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RESEARCH ARTICLE

Sustainable Materials in Concrete Railway Sleepers: A Review of Current Developments and Future Prospects

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ABSTRACT - Concretes have been the favoured material to make concrete railway sleepers due to better accessibility and weathering compared to their timber counterparts. Railway sleepers are crucial infrastructure and 5% of concrete sleepers fail prematurely. Sleeper failure could result in catastrophic railway accidents. Hence, improvement is needed in the concrete sleeper mixes. Previous literature has identified two methods of improving concrete strength in concrete mixes with wastes, through replacement of concrete constituents or the use of alkali-activated materials. Use of wastes as partial concrete material replacements reduces the volume of concrete materials while alkali-activated material forms a concrete-like compound that eliminates the use of cement. These methods improve the strength performance and sustainability aspects of the concrete. While many studies have been conducted on these two types of sustainable concrete, their application in concrete railway sleepers has not been investigated. Thus, this paper looks to review the two different types of sustainable concretes through some previous literature that has been conducted on its application in concrete railway sleepers as well as those that have yet to be studied. Ultimately, identifying the best sustainable materials for concrete railway sleepers.

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1.0 INTRODUCTION

Railway transportation has been playing a vital role throughout history in providing connectivity for both humans and goods, boosting the economies of countries around the world [1]. This makes railway transportation an indispensable transportation mode for countries to promote economic activities and improve social connectivity [2]. The first rail transport has existed ever since the 1800s, powered by steam engines [3]. Ever since, it has been playing a crucial part in history from the First Industrial Revolution to the Fourth Industrial Revolution [4]. The world today sees these rail transports being electrified and controlled through the use of Industry 4.0 concepts. For example, artificial intelligence (AI), especially for the use of signaling trains controls various aspects of the train allowing them to operate normally without human intervention [5].

Railway transport is a mode of transportation where wheeled cartridges travel on a fixed network of rails, without the rail track, it would not be considered railway transport [6]. Figure 1 depicts the civil build-up of the railway infrastructure. When the train is traveling through the rails, the load from the train is subjected to the tracks which are held in place by the railway sleepers [7]. The load depends heavily on the support of the sleepers to maintain the track configuration before transmitting the load in a uniform manner down to the substructure [8]. Railway sleepers can be made up of 4 different materials, timber, iron, composite, and concrete [9; 10]. Back in the day, timber was the preferred material to manufacture railway sleepers [11]. With the increasing loads from the train and lack of sufficient quality timber hardwood, the timber railway sleepers quickly became unsustainable. As a result, out of the 4 different types of materials, concrete is widely preferred today due to its easily accessible raw materials and ability to carry heavy loads while not being easily susceptible to chemical attacks [12].

Nevertheless, as more innovations are being developed in rail transport, its capabilities have been more advanced than before. Presently, to meet the increasing demand for improved mobility and connectivity, corporations and governments from affluent or developing countries alike have continued investing more in rail transport, to further modernize and expand the railway networks in their respective countries [13; 14]. As a result, the railway infrastructure has been tasked to support increased loadings and frequencies causing an increased tendency of concrete sleepers to fail prematurely, which may lead to catastrophic railway disasters [15]. Annually, it is reported that 2-5% of concrete sleepers fail before

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the expected service life [16]. Though this number seems small, it is to not be underestimated. In Iran's railway alone, it is reported that 136,846 prestressed monoblock sleepers were replaced in 2011 [17]. Around the period of 2004 to 2013, the Federal Railroad Administration (FRA) reported that in the United States, at least 25 major railway accidents were due to failure in concrete railway sleepers [18]. Thus, this shows that despite the prestressed concrete sleeper design being used widely around the globe, the reports and statistics still prove that there is a need to improve the performance of concrete railway sleepers to prevent future railway accidents caused by sleeper failure and minimize railway maintenance downtime and costs.

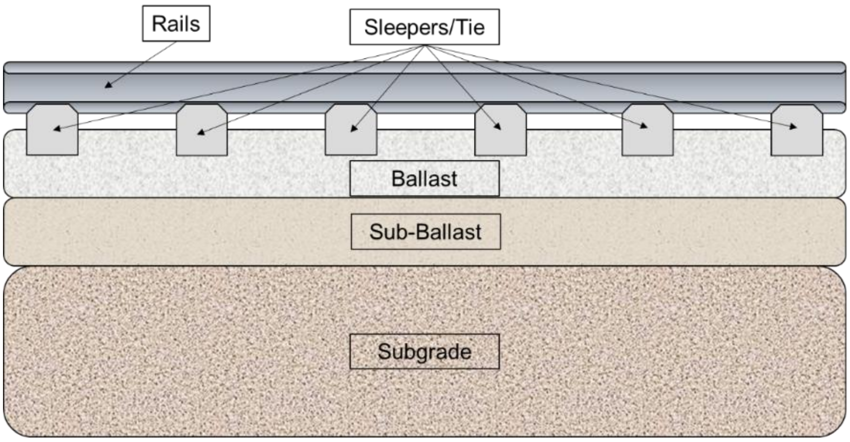

Figure 1. Parts of the railway infrastructure

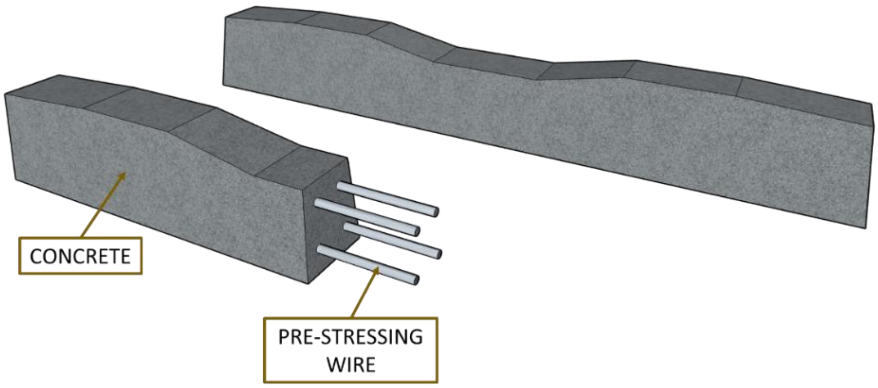

Figure 2. Parts of the railway sleepers

Other than the safety and maintenance concerns of the railway sleepers, another crucial implication of concrete railway sleepers is the environmental impact. Concrete railway sleepers are being used widely around the globe, amounting to approximately 2 billion sleepers being used, with a demand of tens of millions of new sleepers annually for maintenance and replacement works [19]. According to market research in Italy, the demand for concrete railway sleepers is projected to further increase from 2022 up to at least 2030 due to developing nations increasing connectivity of rail transport with a compound annual growth rate (CAGR) of an estimated 5.83% [20]. This presented serious environmental concerns. Concrete railway sleepers like normal concrete are made up of cement, sand, gravel, and water [21]. To give concrete railway sleepers higher dynamic load resistance, prestressing wires are used as reinforcements in concrete railway sleepers [22]. The parts of the concrete railway sleepers can be seen in Figure 2. Premature failures present in these railway structures resulted in more materials required to be used to manufacture these sleepers.

Cement manufacturing has been known to be one of the most destructive industries on Earth [23]. The International Energy Agency has reported that in 2022 alone, about 1.6 million metric tons of carbon dioxides will be produced from the cement industry [24]. This amounted to around 8% of global emissions coming solely from the cement industry [25]. It is also estimated that cement produces at least 900 kilograms of carbon dioxide into the atmosphere for every 1000 kilograms of cement [26]. In 2018, the total cement production volume was around 4129 million tons [27]. The cement industry is also the third largest source of industrial air pollution as it produces not only carbon emissions but also other harmful air pollutants such as sulfur dioxide and nitrogen oxides [28]. Therefore, the need for constant replacement of concrete railway sleepers increases the consumption of cement, becoming a huge environmental concern.

