % fly ash was 2.06, 1.93, and 1.85 mm, respectively, after 28 days of curing and 60 minutes of abrasion, whereas the depth of wear for the control was 2.4 mm. A similar pattern was seen after 91 and 365 days of cure. This demonstrated that given a specific fly ash content, the depth of wear decreased with increasing age, indicating increased abrasion resistance. Enhanced abrasion resistance in the presence of fly ash may be related to a pozzolanic interaction between the fly ash and cement hydration products, which can produce densification of the concrete matrix.

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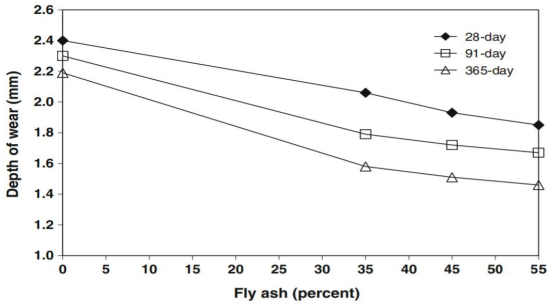

Fig. 4 Depth of wear at 60 min [40]

B. Fibers

Horszczaruk (2009) conducted extensive testing to evaluate the abrasion resistance of HPC to that of high-performance fibre reinforced concrete (HPFRC). In his work, he employed polypropylene and two diameters of steel fibres. The abrasion resistance was determined using the ASTM C1138 – Underwater Method. The results showed that polypropylene fibres gave the largest amount of improvement; little steel fibres also provided improvement, but huge steel fibres had no effect. The abrasive test tends to cut or pull the steel fibres out of the cement matrix. Polypropylene fibres, on the other hand, had greater adherence to the cement matrix and created a more compact, stronger structure. Polypropylene fibres, on the other hand, had better adherence to the cement matrix and created a more compact, stronger structure.

Cheng et al. (2014) also investigated the performance of steel fibre reinforced concrete. The researchers investigated silica fume concrete at various w/cm ratios and with the addition of 0.5 and 1.0 percent steel fibres. They discovered that adding steel fibres when the w/cm ratio was high did not improve abrasion resistance. However, when the researchers tested concrete mixes with lower w/cm ratios, they discovered that after long-term curing, the presence of the fibres gave only a modest improvement in abrasion resistance. This study backs up Horszczaruk's (2009) findings, as adding steel fibres to a mix had little to no influence on the abrasion resistance of concrete.

Sbia et al. (2014) investigated the use of nano- and micro-scale fibres in the optimization of ultra-high-performance concrete (UHPC). Comparing the abrasion resistance of UHPC mixtures was one of the evaluation metrics. The concretes were tested using ASTM C944 by the researchers. While the introduction of nano- and micro-scale fibres improved abrasion performance, there was no clear relationship between the % inclusion of reinforcing particles and the consequent mass loss. The researchers concluded that the addition of nano- and micro-scale fibres has no significant effect on UHPC abrasion resistance.

C. Silica Fume

Hasan et.al (2019) studied the effect of four repair materials to make abrasion resistant concrete for hydraulic structures. Four types of repair materials consisting of portland cement concrete (reference), latex modified repair material, silica fume fiber-reinforced repair material, and fly ash fiber-reinforced repair material were used in this study. The test results depict that standard concrete material is more vulnerable to abrasion than the other repair materials. The silica fume repair material shows the best overall abrasion resistance among the three materials. The silica fume and the randomly distributed micro polymeric fibers in this repair material give the increased resistance where fly ash material has variable results; although, it contains the same polymeric fibers. The abrasion resistance generally improves with age at the time of testing, particularly for the concrete mixture. The test results at 90 days of age of concrete showed higher abrasion rate than it was at 28 days due to the increased sand concentration, again the silica fume repair material exhibited the best abrasion resistance.

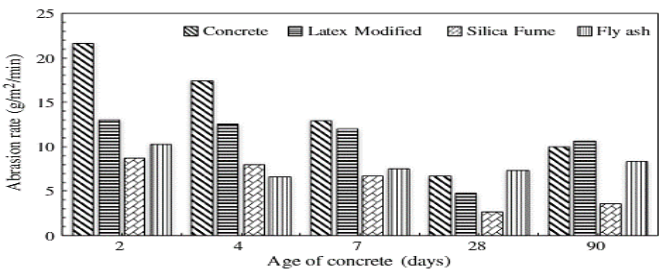

Fig. 4 Abrasion rate at various test ages [19]

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D. Supplementary Cementitious Materials

Rao et al. (2016) studied the abrasion resistance of RCC using GGBFS as a partial replacement for cement. Cement was replaced with GGBFS in pavement mixtures at 10%, 20%, 30%, 40%, 50%, and 60% by weight of cement. Three cylindrical specimens of 300 mm diameter and 100 mm height were employed as testing specimens, and an ASTM C 944 (2012) surface abrasion resistance test was performed. The surface abrasion resistance test findings showed that increasing the GGBFS content increased the surface abrasion resistance by up to 50% for 28 and 90 days.

