Overview of trends in the application of waste materials in self-compacting concrete production

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Abstract

Self-compacting concrete (SCC) production is growing rapidly due to its several advantages in terms of enhanced properties and applications. However, there are associated sustainability issues with the SCC materials. With the demand for SCC expected to continually increase, an ideal solution is therefore required to sustain the technology, such as derivation of alternative materials. Thus, this study explores innovative application of industrial wastes in self-compacting concrete production, with the aim of finding the most appropriate technique in SCC material use. Also, the potential limitations in using some of the waste materials as sustainable alternatives were highlighted. This study found that several materials emanating from industrial rejects have been mostly investigated as a potential material for making SCC, which showed that the incorporation of waste materials into SCC could be a viable approach. However, in order to achieve optimal performance of SCC, an adequate material composition is necessary. It is clear from this study that factors such as embodied carbon, energy and cost of SCC production can notably be reduced with the incorporation of waste materials. The study also identified areas for further investigations that can help in the improvement of SCC for construction applications.

Keywords Cement · Compressive strength · Durability · Self-compacting concrete · Sustainability

Abbreviations

SCC	Self-compacting concrete
OPC	Ordinary Portland cement
SCM	Supplementary cementitious material
CBA	Coal bottom ash
ASR	Alkali–silica reaction
RCA	Recycled concrete aggregate
GW	Glass waste
FA	Fly ash
SF	Silica fume
SA	Sawdust ash
BW	Brick waste
SL	Slag
TSM	Two-stage mixing
RW	Rubber waste
CC	Conventional concrete
NA	Natural aggregates

SF	Silica fume
RHA	Rice husk ash

1 Introduction

Advances in concrete material research, in recent years, have opened pathway for the use of alternative materials as sustainable alternatives for the conventional ones. The materials represent mostly industrial, construction and agricultural rejects. Thus, reusing the aforementioned materials is believed to largely contribute to an effective waste management through recycling.

This study explores the various potential materials that can be utilized for production of self-compacting concrete (SCC). The application of SCC is evolving, due to its enhanced workability and low segregation compared to conventional concrete (CC), and its ability to fill up

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complex formwork sections [1]. In addition, the use of SCC can significantly reduce the energy, cost and construction time due to its ability to flow and self-compact under its own weight [2]. However, despite considerations for SCC as a sustainable concrete, in that energy consumption is reduced in its production (no vibration involved), the materials used to make SCC pose a sustainability threat to the environment [3]. The production of Ordinary Portland cement (OPC) which is the major binder in SCC is energy intensive and emits a significant amount of carbon dioxide in the environment. In addition, the mining and processing of natural aggregates used for SCC also contribute significantly to the carbon emission of the concrete industry while also deteriorating the environment [3]. On the other hand, the cost of production of SCC is high, which is one of the major issues that limit its usage. OPC covers high amount of the cost of SCC production, as it uses more OPC than conventional concrete (CC). Therefore, provision of alternative materials as replacement of the conventional materials can make SCC more sustainable, and moreover, there will be significant cost savings while achieving desirable SCC properties.

Several waste materials have been investigated for the possible incorporation into SCC, as a replacement for the binder, aggregates, and reinforcing elements. In the case of binders, materials having significant cementitious properties are considered, such as fly ash, limestone powder, slag and metakaolin [4, 5]. The aggregates counterparts are those having high crushing strength and moderate water absorption properties, such as steel slag, ceramics, recycled aggregate and palm kernel shell [6–12]. Also, numerous reports have shown that steel fibre possesses tensile properties suitable for improving the performance of SCC [13–17]. Particularly, the macro-hooked ends steel fibre with multiple hooks exhibited strong impact on strength of SCC as discussed in [18]. Most of the materials were found somewhat suitable in terms of mechanical characteristics of concrete; however, an optimum objective of SCC includes that it has an excellent fresh properties regardless of its composition. Also, some of the problems of waste materials used as aggregate are poor physical properties, which yet serve as a major challenge for achieving the workability of SCC mix.

Also, higher replacement of OPC with waste materials at higher levels can be detrimental to the mechanical properties of the SCC due to the slow nature of the pozzolanic reaction. Therefore, when waste materials are incorporated into SCC as a replacement for either binder or/and aggregate, the suitability of such materials can only be ascertained if the SCC exhibits similar or better fresh and hardened properties compared to the conventional mixture. Finding ways to incorporate waste materials into concrete will not only create ways to manage these wastes

effectively, but it will also create an avenue to produce sustainable concrete. It will also preserve the sources of raw materials and reduce the carbon footprint of SCC.