Concrete railway sleepers also use sand and gravel in their mixes. These materials are obtained through the mining of natural resources that are hard to replenish [29]. It is also crucial to understand that these materials though largely available are limited in volume. In South Korea, sand deficiency is slowly becoming an issue due to the limited sand volume unable to be replenished quickly enough for mining [30]. Mining of sand and gravel also leads to deforestation and ultimately disrupts the ecology of a habitat [31]. Concrete railway sleeper production also uses steel as reinforcing wires, and though low in volume in compared to cement, the steel industry is also notorious for its environmental impacts [32]. 8% of global carbon dioxide emissions come from the steel sector [33]. For every 1000 kilograms of steel, 1400 kilograms of direct carbon emissions are emitted [34].

With the high replacement rate of concrete railway sleepers, the sustainability of concrete railway sleepers become a crucial aspect to be investigated. With that, the main purpose of this review study is to identify the performance of conventional concrete railway sleepers and what solutions have been proposed by researchers in the formation of high-strength concrete railway sleeper mixes that are less harmful to the environment in comparison to conventional concrete railway sleeper counterpart.

2.0 COMPOSITION AND CHARACTERISTICS OF CONCRETE RAILWAY SLEEPERS

Concrete railway sleepers are made from typical concrete materials, which are cement, sand, gravel, and water [35]. Concretes have been widely used around the world, for the construction of buildings, pavement areas, and even railway sleepers. The adverse environmental effect that the production of concrete has brought about is not to be ignored [36]. Cement production and the mining of natural rocks to obtain gravel and sand are all harmful to the natural ecosystem [37]. To promote sustainable concepts in the construction industry, waste materials are being used as replacements for concrete materials [38]. Align with the United Nations Sustainable Development Goals, Goal 11: Sustainable Cities and Communities, Goal 12: Responsible Consumption and Production, and Goal 13: Climate Action, the use of wastes as concrete materials is becoming popularized and increasingly researched [39]. However, the application of wastes as concrete materials is not an entirely new concept [40].

There have been numerous wastes that have been studied for their application into concrete [41]. Recent studies have suggested that the use of these wastes could improve the properties of the concrete [42]. With the vast benefits that waste application as concrete materials have to offer, researchers have become increasingly interested in the modification of concrete railway sleeper materials for the formation of stronger and more durable concrete railway sleepers [43]. Nevertheless, in contrast to the use of wastes as concrete materials, so far there is still very little discussion as to the effects of the application of these wastes into the concrete railway sleeper mixes.

When researchers study the effects of using these wastes in concrete railway sleeper mixes, to obtain a quantifiable result and determine whether the sustainable concrete mixes could be applied, previous literature has established that sustainable concrete mixes could be tested through conventional concrete testing methods aligned with the standards set by their respective countries [44]. Some of these tests include but are not limited to, some form of compressive strength test, flexural strength test, and splitting tensile test [45]. When the sustainable concrete mixes have a positive strength increase, researchers proceed to cast concrete railway sleepers with the identified mixes.

Researchers have cast the prestressed concrete sleeper samples applying the sustainable concrete mixes and utilized both the static and dynamic bending test to measure the performance of the concrete railway sleepers the data that is being observed were the failure loads at the rail seat and the centre of the railway sleepers [46]. The reason that these two parts were being observed is because the rail seat section would be the section in which rails were fastened on top, resulting in increased loads subjected onto the section and failure could lead to track deformation leading to train derailments [47]. The failure load of the centre point of the concrete railway sleepers were also considered important as concrete is known to be weak in tension and the tension forces mainly concentrate on the centre point of a concrete railway structure, which to a huge number of forces needed to be withstand at the centre point of the concrete railway sleepers leading to the need for increased attention [48].

A series of studies have also suggested the importance of investigating the concrete railway sleeper's ability to withstand multiple loads subjected over a long period of time such as the fatigue test [49]. The fastening bond test has also been recommended in several studies as it investigates the concrete railway sleeper's ability to withhold parts that were meant to be installed onto the railway sleepers to support the entire railway infrastructure without falling out of place [50].

Thus, the following subsection looks to present some of the wastes that have already been studied as concrete railway sleeper materials, and looks to review the numerous wastes that have been recently studied for their application into concrete but not yet as railway sleeper materials. The subsection will also cover some of the test methods involved and the findings of the researchers as a result of the covered test methods.

2.1 Replacement of Cement, Fine and Coarse Aggregates in Concrete Railway Sleepers

As mentioned before, similar to conventional concretes, concrete railway sleepers are made with the main 4 ingredients, which are cement, sand, coarse aggregates, and water [51]. Concrete is known to be a material that is damaging to the environment largely due to the materials used to make concrete [52; 53]. To decrease the carbon footprint of the construction industry, researchers have used different waste materials at zero commercial value generated from human activities in place of concrete materials and reported improved concrete properties [54; 55]. These waste materials with different physical and chemical properties allow them to be used as cement, sand, and coarse aggregates. The replacement could only be done partially as full replacement proved to decrease concrete properties [56; 57]. The following section reviewed the use of waste materials as either cement, fine, or coarse aggregate replacement, which in some cases could be used in combination.

To begin, wastes deployed as cement replacements are sometimes known as supplementary cementitious materials. Examples of these wastes include ground granulated blast furnace slag (GGBFS), fly ash (FA), rice husk ash (RHA), silica fume (SF), and many more. One of the standard determination methods set by ASTM C618-19 is to investigate the chemical composition of the materials. Materials without the said chemical composition are mostly investigated for their use as fine or coarse aggregates of concrete. However, there are cases in which materials complying with the chemical composition are deployed nevertheless as fines and coarse aggregates of concrete. Examples of wastes deployed as fine and coarse aggregates are palm kernel shells (PKS), plastic wastes, steel slag, eggshell wastes, and many more. In the emphasis on the materials in the field of concrete railway sleeper research, there has been little attention given to the use of wastes as either supplementary cementitious material, fine aggregate replacement, or coarse aggregate replacement.

Previous literature findings have reported an increase in strength properties when introducing the use of wastes into concrete railway sleeper mixes. This is seen in a study by Koh et al. [46], where a comprehensive research study was conducted on the structural performance of eco-friendly prestressed concrete railway sleepers with the use of ground granulated blast furnace slag (GGBFS) as 30% replacement of type III Portland Cement (PC) and electric arc furnace (EAF) oxidizing slag replacing fully the natural sand aggregate. In another study by Prabhu et al. [47] studied the use of sintered fly ash (SFA) as partial coarse aggregate replacement of 40% while considering three different mixes of cement replacement. The three different mixes studied involve an initial mix of 80% cement with 10% fly ash while the remaining 10% was substituted with 10% ground granulated blast furnace slag for the first mix (TBC-1), 10% metakaolin (MK) for the second mix (TBC-2) and 10% silica fume (SF) for the third mix (TBC-3). The composition of their concrete railway sleeper mixes is illustrated in Figure 3.

