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Abrasion Resistance of Manufactured Sand (MS) Concrete and Its Influence Factors

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Abstract. The feasibility of using MS to replace river sand (RS) in concrete pavement has been widely concerned by scholars, however the abrasion resistance of MS concrete pavement serves as a major factor restricting application. Published literature shows huge potential of MS as a replacement of natural fine aggregate. A detailed overview of published literature on property of MS and influencing factors on abrasion resistance of MS concrete is being presented. Regarding the characteristics of MS, the granular shape is characterized by irregular shape, multi-angle and large aspect ratio, the gradation shows a phenomenon of less in the middle and more on both ends, and MS contains high content of stone powder and little mud powder. The influencing factors include mix ratio, lithology, stone powder, admixture, polymer, etc. Among them, stone powder has attracted the attention of many scholars. Nevertheless, few related studies exist at present, source selection and in-depth research merit consideration.

1. Introduction

With the vigorous development of Chinese transportation and hydropower infrastructure, industrial and civil buildings, the demand of sand for construction becomes increasingly larger. Being used as fine aggregate in concrete for centuries, RS has been excessively exploited. In some areas, the supply of natural sand is insufficient because of the high transportation cost. The excessive exploitation of RS endangers river ecology and waterway safety. Therefore, Seeking for RS alternatives has become urgent and MS acting as a substitute for RS in concrete pavement has feasibility.

As the main durability parameter of concrete pavement, abrasion resistance is related to the service life of pavement. In fact, part of the road surface damage doesn't caused by problem of strength, but mostly results from poor abrasion resistance. At present, the abrasion resistance of MS concrete has not attracted enough attention and relevant research is relatively scattered when most scholars pay attention to the abrasion resistance of RS concrete. It is crucial to master the abrasion resistance of MS concrete and improve it in order to achieve good abrasion resistance better than RS concrete, since in many cases abrasion resistance has become the primary problem of promotion and application of MS concrete pavement. Thus there is a need for in-depth review of MS characteristics (e.g., Granular) and influencing factors of the abrasion resistance of MS concrete.



2. Properties of MS

2.1. Particle Shape and Surface Texture

The formation of natural sand usually undergoes long-term effect of natural environment, so it is gradually close to the sphere. Whereas MS derived from rock-cracking is more irregular, angular, and slim. This was confirmed by the study of Huang et al. [1] who used 2D static digital image acquisition technology (DIP) for testing. Huang found that compared with natural sand, MS was more 19.0% in lengthwise ratio, less 11.5% in flatness ratio, more 0.3% in convexity ratio, more 0.2% in fullness ratio, less 19.3% in particle shape parameters, and less 14.8% in sphericity. Therefore, natural sand was more nearly spherical and smoother while MS was thinner, flatter and rougher. The findings of Shen et al. [2] in line with the above differed from parent rock types which were more extensive. They found that the roundness and Length-width ratio values of all the MS were higher than those of RS. Among them, the Length-width ratio values of Metamorphic siltstone MS were higher than those others while sandstone MS had the highest roundness.

Production equipment makes a big difference on the shape of MS. During production process of MS, taking advantage of impact crusher, rod mill, etc. could effectively reduce the aspect ratio of MS and improve angularity [3]. GonçAlves et al. [4] showed that crusher (impact crushing, cone crushing) had an effect on the shape of MS. Compared with RS, MS produced by cone crushing presented more irregular form and particles of it had the smallest roundness, the highest aspect ratio and angularity.

2.2. Gradation

Due to the limitations of the production machinery, there generally exists a big difference on gradation between MS and RS. From the statistical analysis of gradation of MS, the particles of it larger than 2.36mm or less than 0.15mm may be more than normal and the content of stone powder (less than 0.075mm) can be as high as 15% or even higher [5], which means a phenomenon of less in the middle and more on both ends.