Researchers have explored the use of waste materials in conventional concrete [19, 20]. Most of the studies have reported a decrease in mechanical properties of concrete, which becomes more significant as there was an increase in the amount of waste materials incorporated. The decrease in mechanical properties may be traced to the deficient physical properties of the waste materials; this includes higher water absorption capacity of aggregates [21] that can result in the need to increase the water-to-cement ratio of the mixture.

While there are several reports in open the literature on using alternative aggregates in concrete, it is observed that there is currently no major framework for the commercial application of the materials. Therefore, this review is carried out to extensively explore several experimental studies in the open literature in which waste materials have been incorporated into concrete either as replacement of binder or/and aggregates. It is aimed that the best approach for application of alternative materials for SCC production will be revealed in this study. Also, it is hoped that this article will contribute significantly to the development of a more sustainable SCC. The study will also guide concrete's stakeholders on possible ways to incorporate different waste materials into SCC and other types of cementitious composites.

2 Effect of different waste materials on properties of SCC

2.1 Recycled concrete aggregate

Recycled concrete aggregate (RCA) is obtained from concrete structures being destroyed for various reasons, ranging from a need for new construction, or destruction by natural and human disasters. The crushing and processing of these demolished concrete structures to smaller sizes result in RCA, which can be incorporated into concrete as aggregate. RCA is typically made up of natural aggregates (NA) and about 35% adhered mortar. Depending on the resulting crushed size of the RCA, it can be classified as either fine or coarse aggregate. The adhered mortar on RCA and the overall property of the RCA have been found to be dependent on the properties of the parent concrete [22, 23]. Due to the adhered mortar on RCA, it possesses higher porosity and water absorption when compared to NA. This higher porosity means that there will be a significant absorption of water when RCA is incorporated into a concrete mixture. Also, the presence of higher porosity will create weak points along the matrix which will result in

Fig. 1 Effect of RCA level on slump of SCC

lower mechanical properties of the composite made with RCA. The workability of the concrete can also be altered by incorporation of RCA, owing to its high water absorption. The effect of RCA substitution on the workability of SCC is presented in Fig. 1. As can be seen, the higher slump values were obtained in mixtures containing RCA, which can be attributed to mixing water absorption in RCA. It is also worthy of note that no certain pattern can be seen as the RCA contents were increased.

Reduction in slump ensues when RCA is incorporated into SCC [22, 23]. This reduction can be attributed to the presence of high pores in the RCA as mentioned earlier, which consequently absorb the water meant to achieve good workability and hydration. However, in order to improve the workability of SCC incorporating RCA, the use of superplasticizer has been found to moderate the slump of the SCC to the required flow [23]. As presented in Fig. 1, it will be observed that it is possible to achieve acceptable slump around 600 mm for SCC incorporating RCA at different levels of RCA replacements when superplasticizers are incorporated. However, the amount of superplasticizer required to achieve excellent slump has been found to increase with increasing RCA content [22–25]. For instance, a study by Manzi et al. [24] focused on the long-term effect of using up to 40% fine and coarse RCA in SCC. It was reported that an acceptable fresh properties of SCC could be achieved by the use of superplasticizers ranging between 1 and 1.2% by mass of the binder. But contradicting observations have been reported for the flow rate as presented in Fig. 2. Kou and Poon [26] reported a decrease in the slump with the use of RCA as a replacement of natural fine aggregate. This decrease in the slump has been attributed to the ability of the fine RCA to absorb a high amount of water when compared to that of the fine NA as mentioned earlier. The high water absorption of fine RCA led to a significant slump loss which is detrimental to SCC applications, and a continuous slump