Before its application as a concrete sleeper, the initial properties of the concrete mix have been investigated by Koh et al. [46]. The findings are summarized in Figure 4. The study reported that the initial compressive strength of the cylindrical eco-friendly concrete and conventional concrete mixes have a maximum of 51.2MPa and 36.7MPa respectively at prestressing release. The strength continues to increase with the maximum strength of eco-friendly concrete reported to be at 72.8MPa and normal concrete at 58.5MPa. This illustrated that eco-friendly concrete mixes can present improved strength properties even before their application as concrete railway sleepers. The eco-friendly concrete mix also presented properties similar to that of normal concrete where the strength continues to increase up to 28 days of curing.

Koh et al. [46] proceeded to study the properties of the concrete railway sleepers incorporating sustainable concrete mixes. From the study, it was identified that generally, all sustainable mixes, termed eco-friendly prestressed concrete sleepers (EF-PSC) were outperforming the conventional prestressed concrete sleepers (C-PSC) in terms of both the static and dynamic bending test. Earlier mentioned Prabhu et al. [47] did not report the basic properties of the sustainable concrete mixes but proceeded to the application as concrete railway sleeper materials. Prabhu et al. [47] which studied 6 different sustainable concrete railway sleeper mixes reported a strength decrease when containing SFA. Nevertheless, it was evident that EF-PSC contained the highest strength among all the sustainable concrete railway sleepers researched. The results obtained by the researchers were summarized as shown in Figure 5.

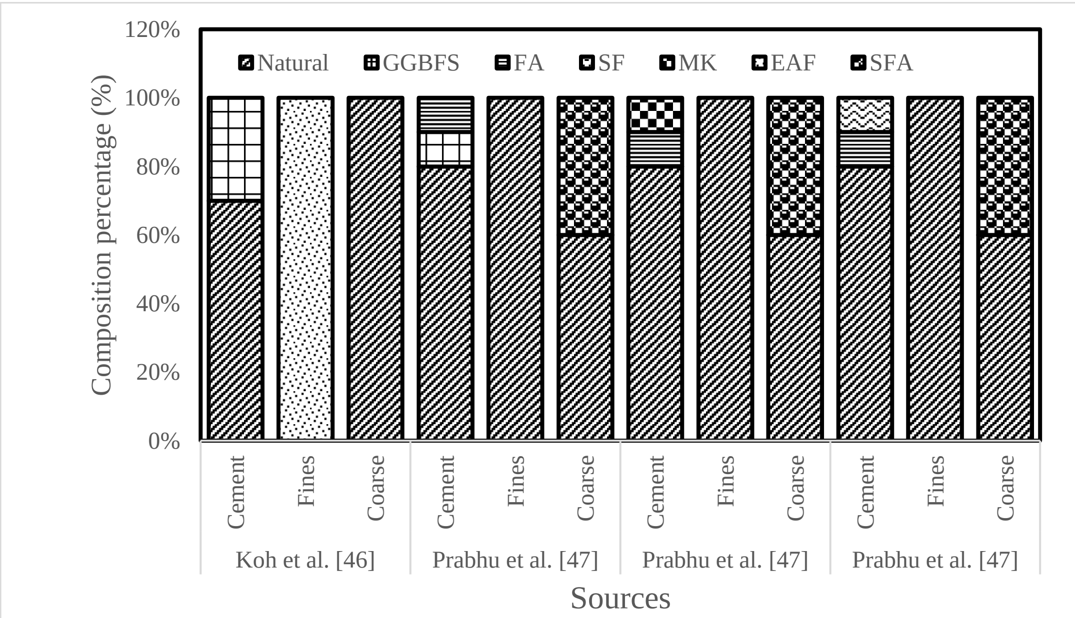

Figure 3. Concrete railway sleeper mixes. Data adapted from Koh *et al.* [46] and Prabhu *et al.* [47].

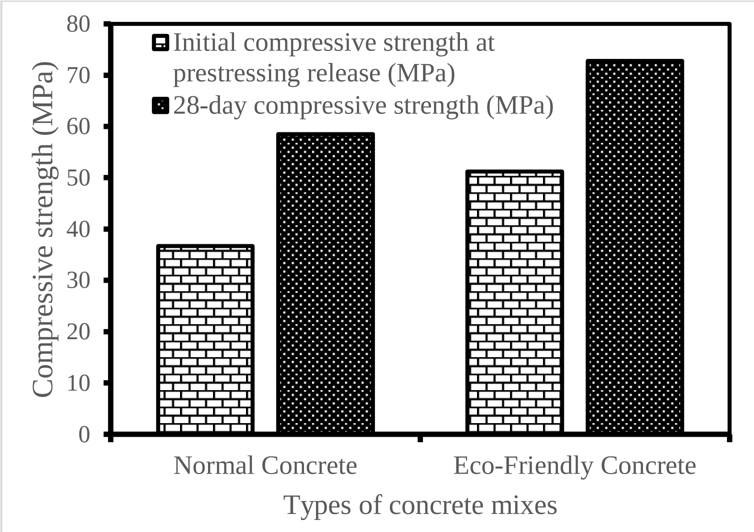

Figure 4. Types of concrete mixes and the compressive strength performance. Data adapted from Koh *et al*. [46]

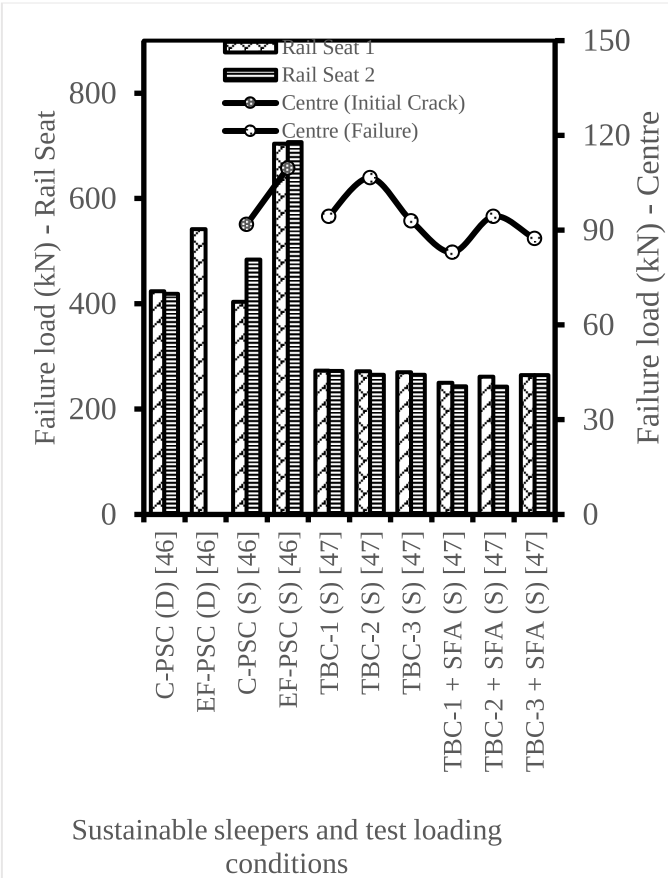

Figure 5. Types of concrete railway sleepers mixes and bending strength of PSC sleepers. Data adapted from Koh *et al*. [46] and Prabhu *et al.* [47]

In terms of the fatigue test carried out by Koh et al. [46], reported that a deflection of 1.623mm is present in the C-PSC sleepers whereas the EF-PSC only had a maximum deflection of 0.801mm. A vertical load test was also carried out on the cast-in fastening components of both the normal and eco-friendly PSC sleepers for the fastening bond (FB) strength. Overall, initial cracks only developed at a minimum force of 65kN in C-PSC whereas the EF-PSC sleepers presented a minimum force of 80kN needed, indicating that the Ef-PSC were able to form better bonding strength with the railway components in comparison to that of the C-PSC sleepers. The results are summarized in Figure 6.

