Utilization of Pozzolanic Material to Improve the Mechanical Properties of Crumb Rubber Concrete as Rigid Pavement – A Review

H Abdurrahman¹, N Rizaldi², M F Wijaya¹, M Olivia¹, and G Wibisono¹

¹Department of Civil Engineering, Faculty of Engineering, Universitas Riau, Pekanbaru 28293 Indonesia
²Department of Civil Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132 Indonesia
g.wibisono@eng.unri.ac.id

Abstract. Over the last few decades, waste tires have piled to an explicitly large number, posing a serious environmental threat in the worldwide. By reusing waste tires in concrete mixes in the form of crumb rubber, it was reported that crumb rubber improved concrete energy absorption, delayed the deformation time, and prevented sudden failure, which could enhance the rigid pavement performance. However, crumb rubber tends to reduce concrete strength primarily because of a lack of bonding between the smooth rubber surfaces and cement paste, resulting in a tiny gap in the concrete ITZ. The decrease in strength caused by crumb rubber can be solved by utilizing pozzolanic materials such as nano-silica, fly ash, and rice husk ash as additive materials or partial replacement of cement to improve the concrete pore structure through pozzolanic reaction and to enhance the adhesion between crumb rubber and cement. It was shown that pozzolanic materials, as mentioned above, managed to improve the strength of crumb rubber concrete with nano-silica showed the best effectiveness compared to fly ash and rice husk ash in creating high-strength crumb rubber concrete for application as a rigid pavement material.

1. Introduction
Concrete pavement, or commonly called rigid pavement, is a road construction built of a concrete slab resting on a stabilized base course and subgrade soil. Compared to asphalt pavement, concrete pavement has a higher modulus of elasticity which makes it able to withstand loads and distribute them to a wider area below. Owing to this characteristic, concrete pavements are commonly used in soils with low bearing capacity. Furthermore, in terms of economic and sustainability, concrete has more advantages than asphalt because of its durability against repeated flooding and surface water, longer life span, and lower maintenance cost. However, owing to its brittle properties, concrete cannot bear high tensile stress, thus allowing fine crack to occur on the concrete surfaces and increasing the possibility of deterioration. Materials such as crumb rubber from waste tires can be added to improve ductility, delay cracks generation and enhance the elastic properties of concrete [1].

Over the last several decades, waste tires have piled to an explicitly large number, posing a serious environmental threat in the worldwide. According to the Central Bureau of Statistics (BPS), in 2019,
the number of vehicles in Indonesia increased by 17 million in 2017 [2]. This number is predicted to continue to increase, leading to a significant environmental concern regarding waste tire management. Burning them is the shortest way to get rid of them, but this option causes several issues and pollution due to smoke, which can even cause severe respiratory diseases. On the other hand, leaving them to pile up on empty land will indirectly create other issues as they will turn into a habitat for disease-carrying insects and animals. Hence, it is necessary to look for an alternative solution to overcome this problem by reusing waste tires in concrete mixes in the form of crumb rubber.

Crumb rubber (CR) is a type of waste tire produced by milling and crushing the scrap tire into smaller and homogenous granules with sizes ranging from 0.075 mm (no.200 sieve) to 4.75 mm (no.4 sieve) [3]. Researchers have conducted various studies have investigate the effect of CR in concrete as an additive material or the partial replacement of fine aggregates. Because CR has a lower mass per volume compared to fine aggregate, ranging from 500 kg/m$^3$ to 1200 kg/m$^3$ [4-8], partial substitution of fine aggregates with CR in concrete is usually done by the volume percentage of fine aggregates. According to reports, CR tends to reduce concrete strength primarily due to an inadequacy of bonding between the soft surfaces rubber and cement paste, thus forming a microscopic gap in the concrete ITZ, causing cracks to form quickly around the rubber particles during loading [9-16]. Other researchers have reported that concrete containing CR has a higher resistance under tensile and flexural loads. CR has been reported to improve concrete energy absorption, delay the deformation time, and prevent sudden failure [17-18]. These results show that CR can improve the rigid pavement performance against tensile loads. However, the decrease in strength caused by CR must first be solved.

Pozzolanic materials with high silica content were utilized as an additive or partial substitution of cement to refine the concrete pore structure through pozzolanic reaction in the form of Calcium Silicate Hydrate (CSH) gel to enhance the adhesion between CR and cement and mitigate the loss in strength caused by CR. In this review paper, pozzolanic materials are limited to nano-silica (NS), fly ash (FA), and rice husk ash (RHA). This paper also shows the effect of incorporating the three pozzolanic materials on the mechanical behaviour of CR concrete, such as compressive strength, splitting tensile strength, and flexural strength, and investigates the results with the strength requirement of rigid pavement provided by AASHTO 1993, Austroads 2017, and Bina Marga 2018.