Since MS is generally manufactured by crushing, the particle distribution of it, under the same crushing condition, could be determined by different lithology. Meanwhile, manufacturing process plays a part in gradation without regard to lithology. Comparing the gradation curves of quartz MS, basalt MS and RS, Tang et al. [6] found that the quartz MS had a more optimized gradation distribution and lower porosity, which was conducive to the formation of close packing, increase of density. Zhou et al. [7] showed that the new dry-process sand production could significantly improve the phenomenon of less in the middle and more on both ends. In the case of new dry-process sand production, the content of basalt and granite particle larger than 2.36mm was much higher than that of limestone, while particle less than 0.15mm was just the opposite, which meant that lithology had a certain effect on gradation of MS.

2.3. Characteristics of Stone Powder

After mechanically crushing and sieving, MS is born. In this production process, a certain amount of stone powder less than 0.075 mm is inevitably produced, which is one of the most obvious differences between MS and RS. As a by-product of production process, stone powder has the same physical and chemical properties as parent rock, and the mineral composition is consistent with parent rock, too.

Dong et al. [8] observed the microscopic morphology of mud powder and lime stone powder, which showed that the edge of mud powder particles was not obvious, slightly round and most of them were sticky. In terms of stone powder, it was mostly blocky and slightly angular, close to the particle morphology of cement or slag. For different lithological stone powders, Li et al. [9] showed that the limestone powder was mainly composed of calcium minerals, containing high content of MgO. Besides the main components of gneiss powder and granite powder were SiO₂ and Al₂O₃. The particles of gneiss powder had many layered, flaky structures and rough pore structures. As for basalt powder and limestone powder, the surface of both particles was smooth, and granite powder had many layered debris.

2.4. Mud Content (MB Value)

In the production process of MS, the product will inevitably be brought into part of mud, resulting in a certain amount of mud powder (i.e. clay) in MS. Nevertheless, the presence of clay can deteriorate the workability of concrete mixture, hinder the normal hydration reaction of cement, decrease the chloride ion penetration resistance and crack resistance of concrete gradually [10]. To this end, national standard in China adopts the methylene blue (MB) value to determine the content of clay in MS and limit it.

Clay minerals (i.e. generally aqueous aluminium silicates, magnesium silicates and iron silicates) are commonly composed of SiO_4 tetrahedrons and AlO_6 octahedrons forming two-dimensional layered structure [11]. When impurities are substituted for Si (Al) and Al (Mg), other ions such as Ca, Na, K, etc. are filled between the layers to maintain the charge balance, and such a structure imparts strong adsorption to mud powder [12].

As an important indicator for detecting clay content in MS, MB value is affected by various factors. Hu et al. [13] showed that mud powder content in MS had a great influence on MB value apparently and the two were linear relation, which was consistent with the finding of Li et al. [14]. In addition, they found that when clay content in MS kept constant, MB value tended to increase with increasing liquid limit W_L , plastic limit W_P and plasticity index I_P . Dong et al. [15] found that MB values of five lithologic MS were not much different, while Shen et al. [16] believed that these different values represented the background values of different lithological MS, which affected the accuracy of MB value. Moreover, Dong et al. [15] observed that the effect of different content of stone powder on MB value of MS was also small and different sieving approaches (dry sieve and water sieve) affected MB value.

2.5. Brief Summary of Characteristics of MS

Through the comprehensive description of the above-mentioned, the relevant characteristics of MS are briefly summarized.

- Particle shape and surface texture: Irregular, multi-angled, rough surface, large aspect ratio.
- Gradation: Less in the middle and more on both ends, affected by lithology and manufactured process.
- Characteristics of stone powder: High content, the physicochemical properties are consistent with parent rock, and the microscopic morphology is affected by lithology.
- Mud content (MB value): Variable content, harmful to concrete performance. The main influencing factor of MB value is mud powder content.

3. Factors Affecting Abrasion Resistance of MS Concrete

3.1. Effect of Mix Proportion

3.1.1. Effect of Water-Cement Ratio

Figure 1 depicts influence of water-cement ratio on abrasion resistance of MS concrete by various researches.