As a summary, there is success in the use of recycled waste materials in concrete railway sleepers that lead to an increase in the performance. Generally, as a comparison between the two different sustainable concrete railway sleeper mixes as shown in Figure 4, the concrete railway sleepers containing 30% cement replaced with GGBFS and EAF as full sand replacement could create a PSC railway sleeper with increased strength properties. The comparison in Figure 4 for dynamic loads is indicated as (D) and static loads are indicated as (S). To date, whilst extensive research has been conducted on the use of wastes generated from human activities in conventional concrete with improved properties, there still seems to be a lack of attention given to the concrete railway sleeper mixes. The role of supplementary cementitious materials, sand replacement, and coarse aggregate replacement in the formation of stronger and more sustainable concrete railway sleepers is understudied, presenting a need to fill in this gap of knowledge.

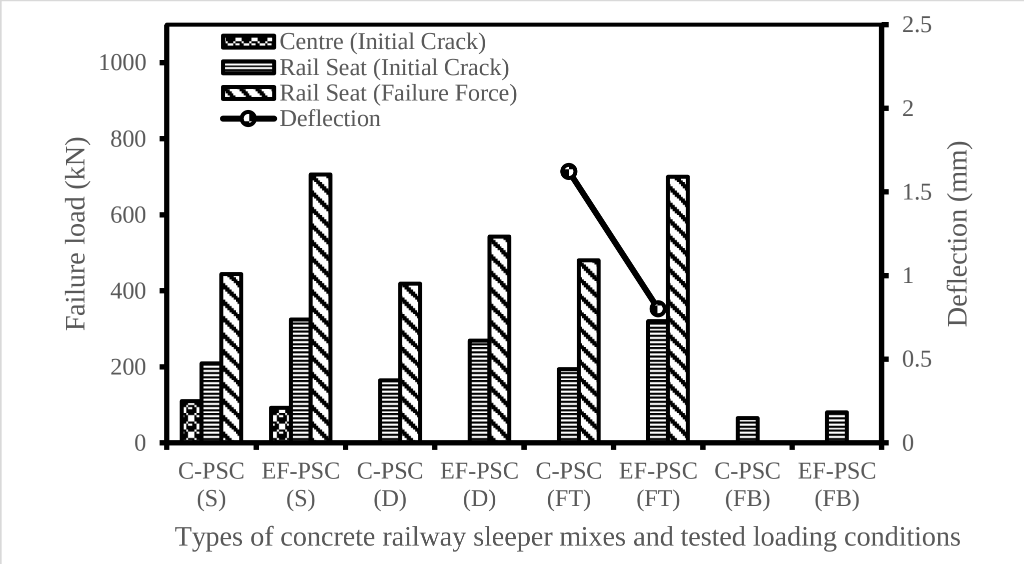

Figure 6. Types of concrete railway sleepers and bending strength. Data adapted from Koh *et al.* [46].

2.2 Alkali-Activated Concrete Technology as Concrete Railway Sleeper Materials

Differing from the concept of replacing some parts of the concrete materials with wastes, one of the increasingly researched concepts utilized full cement replacement with alkali-activated materials [58]. This concept is viewed as the future of construction as it eliminates the use of cement completely from the concrete mix. Contrary to the cement hydration process, the alkali activation process undergoes a polycondensation process which helps form large insoluble bonds of molecules [59]. Based on previous literature findings, these hydrated alkali-activated materials initially present themselves in a liquid form. Upon hardening, the alkali-activated concrete provided strength properties similar to or even higher than that of conventional concrete [60].

To manufacture the binder in alkali-activated concrete, a two-part process is involved, meaning that two different parts of materials were required to be prepared as concrete aggregate binders before use [61]. First, the precursor materials, preferably a material high in siliceous and aluminous compound, waste materials commonly used were a mixture of fly ash with a mix of metakaolin. The second part required is the alkali activator which is a liquid mixture of alkali hydroxides and alkali silicates, where most studies utilize a reactive potassium hydroxide and a potassium silicate mixture. When both the precursor materials and alkaline activators were mixed, a gel-like liquid formed, and after either heat curing or air curing, this gel liquid would then harden allowing for the binding effect of the waste materials with the concrete constituents [62].

Previous literature studying the properties of alkaline-activated concrete mixes found improvement in terms of its performance when compared to that of conventional concrete [63]. The alkali-activated concrete has even been reported to possess high-strength properties [64]. This eventually resulted in increased interest in the use of alkali-activated mixes for the preparation of sustainable concrete railway sleepers, also known as alkali-activated sleepers (AAS) [65]. Hence, the following section looks to review some of the alkali-activated concrete mixes and their application in concrete railway sleepers.

Starting with the mix design, unlike conventional concrete mix where various international and government bodies have established standardized mixture design codes, the alkaline-activated concrete lacks standardizations on the alkaline-activated concrete mixture design, which results in researchers only being able to trial and error with the mixes [66]. These variations can come from altering the proportions of the precursor materials, differing the proportions of the alkaline solution, and also the differing proportions of the aggregates. However, the generalized value assumed by most researchers is to estimate that the final alkaline-activated concrete should have a density of around 2400kg/m^3 [67]. Investigating some of the alkaline-activated concrete designs studied for the concrete railway sleeper application, Rathinam and Kanagarajan [65] found the application of fly ash (FA) and ground granulated blast furnace slag (GGBFS) as the precursor materials with sodium hydroxide (NaOH) and sodium silicate ($NaSiO_3$) as the alkaline solution for its alkaline-activated concrete railway sleeper mixes. This is similar to the mix design attempted by Khan [66] in terms of the precursor materials and alkaline solution. However, the main difference is that to further enhance its sustainability values, Khan [66] also utilized copper slag partially replacing the fine aggregates of the concrete railway sleepers. Another study by Shojaei et al. [67] utilized a full GGBFS alkaline-activated concrete mix to make concrete railway sleepers. The best-performing alkaline-activated concrete binder mixes from each of the studies conducted by the 3 different researchers was summarized in Figure 7.

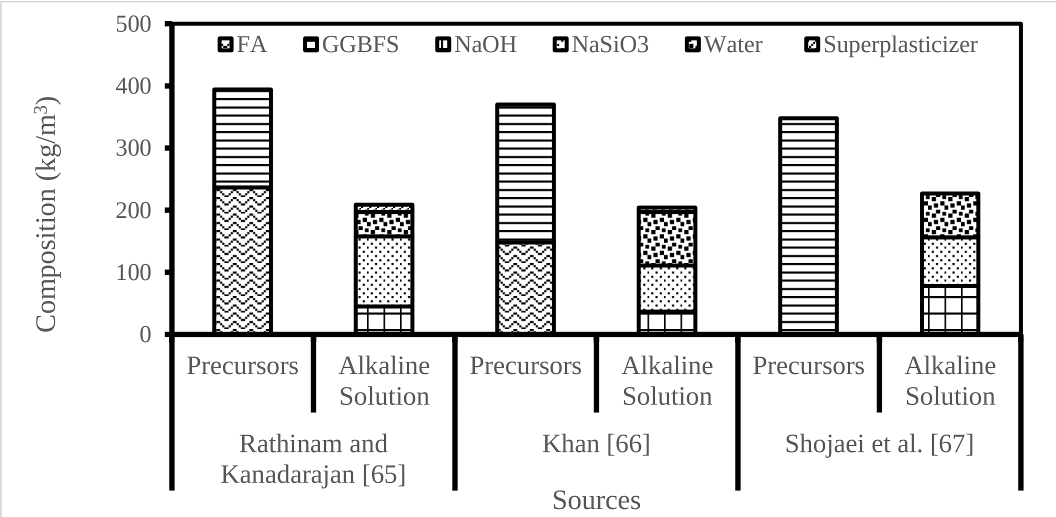

Figure 7. Types of concrete railway sleepers and compositions. Data adapted from Rathinam and Kanadarajan [65], Khan [66] and Shojaei *et al*. [67].