2. Crumb rubber concrete

Researchers have investigated the fresh and hardened characteristics of concrete that contains CR for several years. Owing to its elastic properties, CR is mostly used as a partial substitute for fine aggregates as filler to improve the ductility of concrete. However, due to its smooth surfaces, the hardened cement paste in concrete hardly bonds with CR, thus creating pores and voids that lead to the strength reduction of concrete. Researchers have performed various treatments to strengthen the adhesion between CR and cement, such as soaking the CR with water, limestone powder, or NaOH. Utilizing pozzolanic materials such as nano-silica, fly ash, and rice husk ash can also help rubber particles adhere properly with cement paste and refine the pore structure in CR concrete.

Aiello and Leuzzi [19] studied concrete's fresh and hardened properties with fine aggregates replaced by rubber at 15% to 75%. According to the findings, the compressive and flexural strength had decreased by 37.1% and 7.30%, respectively, at the replacement of fine aggregates at 75%. However, the post-cracking behaviour showed good energy absorption and ductility compared to plain concrete.

An investigation of the effect of various w/c ratios (0.4, 0.45, 0.5) and the replacement of fine aggregates with CR up to 20% with an increment of 2.5% has been done by Thomas et al. [20]. The study showed a decrease in concrete strength when the percentage of CR increased at all w/c ratios. However, the researcher concluded that CR might be used to partially replace fine aggregates up to 7.5% without causing a considerable reduction in concrete strength. Therefore, it was recommended for pavement, structural, and non-structural construction.
Mohammadi et al. [21] applied a water-soaking method to optimize the bonding of their rubber with the cement paste. The main issue with adding rubber directly to the concrete mix is that rubber particles tend to trap air bubbles that attach to them due to the water-repellent characteristic of rubber (hydrophobic). Therefore, the idea was to submerge the rubber in water for 24 hours before concrete mixing to release the entrapped air in the rubber. As a result, it was found that using this method resulted in more uniform rubber particle distribution, less entrapped air, and the concrete had compressive strength higher than rubber concrete without treatment by 22%.

Onuaguluchi [22] had a different method in treating the CR. From the study, the CR was pre-coated with water and limestone powder to 5.25% and 15% of the rubber’s weight, respectively. The treated CR was then air-dried for a day before being kept in a plastic bag at ambient temperature for three months. The study found that concrete with coated CR had a notable increase in strength compared to non-coated CR. Sgobba [23] treated the rubber with saturated NaOH 2% solvent solution for 20 minutes. However, the result revealed a decline in concrete compressive strength compared to untreated CR concrete.

3. Utilization of pozzolan in crumb rubber concrete

3.1. Nano-silica

Nano-silica (NS) is the most frequently utilized nanomaterial in concrete due to its significant pozzolanic reaction and pore-filling capabilities. As a result, it can develop high-strength and durable concrete. Furthermore, the cement hydration can be accelerated by the inclusion of nano-silica. By forming a reaction between \( \text{H}_2\text{SiO}_3 \) and \( \text{Ca}^2+ \), nano-silica produces additional CSH gel in the concrete mixture, filling the void in the cement matrix, resulting in denser concrete [24]. NS’s physical and chemical properties vary from one another, with an average particle size between 10-25 nm, SiO2 concentration between 92% to 99.8%, and an average surface area of 75-160 m2/g [25-27].

Previous researches have shown the influence of nano-silica on the performance of concrete. For example, Amin and El-Hassan [28] reported that partially replacing cement with nano-silica up to 3% improved the compressive strength of concrete by 21%, splitting tensile strength by 44%, and modulus of rupture by 23%. Other researchers reported similar findings, claiming that nano-silica could improve concrete strength at early and long ages due to CSH gel formation from the pozzolanic reaction was quicker when nano-silica was added [24, 29]. Furthermore, incorporating nano-silica in high volume fly ash concrete (HVFA) could increase the early age strength of concrete. This is because nano-silica has a finer particle size than fly ash, which can accelerate the pozzolanic reactivity from an early age more than fly ash [25, 27, 30]. However, due to its high reactivity, nano-silica absorbs some part of mixing water in concrete mixes, thus resulting in the reduction in workability. Hence, a superplasticizer was usually added to maintain the concrete workability.