Özbay et al. (2011) investigated the effect of up to 40% GGBFS substitution with a 20% increment on the abrasion resistance of concretes. They came to the conclusion that the addition of GGBFS in concrete mixtures increased abrasion resistance. However, increasing the GGBFS concentration from 20% to 40% resulted in only moderate improvements in abrasion resistance.

The experimental tests on sand replacement by coal bottom ash (CBA) performed by Singh and Siddique (2016 a, b) indicate that the average depth of wear of concrete integrating low-calcium CBA as sand replacement increases with increasing CBA concentration. According to this study, the abrasion resistance of concrete containing CBA improves with age in the same way that conventional concrete does. The continuing hydration and densification of the concrete microstructure with age could explain the improvement in abrasion resistance. According to this study, the average wear depth of concrete including CBA as sand replacement falls approximately linearly with increasing compressive strength.

Ghafoori and Bucholc (1997) found that when 100% coal bottom ash (CBA) is used as a sand replacement, concrete mixtures comprising 356 and 474 kg/m3 cement content have 47.5 % and 35.2 % higher average depths of wear than control concrete, respectively. However, when compared to control concrete, the concrete mixture including 50% CBA and 50% sand as fine aggregate exhibits approximately 13% greater abrasion resistance.

Aramraks (2006) verifies the hypothesis of decreased abrasion resistance of concrete upon inclusion of coal bottom ash (CBA) as sand substitute, demonstrating that weight loss of concrete containing 100% CBA under abrasion test is 3.29 times that of conventional concrete. According to this study, concrete containing 50% CBA as sand replacement and 2% super plasticizer is the most suitable concrete in terms of abrasion resistance and compressive strength.

The abrasion resistance of concrete containing nano-particles for pavement was experimentally studied by Li et.al (2006). Both nano-TiO2 and nano-SiO2 are employed to be as the additives. The results of abrasion resistance of all specimens at the 28th day demonstrates that the abrasion resistance of concretes containing nano-particles is remarkably improved. The abrasion resistance of concrete containing nano-TiO2 in the amount of 1% by weight of binder increases by 180.7% for the surface index and 173.3% for the side index. Even for the concrete containing nano-TiO2 in the amount of 5% by weight of binder, the abrasion resistance increases by 90.4% for the surface index and 86% for the side index. The similar results can be found for the concrete containing nano-SiO2. The addition of nano-particles can be considered favourable for abrasion resistance of concrete structures.

IV. CONCLUSIONS

Concrete being a brittle material, is vulnerable to damages and one such deterioration of concrete structures is abrasion. Concrete abrasion can be predominant on hydraulic structures, concrete pavements, bridge structures, concrete sleepers, etc. This mechanical wearing can be a catalyst for other forms of deterioration such as cracking and corrosion of reinforcing steel. Degradation of the material condition of concrete structures endangers the structural safety and increases the costs of maintenance and repair. Thus, for safety and economic reasons, it is important to correctly assess the condition of these structures. From the literature review carried, it has been identified that the type and compressive strength of aggregates used, w/c ratio, effect of surface cracks and addition of supplementary materials greatly influence of the performance of concrete structures subjected to abrasion. From the evaluation of effect of types of aggregate it was observed that softer rocks experienced much more abrasive wear than harder rock like granite and trap rock. The concrete sample with low w/cm ratio as much as 0.28 had a denser and stronger cement matrix, and thus had experienced lower abrasion loss. Lowering the w/c and not the aggregate type resulted in higher compressive strength. From the studies made on curing and surface cracks, it was concluded that they have a strong relationship with abrasion. Addition of supplementary materials showed higher abrasion resistance than ordinary concrete specimens. The conclusive outcomes made on the effects of various additives added to make abrasion resistant concrete are as follows:

Abrasion resistance generally improves with age at the time of testing, particularly for the concrete mixture.

- Addition of fly ash can reduce the abrasion in concrete structures to some extend.
- The effective use of fly ash alone for making abrasion resistant concrete is not recommendable. For 50% cement replacement exhibited abrasion depth less than 3 mm for 55 mins and as the time increased, depth of wear was greater than 3 mm.