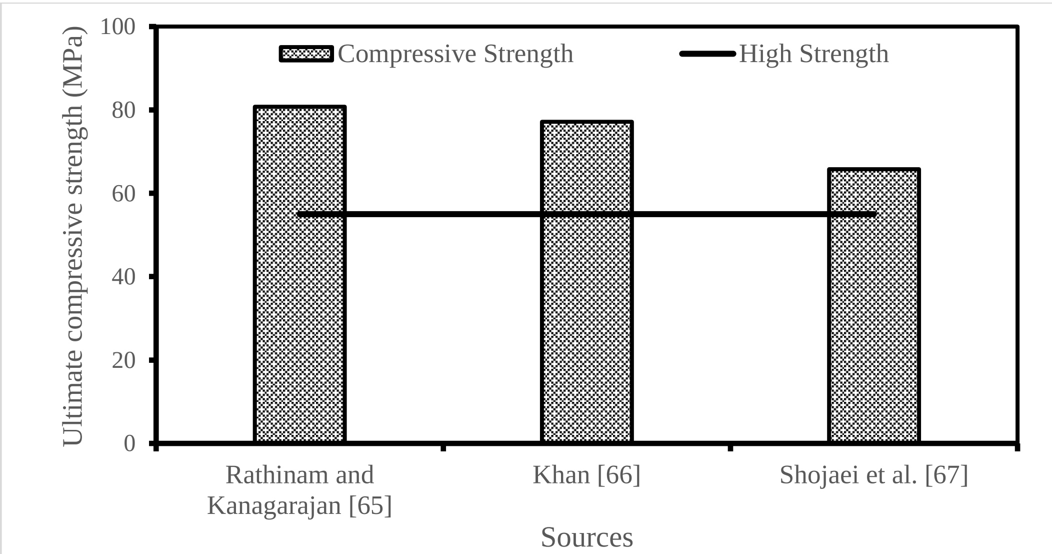

Figure 8. Ultimate compressive strength data for the different optimal alkali-activated mix. Data adapted from Rathinam and Kanadarajan [65], Khan [66] and Shojaei *et al*. [67].

Due to the need for concrete railway sleepers to carry huge loads, concrete railway sleepers are usually made with precast high-strength concrete (HSC) mixes. According to ACI 363R – 11 [68], for concrete to be considered high-strength concrete, the concrete would need to have a strength property of at least 55MPa. Looking into the 3 different alkaline-activated concrete railway sleeper products, it can be expected that the strength performances may differ. Figure 8 summarizes the ultimate compressive strength (UCS) value studied by the 3 researchers with their respective alkali-activated mixes. Rathinam and Kanagarajan [65] found that with the use of FA and GGBFS as precursors and NaOH and $NaSiO_3$ as alkaline-activator, the strength properties were reported to perform better than high-strength concrete. Khan [66] reported that with the use of copper slag as fine aggregate replacement together with the use of FA and GGBFS, the UCS produced is performing better than high-strength concrete. Shojaei et al. [67] also reported UCS higher than that of high-strength concrete. Ultimately, this shows that the basic alkaline-activated concrete cube samples generally have higher UCS than high-strength concrete, making them suitable to be used as concrete railway sleeper mixes.

Another important note is that alterations in the precursor materials the alkaline solution, and the curing methods may differ. In alkali-activated concrete, some mixes require the use of oven curing, steam curing, water curing, or ambient curing. To form the alkaline-activated concrete railway sleepers, Rathinam and Kanagarajan [65] use steam curing at 75°C for up to 11 hours. The curing method is adopted from the study by Khan [66] where a similar steam curing cycle is used. The findings were summarized in Figure 9 for both studies, which have precursor materials, alkaline solution, and curing method similarity. However, when comparing the two, it can be seen that AAS containing copper slag as partial sand replacement generally has lower strength when compared to AAS made without sand replacement. Nevertheless, it can be seen that both mixtures of AAS have higher mechanical in compared to the conventional prestressed concrete railway sleepers (C-PSC).

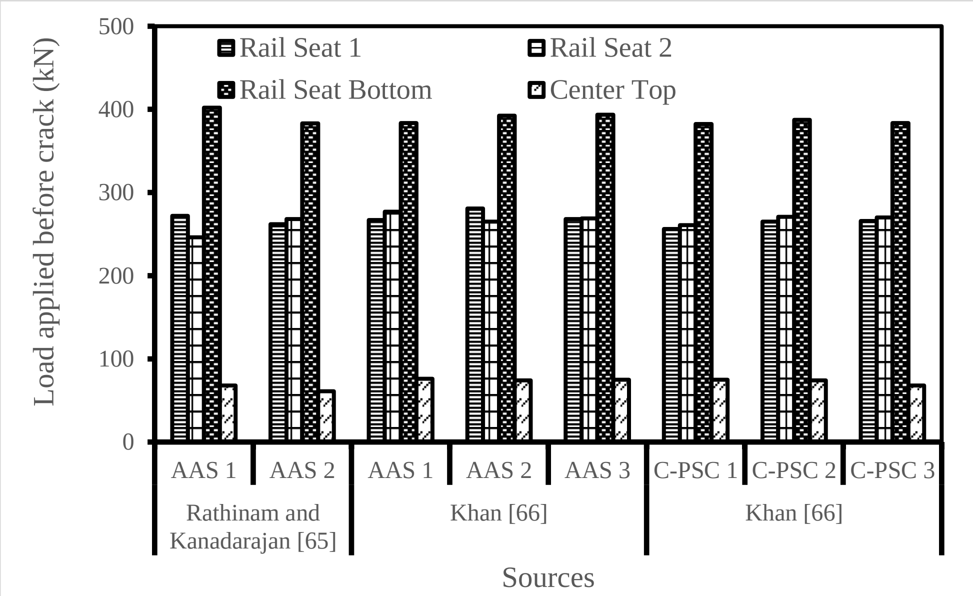

Figure 9 Performance of different alkali-activated concrete railway sleepers. Data adapted from Rathinam and Kanadarajan [65] and Khan [66].

2.3 Summary of Current Developments in Sustainable Concrete Railway Sleepers

Summarizing the current developments of sustainable concrete railway sleepers, it can be seen that there are generally two different methods utilized by researchers. That is through the partial replacement of concrete constituents and also the use of alkali-activated concrete. The main differences between these two methods of manufacturing concrete railway sleepers are that one utilizes partial cement replacement while the latter eliminates the use of cement completely from the mixes. The ultimate compressive strength of eco-friendly concrete containing partial replacement and alkali-activated concrete (AAC) is summarized in Figure 10. The best-performing concrete railway sleepers from each researcher using the different methods of manufacturing concrete railway sleepers are summarized in Figure 10.