Studies regarding the impact of nano-silica on the mechanical strength of CR concrete have been done [26, 27]. For instance, a roller-compact concrete has been developed by Mohammed and Adamu [26] substituting fine aggregates with CR up to 30% by volume and added nano-silica up to 3% by cement weight. The results of the concrete strength test at the age of 28 days are presented in Table 1 below. Fine aggregates replacement with 10% CR improved the concrete strength, but a CR increment of more than 10% would reduce the concrete strength. According to [26], the increased width of the ITZ between the cement paste and the CR leads to weak adhesion between them, resulting in micro fractures and early CR concrete failure. The strength of concrete then increases with the inclusion of 1% and 2% NS but declines at 3%. Thus, the maximum strength was gained at the replacement of fine aggregates by 10% CR and NS by 1%. However, all the mixes combination had strength that complies with rigid pavement minimum strength.

The influence of CR and NS on the durability of HVFA concrete is also investigated by Adamu et al. [27]. Although using the same materials and w/b ratio with [26], the study showed different outcomes. The HVFA concrete started to lose its strength due to replacing fine aggregates by 10% CR and continue to decrease at replacement by 30%. Besides the weak bonding caused by CR, the slower
pozzolanic reaction of fly ash at initial stage, which decelerate the formation of CSH, is also the primary reason for the strength reduction. The inclusion of up to 2% nano-silica to HVFA concrete, on the other hand, was effective in initiating the pozzolanic activity of fly ash at initial stage, minimizing some of the strength drop caused by CR, and so enhancing concrete strength. Based on the results, as shown in Table 1, replacing fine aggregate with CR up to 20% by volume and adding NS up to 2% by cement weight succeeded in improving HVFA concrete strength and achieving the required strength for rigid pavement material.

### Table 1. Mechanical properties of CR concrete with nano-silica at the ages of 28 days.

| Binder | W/b Ratio | CR (%) | NS (%) | CS (MPa) | STS (MPa) | FS (MPa) | Rigid Pavement Minimum Strength | Ref |
|--------|-----------|--------|--------|----------|----------|---------|-----------------------------|-----|
| Cement (kg) | Fly Ash (kg) |        |        |          |          |         | CS (35 MPa) | FS (4.5 MPa) |
| 268.69 | -         | 0.37   | 0      | 52.0     | 4.7      | 5.6     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 10     | 60.0     | 5.5      | 7.8     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 10     | 76.0     | 6.1      | 8.6     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 10     | 68.0     | 5.8      | 7.5     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 10     | 50.0     | 4.8      | 4.8     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 20     | 45.0     | 4.0      | 6.2     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 20     | 55.0     | 5.0      | 6.8     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 20     | 52.0     | 4.4      | 6.0     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 20     | 54.0     | 5.0      | 5.2     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 30     | 42.0     | 3.3      | 5.8     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 30     | 46.0     | 4.2      | 6.1     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 30     | 44.0     | 4.1      | 6.0     | ✓              | ✓   |
| 268.69 | -         | 0.37   | 30     | 30.0     | 3.2      | 5.0     | -              | ✓   |
| 134.58 | 102.54    | 0.37   | 0      | 46.0     | 3.7      | 5.0     | ✓              | ✓   |
| 134.58 | 102.54    | 0.37   | 10     | 38.0     | 3.5      | 4.3     | ✓              | -   |
| 134.58 | 102.54    | 0.37   | 10     | 54.0     | 4.8      | 5.3     | ✓              | ✓   |
| 134.58 | 102.54    | 0.37   | 10     | 44.0     | 4.2      | 5.0     | ✓              | ✓   |
| 134.58 | 102.54    | 0.37   | 10     | 36.0     | 3.4      | 4.1     | ✓              | -   |
| 134.58 | 102.54    | 0.37   | 20     | 35.0     | 3.7      | 4.4     | ✓              | -   |
| 134.58 | 102.54    | 0.37   | 20     | 42.0     | 4.2      | 6.0     | ✓              | ✓   |
| 134.58 | 102.54    | 0.37   | 20     | 38.0     | 3.8      | 5.3     | ✓              | ✓   |
| 134.58 | 102.54    | 0.37   | 20     | 30.0     | 3.9      | 4.1     | -              | -   |
| 134.58 | 102.54    | 0.37   | 30     | 32.0     | 3.7      | 4.7     | ✓              | -   |
| 134.58 | 102.54    | 0.37   | 30     | 28.0     | 3.5      | 4.1     | -              | -   |