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- It was observed that compared to plain cement concrete, the use of 5 % by weight of silica fume and 20 % by weight fly ash increased abrasion resistance, compressive and cracking tensile strengths by roughly 4–9% at all ages evaluated.
- Addition of fibres can result in decreased abrasion rates in structures.
- Adding steel fibres with lower w/cm ratios gave a modest improvement in abrasion resistance.
- Carbon fibers can reduce drying shrinkage as well.
- The addition of nano- and micro-scale fibres has no significant effect on UHPC abrasion resistance.
- The addition of silica fume could possibly reduce the abrasion wear in hydraulic structures.
- The surface abrasion resistance test findings showed that increasing the GGBFS content increased the surface abrasion resistance by up to 50% for 28 and 90 days.
- Concrete mixture including 50% Coal Bottom Ash (CBA) and 50% sand as fine aggregate exhibits approximately 13% greater abrasion resistance compared to control specimen.
- The average wear depth of concrete including CBA as sand replacement falls approximately linearly with increasing compressive strength.
- From one of the studies, it has been identified that concrete containing 50% CBA as sand replacement and 2% super plasticizer is the most suitable concrete in terms of abrasion resistance and compressive strength.
- The results of abrasion resistance of all specimens at the 28^{th} day demonstrates that the abrasion resistance of concretes containing nano-particles is remarkably improved.
- The use of nano particles for concrete pavements, especially TiO2 could enhance the abrasion resistance by 90 %.

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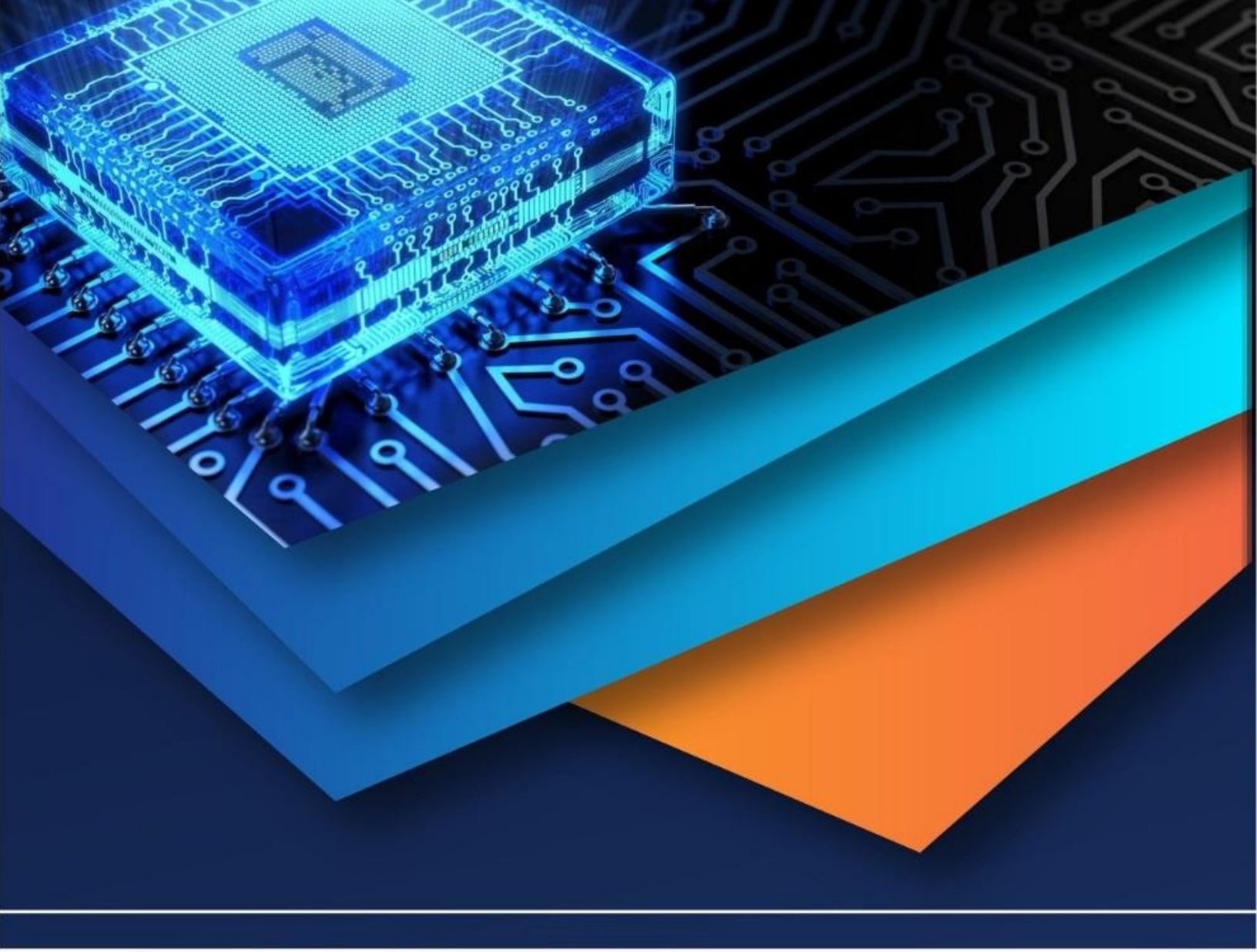

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