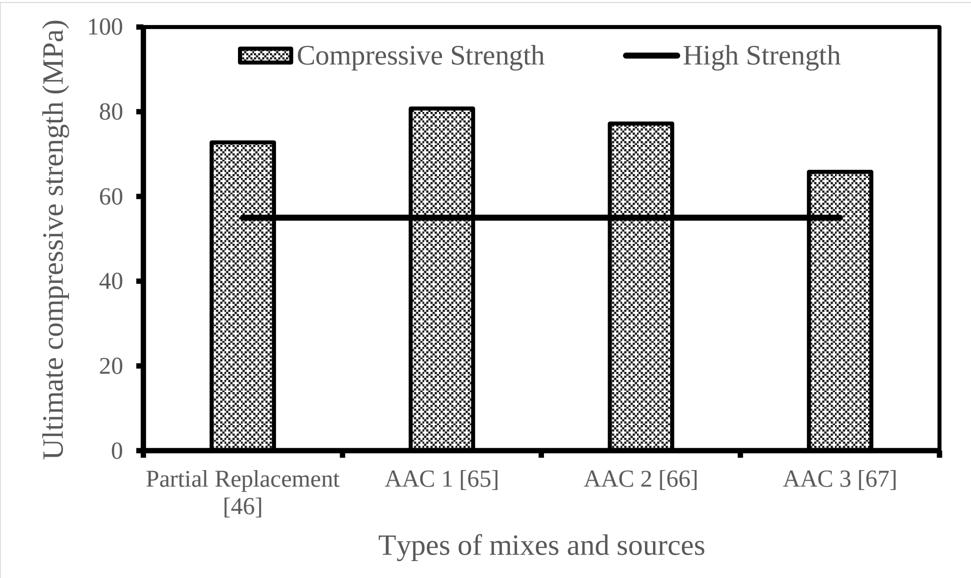

Figure 10. Ultimate compressive strength data for the different optimal alkali-activated mix. Data adapted from Koh *et al*. [46], Rathinam and Kanadarajan [65], Khan [66] and Shojaei *et al*. [67].

Generally, it can be seen in Figure 11 that among the two methods discussed above, (the partial replacement of concrete constituents presented higher mechanical properties compared to the use of alkali-activated mixes. However, when looking into the data in Figure 10, the best performing mixes are AAC mixes except AAC 3 when compared to partial replacement of concrete constituents. This shows that generally, although alkali-activated concrete mixes have higher compressive strength performance compared to the concrete containing partial replacement, the utilization of concrete railway sleepers presented contrasting properties where all concrete railway sleepers containing partial replacement have better performance than all alkali-activated concrete railway sleepers. This meant that there should be more work needed to be done on alkali-activated concrete mixes to improve their properties while being used as concrete railway sleeper mixes to achieve alkali-activated concrete with high compressive strength and high performance when concrete railway sleeper mixes. Nevertheless, all mixes generally satisfy the conditions of being classified as high-strength concrete while being able to present satisfactory values when applied to concrete railway sleepers.

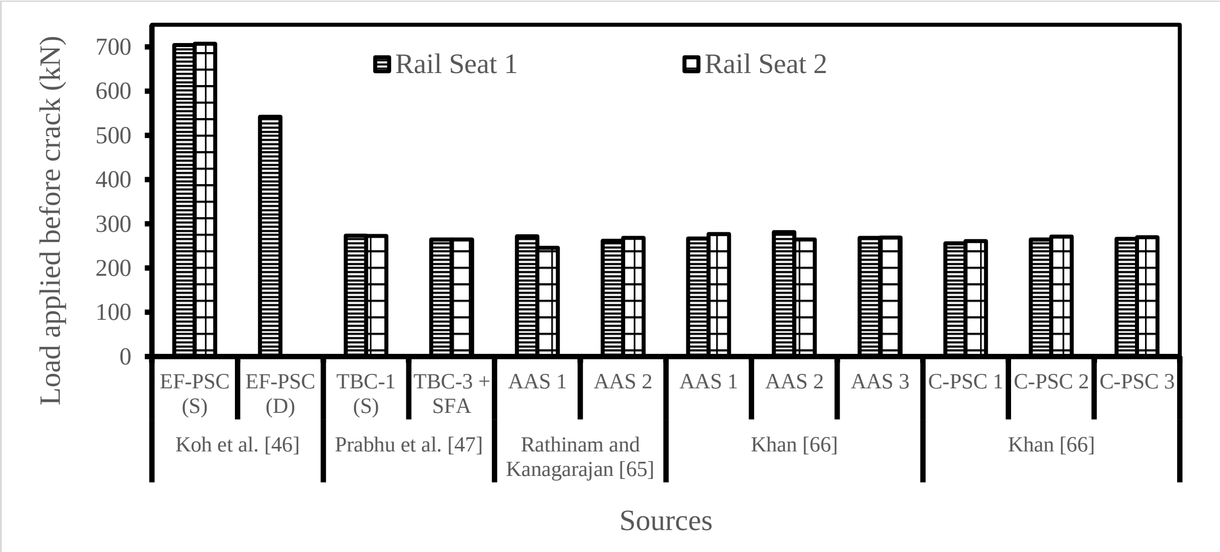

Figure 11. Performance of different alkali-activated concrete railway sleepers. Data adapted from Koh *et al*. [46], Prabhu *et al.* [47], Rathinam and Kanadarajan [65] and Khan [66].

3.0 ADVANCEMENTS IN ALKALI-ACTIVATED CONCRETE RESEARCH

Presented in earlier sections, alkali-activated concretes have the ability to present improved compressive strength but do not significantly improve the concrete railway sleeper properties. Hence, improvements are required to be made to the alkali-activated concrete railway sleeper mixes. The following sections will review some of the other wastes that could be used for high-strength alkali-activated concrete mixes but not yet as concrete railway sleeper mixes. This is to identify some possible improvement methods that could be used to improve the alkali-activated concrete railway sleeper properties. As reviewed in the earlier sections, most studies have utilized waste materials such as silica fume, fly ash, and ground granulated blast furnace slag. So far, however, there are still multiple types of wastes available to be used for the formation of concrete railway sleepers which remained unstudied. Some of these wastes have reported high siliceous and aluminous composition which could be beneficial for the use as the precursor materials in alkali-activated concrete. Thus, the following section is aimed at identifying some of the other waste materials to provide an overview of some of the wastes that have been studied as concrete materials but not yet discussed for their role as concrete railway sleeper material.

3.1 Precursor Materials in Alkali-Activated Concrete

As explained in the earlier section, alkali-activated concrete (AAC) is formed through a two-part process involving the reaction between precursor materials and activated through a mixture of alkaline solutions. Unlike cement which undergoes a hydration process, AAC undergoes a polymerization process, which is a 5-step process. According to Duxson et al. [69], to simplify the polymerization process, the steps involved include dissolution, speciation equilibrium, gelation, reorganization, and polymerization. The first step is the dissolution process in which the precursor materials should be an aluminosilicate source which upon reaction with an alkaline solution undergoes a dissolution process forming free aluminate and silicate species [70]. The second step, a speciation equilibrium, which has been thoroughly investigated by Swaddle et al. [71], is reached between the interaction of aluminate, silicate, and aluminosilicate species starting the particle-to-gel conversion. Afterwards, the gelation, due to the high pH present, the amorphous aluminosilicate dissolute into a solution resulting in gelation, converting the particles into a gel [72]. Then, the reorganization, where these oligomer gels slowly reorganize to form a large chain of aluminosilicate network through polycondensation [73]. Lastly, upon polymerization and hardening, the gel forms a hardened alkali-activated material.

Due to the need for aluminosilicate sources as precursor materials of alkali-activated concrete (AAC), this resulted in a growing body of literature that investigates the use of pozzolanic materials, materials high in alumina and silica, as precursor materials in AAC [74; 75]. In a study conducted by Huo *et al.* [76], investigated the use of RHA with GGBFS as precursor materials. As a result, it was found that 5% RHA and 95% GGBFS mix, produced an AAC with a compressive strength of 94MPa at 90 days of curing. Another study by Soumya Pradhan *et al.* [77] similarly used 5% RHA and 95% GGBFS mix and was able to produce an AAC with an ultimate compressive strength of 64.54MPa after 90 days of curing.