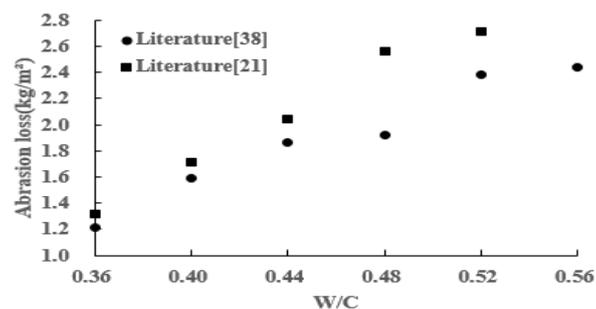


Figure 1. Influence of water-cement ratio on abrasion resistance of MS concrete by various researches.

Wang et al. [17] studied the effect of different water-cement ratios on abrasion resistance of MS and natural sand concrete, which showed that the reduction of water-cement ratio increased the compressive strength of both concrete and reduced abrasion value. As a matter of fact, the reduction of water-cement ratio results in the increase of amount of cementing material, reduction of water consumption, the matrix densely packed and the ITZ improved, which makes the strength of concrete increase and the abrasion value lowered. Ke et al. [34] also reached a consistent conclusion at this point.

3.1.2. Effect of Sand Rate

Ke et al. [18] studied the effect of sand rate on the mechanical properties of MS concrete. The result showed that with increase of sand rate, the compressive strength of concrete didn't change much but abrasion rate increased. In line with Ke, Wang et al. [17] suggested that with increase of sand rate, the slurry content in concrete increased, the amount of coarse aggregate decreased, and the abrasion value of concrete increased. Whereas it should be noted that too small a sand ratio will be a hazard to the workability of fresh concrete, reduce its compactness, and deteriorate the internal pore structure of concrete, which is not conducive to improvement of abrasion resistance and strength of concrete.

3.2. Effect of Lithology

Li et al. [19] studied the influence of lithology on the abrasion resistance of MS concrete, which showed that abrasion resistance of four kinds of MS (i.e. MLS, MQS, MGS and MBS representing MS from limestone, quartzite, granite and basalt, respectively) concrete was better than that of RS concrete, and MBS concrete had the best abrasion resistance. He further analysed and found that SiO_2 content in limestone was the smallest, but in terms of abrasion resistance, MLS concrete was better than RS concrete with high SiO_2 content, which might be caused by the small roughness and the largest crushing value of RS. The abrasion resistance of MQS concrete with the highest SiO_2 content and the smallest crushing value was worse than that of MBS concrete because of its small roughness (MBS had the largest roughness) which affected the bond between aggregate and slurry. Li et al. [19] believed that the SiO_2 content, crushing value and roughness of MS played a coupling role in abrasion resistance of concrete.

3.3. Effect of Stone Powder

Figure 2 depicts influence of stone powder content on abrasion resistance of MS concrete by various researches.

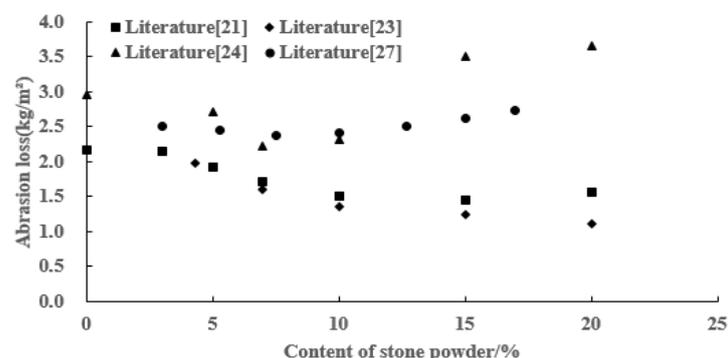


Figure 2. Influence of stone powder content on abrasion resistance of MS concrete by various researches.