#### 3.2. Fly ash

A high-silica industrial waste product produced by coal-fired power stations, known as fly ash, is frequently utilized to replace cement in concrete to improve mechanical properties and durability, particularly at later ages. Also, using fly ash as supplementary cementitious material in concrete provides environmental benefits by lowering CO₂ emissions from the cement manufacturing process. According to ASTM C618, the classification of fly ash is divided into two categories, F and C. Class F fly ash is primarily composed from the combustion of anthracite or bituminous coal, but it can also come from sub-bituminous coal and lignite and it contains more than 70% SiO₂, Al₂O₃, and Fe₂O₃. Meanwhile, class C fly ash is mainly generated by blazing lignite or sub-bituminous coal and may also be made from anthracite or bituminous coal with a total percentage of SiO₂, Al₂O₃, and Fe₂O₃ ranging from 50% to 70%.
Several researchers have done the study regarding the mechanical performance of fly ash concrete. For instance, Huang et al. [31] reported that partially replacing cement with fly ash up to 40% could increase concrete's compressive and flexural strength since the age of 28 days and continually increased to 365 days. A similar result was also reported by Harison et al. [32]. In addition, it was observed that concrete with up to 20% fly ash substitution had higher compressive strength than normal concrete.

| Binder | W/b Ratio | CR (%) | FA (%) | CS (MPa) | STS (MPa) | FS (MPa) | Rigid Pavement Minimum Strength |
|--------|-----------|--------|--------|----------|-----------|----------|---------------------------------|
| n/a    | 0.27      | -      | 62     | 34.6     | -         | 10.59    | -                               |
| n/a    | 0.27      | -      | 69     | 28.4     | -         | 9.60     | -                               |
| n/a    | 0.27      | -      | 75     | 20.6     | -         | 8.00     | -                               |
| n/a    | 0.27      | 20     | 55     | 20.3     | -         | 7.40     | -                               |
| n/a    | 0.27      | 20     | 62     | 17.3     | -         | 7.62     | -                               |

Table 2. Mechanical properties of CR concrete with fly ash at the ages of 28 days.

The performance of CR concrete incorporating fly ash has also been investigated by many researchers, as shown in Table 2 below [33-35]. Noorvand et al. [33] studied the impact of replacing 20% of the sand with CR and up to 75% of the cement with fly ash on the mechanical properties of concrete. The results showed that as the percentage of cement replaced by fly ash increased, the
compressive and flexural strength of concrete decreased, both for normal and CR concrete. The high fly ash to cement ratio was suspected of obstructing the fly ash secondary hydration. Also, the strength reduction could be affected by low stiffness behaviour from CR and weak bonding with cement matrix. However, it was reported that adding more fly ash to concrete strengthened the ductility of normal concrete and CR concrete. It was observed that the bending capacity grew up to 41% for FA concrete and 151% for FA-CR concrete.

Najmi et al. [34] examined the hardened characteristics of concrete with CR replacing fine aggregates in the range of 0%-20% and fly ash substituted cement by 0%-30%. Overall, the strength of CR concrete is found to significantly reduce as the quantity of CR increased, with 5% CR showing the lowest decline in strength. The strength of CR concrete is improved by substituting 10% of the cement with fly ash; however, it was still lower than normal concrete strength. The loss in strength was mainly due to the formation of void caused by the lower density of CR, thus quicken early crack propagation at the ITZ.

Fauzan et al. [35] also investigated the influence of CR on the mechanical properties of fly ash concrete. CR replaced fine aggregates as much as 5%, 10%, 15%, and 20% of the volume, while fly ash replaced cement by 15%. The study found that the strength of both normal and FA concrete dropped gradually as the level of CR substitution went up. This was owing to the CR lower stiffness, as well as a lack of adequate adhesion between rubber and cement pastes, resulting in cracks due to non-uniform stress distribution. However, it can be seen that incorporating fly ash in CR concrete slightly improved the strength of the concrete at all CR variations. According to the author, the concrete without CR showed a brittle failure under load, whereas the CR concrete did not. Also, the cracks that developed were smaller than normal concrete, indicating that CR concrete had better crack resistance than normal concrete.

From the researches mentioned above, the optimum composition of CR and FA concrete that meets the requirements of rigid pavement strength has not been seen, so researchers must carry out further investigations related to these materials.

3.3. Rice husk ash
Rice husk ash (RHA) has been studied as a greatly reactive pozzolanic substance in concrete for decades. RHA possesses a significant silica concentration, ranging from 90% to 95%, in the form of non-crystalline or amorphous silica and has been utilized as a pozzolanic compound in concrete for various purposes, including enhance concrete strength and reliability, give environmental benefits related to waste management, and reduce CO₂ emissions from cement production [36-38].