This provided ample evidence to hypothesize that the use of GGBFS at 95% and RHA at 5% would be able to produce an AAC that is considered high strength and feasible to be studied in its application as a concrete railway sleeper.

Other than the use of RHA and GGBFS, another study by Yurt and Bekar [78], used hazelnut ash (HA) at 10% with 10% MK and 80% GGBFS and found that AAC produced contains compressive strength up to 86MPa. A study conducted by Zhang *et al.* [79] utilized mineral powder (MIP), a by-product of the steel industry, fully as a precursor material in the AAC, and reported that by 28 days, the strength could achieve 118MPa. Liang et al. [80] studied the addition of 6% ultrafine waste concrete powder (UWCP) into 50% GGBFS and 50% FA precursor AAC mixes and found that the strength performance of AAC concrete could reach 83.1MPa by 28 days of curing and increases to 86.3MPa after 56 days curing. While Marathe *et al.* [81] investigated the use of 15% waste glass powder (WGP), 75% GGBFS and 10% FA showed a maximum strength of 68MPa after 28 days of curing. Hence, it can be seen that recent studies have suggested that the use of pozzolanic materials other than RHA and GGBFS could also form high-strength AAC mixes. The findings of the research were summarized as shown in Figure 12. In contrast to the literature on high-strength AAC mixes, to date, there is little attention given to its application as concrete railway sleepers, which provided a gap of knowledge that researchers today could pay attention to.

As discussed earlier different pozzolanic materials could potentially contain different chemical compositions. For it to be used as precursor materials in AAC, recent studies have reported that the chemical composition of precursor materials could affect the curing methods and quality of AAC produced. This is shown in one study conducted by Alomayri *et al.* [82], which attempted the use of raw RHA (RRHA) with GGBFS, and at 10% RRHA to 90% GGBFS found that the compressive strength of AAC undergoing thermal curing had strength higher than ambient curing. Another study by Mengasini *et al.* [83] utilized paper sludge ash (PSA) and GGBFS mixed and cured with seawater was found to produce AAC concrete of 58MPa after 56 days of curing. A recent investigation by Xiang *et al.* [84] identified that slag AAC mixes containing NaOH and 1M water glass, may perform better cured under low temperatures than ambient cured. The chemical composition of different precursor materials studied for the formation of high-strength AAC is summarized in Figure 13. Therefore, this identified that differences in the source of precursor materials and molarity concentration of the alkaline solution may lead to a possibility in the variations of performance in the AAC products when it is cured through different methods. Due to the lack of global standardizations, it may be required to study the chemical composition of precursor materials to identify the most suitable curing methods for the respective AAC concrete mixes.

From all the reviewed articles, whilst a considerable body of research has been carried out on the application of pozzolanic materials as precursor materials in high-strength AAC, much less is known about the performance of the AAC synthesized through the use of these pozzolanic materials in the application as concrete railway sleeper. Hence, this presents a significant gap of knowledge in which other pozzolanic materials, other than FA, SF, and GGBFS could be used for the application as alkaline-activated concrete railway sleeper materials. Aiming at improving the compressive strength properties of alkali-activated concrete while anticipating its applicability in enhancing concrete railway sleeper properties.

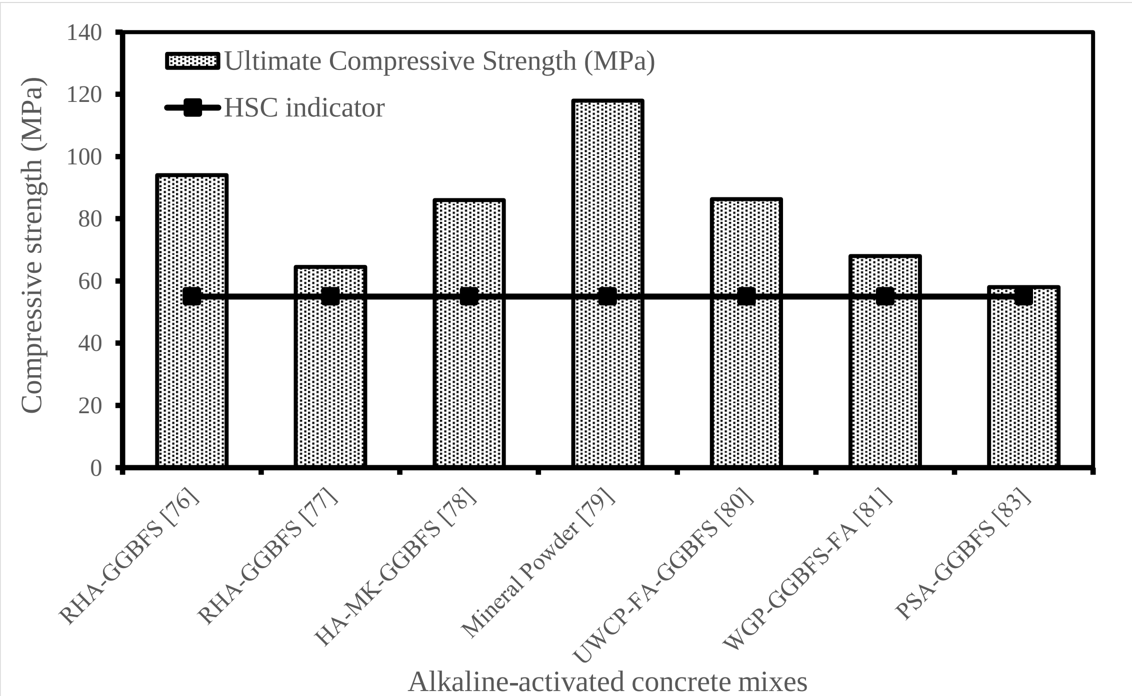

Figure 12. Alkaline-activated concrete mixes with their ultimate compressive strengths. Data adapted from Huo *et al.* [76], Soumya Pradhan *et al.* [77], Yurt and Bekar [78], Zhang *et al.* [79], Liang *et al.* [80], Marathe *et al.* [81], and Mengasini *et al.* [83]