Li et al. [20] showed that 7% and 10% stone powder in limestone MS became the optimal content for attaining the best abrasion resistance. However abrasion loss increased significantly when the content of stone powder exceeded 10%. Singh et al. [21] found that Granite Cutting Waste (GCW) as a partial replacement for natural sand in concrete achieved best abrasion resistance when replacement increased up to 30%, which was ascribed to the fact that stone powder in GCW could fill the pores to

form a denser matrix. Shen et al. [22] and Liu et al. [23] agreed on the filling effect of stone powder, but excess content of stone powder resulted in a downward trend in abrasion resistance. Wang [17] believed this case caused by a large amount of free stone powder existing in the ITZ, which was not conducive to improvement of performance of ITZ and led to the deterioration of abrasion resistance of concrete.

The role of stone powder is not only in physics, but in chemistry possibly. Li et al. [19] found that stone powder in concrete presented nucleation effect, which led to acceleration of hydration process, improved micro-particles accumulation and pore structure of ITZ, which meant increase of abrasion resistance of concrete. Yang et al. [25] showed that most of the limestone powder was inactive. However he observed that the area of characteristic peak of $\text{Ca}(\text{OH})_2$ for sample with 15% limestone powder (LP) was larger than that contained no LP, indicating an acceleration of calcium silica, for which Bonavett et al. [24] also gave some evidence. At the same time, the reaction of CaCO_3 in limestone with hydrated calcium aluminate to form calcium carboaluminate might be responsible for that the content of hydrated calcium aluminate in sample with 15% LP was lower than that contained no any LP. Actually most scholars have reached a consensus that CaCO_3 particles in stone powder have an active effect [26-29].

The above studies are all conducted on limestone stone powder, which may not be the case for other lithological stone powders. Yang et al. [30] studied the effect of diabase stone powder on cement hydration products. It was found by SEM that no hydrates were formed on the surface of diabase stone powder, and only micro-aggregate filling effect was observed. In addition, it served as a fulcrum for the development of hydrates.

Table 1 summarizes the effect of MS stone powder.

Table 1. Influence of MS stone powder on abrasion resistance of MS concrete.

Advantage	<p>The main function of the stone powder is the filling effect, which can increase the compactness of the concrete and improve the pore structure of the worn area.</p> <p>The nucleation effect of stone powder can provide a nucleation site for cement hydration products and accelerate the hydration process.</p> <p>Some CaCO_3 particles in the stone powder have an active effect. When CaCO_3 reacts with C3A in cement to form a carbon aluminate, it also improves the surface state of the stone powder particles, which is beneficial to the improvement of bond strength between stone powder particles and hydration product.</p>
Disadvantage	<p>The low content of stone powder has an adverse effect on the grading, and the capillary pores are not sufficiently filled, resulting in poor compactness of concrete.</p> <p>Too much stone powder will cause a large amount of free stone powder in ITZ. The increase of the powder composition (i.e. easy-grinding component) in concrete will weaken interfacial adhesion between slurry and aggregate.</p>

3.4. Effect of Admixtures

Zhao [31] showed that when the content of fly ash increased from 9% to 15%, the abrasion loss of MS concrete appeared a fluctuation trend indicating the indistinctive effect of fly ash on the abrasion resistance of MS concrete. Li et al. [37] showed that under the same strength, replacing cement with 15% fly ash or limestone powder didn't affect the abrasion resistance of MS concrete. Rao et al. [32] saw that with increase content of ground blast furnace slag (GGBS) from 0% to 60%, Cantabro loss increased at the age of 3 days and decreased at the ages of 7, 28 and 90 days. They believed this was because of that the pozzolanic reaction of GGBS was weaker in the early stage and then increased with time. Similarly, Rao et al. [33] found that slow pozzolanic reaction of Fly Ash gave rise to poor abrasion resistance of MS roller compacted concrete.

3.5. Other Influencing Factors

Ke et al. [34] studied the effect of MS fineness modulus on the abrasion resistance of MS concrete. The result showed that abrasion loss increased with decrease of fineness modulus and Ke believed

abrasion resistance of concrete related to aggregate size. The bigger the MS, the larger the surface area and the bond strength between slurry and sand, particles were relatively less likely to fall off during wear process.