Several studies have been done to examine the impact of RHA on the strength and durability of concrete. For example, Madandoust et al. [39] found that the RHA concrete had lower strength than normal concrete in all cement replacement levels at 28 days but showed a higher strength after 270 days. This finding indicated that the strength gain for RHA concrete is lower than ordinary concrete at the early age due to RHA's pozzolanic reaction is more significant at later ages than at earlier ages. Furthermore, Chopra et al. [40] studied the strength of self-compact concrete containing RHA. It was reported that with an increase in RHA percentage from 0% to 20%, the concrete strength improved at all ages due to pore filling ability through the pozzolanic reaction from RHA result in a denser concrete.

The utilization of RHA in CR concrete has been investigated through many studies, as shown in Table 3. For example, Isberto et al. [41] analyzed the influence of RHA and CR on the strength and microstructure of concrete. In this study, the RHA content was maintained at 10%, replacing cement by weight, and CR was varied from 0% to 10% replacing fine aggregates in concrete mixes. Test results showed that adding CR by 5% decreased the compressive capacity of concrete from 28.98 MPa to 25.54 MPa due to the lack of bonding between CR surface and cement paste. However, after incorporating RHA in CR concrete, the loss in concrete strength could be minimized and showed higher strength than CR concrete without RHA at the same percentage of CR. RHA generated the
CSH gel through pozzolanic reaction and filled the gap between CR and cement matrix, thus improving the concrete strength.

Abdurrahman et al. [42] studied the mechanical characteristics of concrete that had various ranges of w/c ratio, CR, and RHA. This study incorporated CR and RHA in concrete as additive materials without replacing any natural ingredients. It was reported that the compressive strength of concrete went up as the w/c decreased. CR addition in the mix until a certain number would enhance the compressive strength of concrete but then decline observed after the peak strength. Furthermore, the flexural strength test showed continuous growth with an increase of CR content up to 12.5% because CR improved concrete's ductility and prevented brittle failure during loading. In addition, RHA also contributed to enhancing the concrete strength by producing CSH gel through pozzolanic reaction, which generates a denser concrete and improves its strength.

Similar findings were also reported by Brari et al. [43]. The concrete strength dropped considerably when CR replaced natural sand in concrete, and the inclusion of RHA up to 4% slightly improved the concrete strength, although still lower than normal concrete. Based on these studies, to be applied as rigid pavement material, the addition of CR by 5% and RHA by 10%, as mentioned by [43], can achieve the required strength. However, further investigation of CR RHA concrete as rigid pavement material is still needed.

### Table 3. Mechanical properties of CR concrete with rice husk ash at the ages of 28 days.

| Binder | W/b Ratio | CR (%) | RHA (%) | CS (MPa) | STS (MPa) | FS (MPa) | Rigid Pavement Minimum Strength | Ref |
|--------|-----------|--------|---------|----------|-----------|----------|---------------------------------|-----|
| Cement (kg) | Rice Husk Ash (kg) | 0.5 | 5.0 | 28.98 | - | - | - | |
| 4.37 | | 0.5 | 2.5 | 31.72 | - | - | - | |
| 4.37 | | 0.5 | 7.5 | 24.92 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 32.18 | - | - | - | [41] |
| 3.93 | 0.39 | 0.5 | 5.0 | 25.54 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 23.82 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 2.5 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 24.92 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 32.18 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 5.0 | 25.54 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 23.82 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 2.5 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 24.92 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 32.18 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 5.0 | 25.54 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 23.82 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 2.5 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 24.92 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 32.18 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 5.0 | 25.54 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 23.82 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 2.5 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 7.5 | 24.92 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 22.66 | - | - | - | |
| 3.93 | 0.39 | 0.5 | 10.0 | 32.18 | - | - | - | |

### 4. Conclusion

Previous studies showed that the presence of crumb rubber in concrete decreased the concrete compressive strength, split tensile strength, and flexural strength. Adding pozzolanic material with high silica content such as nano-silica, fly ash, and rice husk ash to concrete is one technique to counteract the loss of strength caused by crumb rubber and increase concrete performance through the pozzolanic reaction to give proper adhesion between rubber particles and cement as well as refine the
pore structure in CR concrete. Although all three pozzolanic materials boosted the strength of CR concrete, nano-silica showed better effectiveness than fly ash and rice husk ash in creating a high-strength crumb rubber concrete to be applied as a rigid pavement construction material.

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