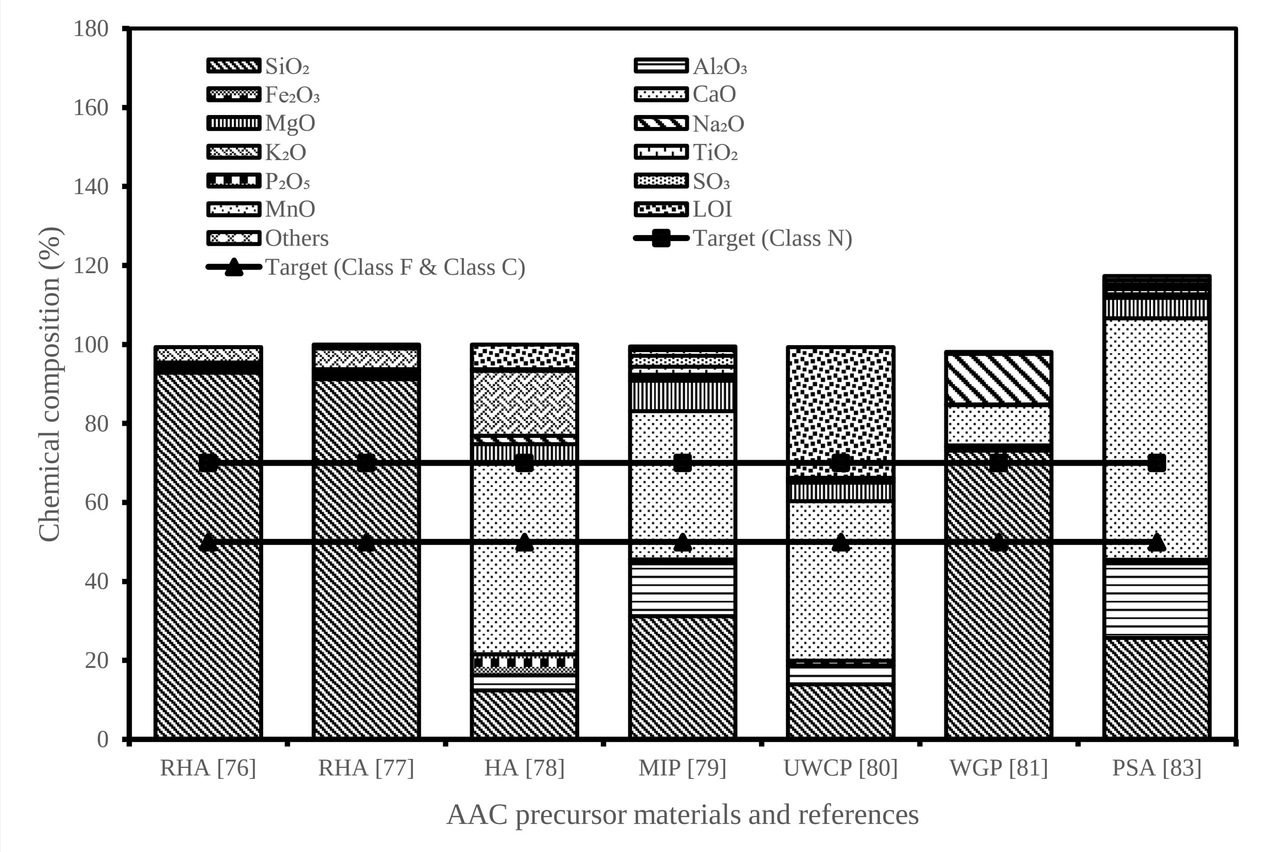

Figure 13. Chemical composition of precursor materials. Data adapted from Huo *et al.* [76], Soumya Pradhan *et al.* [77], Yurt and Bekar [78], Zhang *et al.* [79], Liang *et al.* [80], Marathe *et al.* [81], and Mengasini *et al.* [83]

4.0 PERSPECTIVE AND RESEARCH GAP

From all the studies reviewed, generally, it can be seen that there are a few studies that have been conducted on concrete railway sleeper performance with the use of waste materials. These waste materials could be used as cement replacement, fine aggregate replacement, coarse aggregate replacement, and precursor materials in alkaline-activated concretes. From the study, the strength performance of the concrete railway sleeper containing waste materials could be improved, resulting in the decreased use of natural resources that are hard to replenish while at the same time increasing the service life of the concrete railway sleepers. However, it can also be seen that there is lack of studies in this field of sustainable concrete railway sleepers.

When comparing the compressive strength data, alkali-activated materials generally presented higher strength than supplementary cementitious materials. However, the application into concrete railway sleepers resulted in contradicting results as supplementary cementitious concrete railway sleepers have better performance than alkali-activated materials. This shows that the role of alkali-activated materials in improving the properties of concrete railway sleepers remains largely understudied and could be further improved to form a high-compressive strength concrete with high-performance alkali-activated concrete railway sleepers. Also, reviewing the alkaline-activated concrete based on waste materials indicates that in contrast to studies that have utilized pozzolanic materials as precursor materials forming high-strength alkali-activated concrete, there is too little information on the application of these special mixes for a sustainable concrete railway sleeper.

To improve the alkali-activated concrete properties when waste materials are utilized, the pozzolanic properties of a material are key to improving the properties of concrete and can be used in place of cement totally. The materials, containing high calcium and aluminosilicate characteristics could also be beneficial to be investigated for their use as precursor materials in alkali-activated concrete. From all the sustainable materials reviewed, supplementary cementitious materials are more suitable to be used as concrete railway sleeper materials as opposed to alkali-activated materials. This is because while alkali-activated materials presented superior compressive strength compared to supplementary cementitious materials, the dynamic load aspects of alkali-activated materials presented detrimental performances compared to supplementary cementitious materials. This also meant that alkali-activated materials while having high capacity to withstand compressive force presented weaker tensile force capability. Nevertheless, among all the reviewed sustainable concrete materials, it can be seen that the best performing sustainable concrete railway sleeper could be obtained when using 30% of GGBFS to replace cement and a fully sand replaced with EAF.

Some of the challenges faced by researchers in terms of alkali-activated concrete, the biggest challenge would be the lack of standardizations set by relevant agencies, resulting in the need for assumptions and trials. The numerous types of waste materials have diverse chemical properties and effects on the concrete, in some cases, forming high-strength concrete with over 100MPa. It is worth trying these waste materials as part of the concrete railway sleeper mixes for use in casting environmentally sustainable concrete products such as concrete railway sleepers. The improved sleeper properties can not only reduce the negative environmental impact but also reduce the infrastructural service and maintenance costs of railway transportation. The increase in bearing load and strength of the railway sleepers could also allow for higher service loads during the railway transport operation. In the long run, the application of these wastes as railway sleeper materials could improve the cost benefits of the railway sleeper, with improved sleeper service life and reduced maintenance costs.

5.0 THE WAY FORWARD

The different research that has been conducted on wastes as part of the concrete railway sleepers was reviewed. The alkali-activated concretes have the ability to form ultra-high strength concrete of over 100MPa but their application as concrete railway sleepers have not yet been investigated. At the present moment, the compressive strength of alkali-activated concrete has better performance than supplementary cementitious materials but its performance is weaker when used in concrete railway sleepers. Hence, wastes that could contribute to the improvement of the strength properties of conventional concrete as precursors in alkali-activated concrete were reviewed. Overall, it can be seen that there are still numerous wastes that have yet to be studied for their application in concrete railway sleepers. From the review, it was found that some alkali-activated mixes could potentially form high-strength properties for their use as concrete railway sleepers but the application has not yet been elucidated. Hence, the authors of this paper are currently working on improving the concrete railway sleepers with wastes allowing for the formation of sustainable and environmentally friendly concrete railway sleepers.

6.0 CONCLUSION

In this review paper, the different materials that have been used as concrete railway sleepers were presented. It can be concluded that there are two general methods of improving concrete railway sleeper mixes, that is through the use of supplementary cementitious materials or the use of alkali-activated materials. While alkali-activated materials have better compressive strength, they presented lower railway sleeper performance. Hence, the numerous wastes that have been studied recently as alkali-activated materials were also reviewed. From the review, it can also be seen that there is still a huge gap of knowledge in which research is needed to study the alkali-activated applicability as concrete railway sleeper materials with increased compressive strength and increased concrete railway sleeper properties.

7.0 AUTHORS CONTRIBUTION

J. J. Yee (Conceptualization; Methodology; Formal analysis; Investigation; Writing - original draft)

S. C. Khong (Visualization; Data curation; Validation; Formal analysis; Writing - review & editing)

J. L. Che (Validation; Visualization)

K. F. Tee (Funding Acquisition, Resources)

S. C. Chin (Funding Acquisition, Conceptualization; Visualization; Writing - review & editing; Supervision)

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9.0 CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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