Qing [35] chose two polymers (i.e. polyacrylate emulsion and carboxylated styrene butadiene latex), blending into MS concrete with poly-cement ratio of 1%, 3% and 5%. Compared with ordinary concrete, as the poly-cement ratio increased, abrasion loss of both Polymer MS concrete reduced, which showed that reducing the brittleness and improving the flexibility and deformability of concrete contributed to the improvement of abrasion resistance of the MS concrete.

Li et al. [19] studied the effect of Los Angeles abrasion value of aggregate on strength and abrasion resistance of MS concrete. The result showed that Los Angeles abrasion was not related to the strength of concrete, but tightly linked to abrasion resistance of concrete. The smaller the Los Angeles abrasion value of the crushed stone aimed at producing MS, the smaller the abrasion loss of concrete, demonstrating that fine aggregate also involved in the wear process of concrete. Similarly, Kılıç et al. [36] believed that the abrasion resistance of concrete was associated with the Los Angeles abrasion value of aggregates.

Rao et al. [32] saw that concrete strength and abrasion loss existed negative relation. And Rao [33] also found that the regression coefficients for compressive strength and abrasion loss was closer to 1 than the flexural strength, indicating a stronger relationship particularly. Li et al. [19] revealed that limestone MS concrete owned relatively higher compressive strength but worse abrasion resistance, while quartzite MS concrete owned relatively lower compressive strength but better abrasion resistance, which suggested that the abrasion resistance of concrete depended on its compressive strength lamely.

3.6. Improvements

In view of various influencing factors mentioned above, the corresponding measures to improve abrasion resistance of MS concrete pavement are summarized, which are listed in Table 2.

Table 2. Measures to improve abrasion resistance of MS concrete pavement.

Influence factors		Measures to improve abrasion resistance
Mix	Water-cement ratio	Reduce water-cement ratio appropriately after meeting the requirements of strength and durability.
	Sand rate	Control sand ratio after ensuring the workability and mechanical properties of concrete in order to achieve the optimum abrasion resistance.
Lithology	Stone powder	Adopt suitable parent rock to ensure good abrasion resistance of concrete.
	Stone powder	Control the stone powder content of different lithology in corresponding optimal range.
	Admixtures	Utilize better admixtures, such as blast furnace slag that can change the CH content and improve pore structure, determine the optimal content.
Other factors	Fineness modulus	Use MS with large fineness modulus to increase the bond strength between sand and slurry.
	Polymers	Incorporate an appropriate amount of polymer to improve flexibility and abrasion resistance of concrete.
	Los Angeles abrasion value of aggregate	Use aggregates and gravel with less Los Angeles abrasion loss.
	Strength of concrete	Evaluate and control abrasion resistance through strength of concrete.

4. Conclusions

Reviewing characteristics of MS and influencing factors of abrasion resistance of MS concrete pavement, some conclusions can be drawn:

- The shape of MS is characterized by irregular shapes, multi-angles and high aspect ratios. It shows a phenomenon of more on two ends and less in the middle in terms of gradation, containing plenty of stone powder and a small amount of mud. The physical and chemical properties of stone powder are consistent with parent rock. The mud powder harmful to the performance of concrete has the greatest impact on MB value.
- The influencing factors include mix ratio, lithology, stone powder, admixture, polymer, etc. Among them, stone powder has attracted the attention of many scholars. Nonetheless, in terms of abrasion resistance studies, most of them now are carried out on limestone MS. Therefore, it is possible to consider the MS of different material sources, then compare and analyse to explore the abrasion mechanism of MS concrete.
- At present, there is little systematic and in-depth research on abrasion resistance of MS concrete. Current research is usually limited to macroscopic level and abrasion resistance of concrete is usually measured by abrasion loss or abrasion depth of concrete in a certain period of time lack of research on micro and sub-micro scale. Therefore, in order to comprehensively analyse abrasion mechanism, development law and influencing factors of MS concrete, it is necessary to adopt SEM, AFM, microhardness and other means.

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