Fig. 2 Effect of RCA replacement level on the flow rate of SCC

loss was observed as the content of fine RCA increased. The use of fine RCA has also been found to result in high segregation of the resulting SCC mixture [26]. This high segregation can also be traced back to the high water absorption of the fine RCA. However, despite the slump loss and segregation, the SCC containing fine RCA was found to satisfy SCC's fresh properties requirement according to the specification and guidelines for self-compacting concrete, EFNARC [27]. Similar to conventional concrete, it is reasonable to conclude that the incorporation of RCA will lead to a decrease in the density of the SCC, with more reduction in density with increasing replacement levels. Mechanical properties of any type of concrete are one of the major properties. It is expected that incorporating RCA into concrete will alter its strength properties. The use of RCA in SCC has been reported to have a detrimental effect on its strength [22, 23]. It was found out that SCC incorporation of RCA up to 100% replacement of RCA can result in about 30% reduction in the compressive strength [23]. And as the compressive strength of concrete can be related to other mechanical properties, incorporation of RCA into SCC has been found to lead to a corresponding decrease in other mechanical properties of SCC. The study by Preira et al. [22] agreed with this trend as they observed a significant decrease in mechanical properties of SCC incorporating RCA. However, despite these reductions in mechanical properties, the authors concluded that the use of RCA instead of NA is still beneficial due to the reduction in cost and its positive environmental effect. Also, Preira et al. [22] reported a difference in the compressive strength of 3 MPa between the control and SCC containing 100% RCA. This lower difference can be considered insignificant when related to its economic and sustainable advantages. A similar trend in the insignificant effect of different level of RCA was also reported for the modulus of elasticity of the SCC incorporating different

levels of RCA. The study by Grdic et al. [25] also showed the same trend in strength reduction at all ages with the incorporation as RCA as a substitute for NA. Similar observations were also reported for the tensile strength of the SCC incorporating RCA. On the contrary, Manzi et al. [24] reported an increase in compressive strength with increasing content of RCA. This might be as a result of the source of the RCA used. The higher compressive strength has been attributed to excellent bonding between new mortar and the existing mortar on the RCA. But also, the source of the RCA can play a significant role in the higher strength. For example, RCA obtained from a precast plant will give a better result than RCA obtained from the demolition of a severely deteriorated bridge. Manzi et al. [24] also reported that the use of RCA in SCC has no significant effect on the elastic modulus, and the resulting tensile strength and flexural strength were found to be approximately 3 MPa and 4 MPa, respectively. These similar properties with SCC made with NA shows that depending on the source of the RCA, SCC incorporating RCA as an aggregate can be used successfully to produce a structural grade concrete without any detrimental effect on its properties. As the source of RCA is imperative to its behaviour, it is essential that the source of RCA be investigated and its suitability for different applications determined. The ability to use RCA to produce structural grade concrete will be significantly beneficial to the precast industry where the RCA generated are from high-quality concrete and the production of new concrete can be carefully controlled and optimized. However, a number of studies have shown that fibres could be used to enhance, workability, strength and torsional behaviour of SCC containing RCA [28].

The higher porosity of RCA not only leads to a detrimental effect on the mechanical properties but also been found to affect the durability of concrete past certain replacement levels. Water permeability of concrete is a good indication of concrete's durability as it shows the ease at which water can move through the concrete. A decrease in the water permeability of SCC was observed when RCA is incorporated into SCC until 40% RCA after which the water permeability starts to increase [22]. An increase in the water permeability past the 40% replacement level might be as a result of the introduction of a significantly high number of pores into the system. But in contrast, Grdic et al. [25] reported a significant increase in the water absorption of SCC when RCA is incorporated at all levels. This trend also increased with the increase in the content of the RCA. The author believes that the differences in the results might be as a result of the different sources of RCA used. The increase in the water absorption of the SCC can be attributed to the porous nature of the RCA which makes it easier water to move into and within the matrix. Another test largely used to access the

durability of concrete is the chloride permeability test. Kapoor et al. [29] utilized RCA as both fine and coarse aggregates in SCC. They observed an increase in the chloride permeability of the SCC as a result of the incorporation of both the fine and coarse RCA when compared to that of the control with NA. The higher porosity of the RCA has been attributed to this detrimental effect. However, when metakaolin (MK) was used as a partial replacement of OPC in the SCC, a significant decrease in the chloride permeability was observed [29]. This decrease in chloride ion penetration can be ascribed to the pozzolanic and filler effect of MK which densifies the microstructure of the SCC. This densification of the microstructure coupled with the pore filling of the pores in the RCA inhibits the movements of ions within the matrix. The authors also reported a similar reduction trend in the water penetration of the SCC when fine and coarse RCA are used as aggregate in SCC. Therefore, it can be concluded that to be able to utilize different sizes of RCA in SCC and maximize its benefits, SCMs such as MK can be incorporated as a partial replacement of OPC to complement to a large extent for the porosity of the RCA.

As the higher porosity of RCA mentioned is associated with the coarse RCA, SCC incorporating fine RCA was found to have lower chloride ion penetration compared to the control [26]. This enhanced durability property can be associated with the smaller size of the fine RCA compared to their NA counterpart, which contributed significantly to its filler effect [30]. However, at the higher water-to-cement ratio, high drying shrinkage of the SCC incorporating fine RCA was observed [26]. Therefore, in order to fully maximize the benefits of using RCA as both fine and coarse aggregate, superplasticizers should be employed to achieve good workability instead of increasing the water content of the mixture. The use of superplasticizers will also ensure that the desired strength is obtained, as increasing the water content of the mixture will result in a decrease in strength properties. Figure 3 shows the effect of RCA types on the water absorption properties of SCC.

In order to encourage more application of RCA in different types of concrete, several treatment methods for the RCA have been developed. Some of these methods include a two-stage mixing method and presoaking of the RCA in different solutions. The objective of these treatment methods is to ensure proper bonding between the RCA and the binder paste. And the two-stage mixing method (TSM) and presoaking of RCA in sodium silicate solution have been reported to be the most effective as a result of the resulting densified microstructure achieved. Also, TSM method has been found to be the most practical due to the simplified process involved. Ghneyesi et al. [31] presoaked RCA of different sizes to be used for SCC in different solution to enhance their properties. The solutions

Fig. 3 Effect of RCA treatment types on its water absorption (data from [31])

Fig. 4 Effect of RCA treatment methods on the mechanical properties of SCC (data from [31])

used are hydrochloric acid (HCL), sodium silicate (SS) and cement silica fume slurry (CSF). The study shows that soaking the RCA in SS is more effective compared to other solutions as shown in Fig. 3. Also, it can be observed from Fig. 3 that RCA treated with SS has water absorption about one-fourth of the others. Correspondingly, the effect of the RCA treatment was evident in the microstructure of the SCC made with the treated RCA [31]. Loose particles were observed in the microstructure of the SCC made with untreated RCA which shows improper bonding of the aggregate with the binder paste. An enhanced and densified microstructure was also achieved when TSM was employed to produce the SCC with all types of treatment methods mentioned earlier. And the combined pre-soaking in SS and production of SCC using TSM gave the most desired properties as presented in Fig. 4, alongside

a densified microstructure [31]. As one of the major challenges of SCC is its high powder content, an eco-friendlier and more economical SCC has been produced by using a low powder content and RCA [32]. A reduction in the embodied carbon more than 100 kg CO_{2-eq}/m³ compared to the conventional SCC was achieved with the use of the binary combination of OPC and FA as binder and RCA as aggregate. The use of chemical admixture alongside the aforementioned composition was found to result in SCC with acceptable fresh and hardened properties while having a lower environmental impact compared to conventional SCC. And the higher quantity of angular and finer RCA aggregates utilized was observed to result in a more inert mixture [32]. However, Assad [33] has reported that using RCA at about 30% replacement of aggregates in SCC will ensure its static and dynamic stability. The use of RCA as replacement of fine or/and coarse aggregate in SCC has been found to lead to carbonation of the SCC at all ages [34]. And the carbonation depth increases with the increase in the RCA content. This deterioration due to carbonation can be associated with the higher porosity of SCC incorporating RCA and the physical properties of the RCA. But a more carbonation resistance SCC can be produced by incorporating 50% RCA as replacement of NA and 10% SF as partial replacement of OPC [34]. The resistance to carbonation with the incorporation of SF is as a result of the densification and pore-filling capability of the microstructure. Densified microstructure will result reduce the ease at which different ions and chemicals including carbon dioxide ingress into the SCC.

2.2 Limestone powder

Limestone powder (LSP) is obtained as a by-product from the quarry of limestone. It is paramount to mention that LSP mentioned in this article is different from industrial LSP which is produced solely for specific applications and cannot be classified as waste. The high-volume production of aggregates has led to a significant production of this waste product which has made it an environmental threat as its ineffective disposal is detrimental to both the living organism and the environment. A limited study is available in the open literature about the use of LSP in SCC. However, with the available results, an increase in the slump was reported when LSP was used as a partial replacement of OPC in SCC [35]. And the optimum level of LSP to be used to improve the slump of SCC is 20%, as the use of LSP at levels above and below 20% gave a similar slump. But, at all levels of LSP, the slump observed was higher compared to the control without LSP [35]. Similar to other trends observed with the incorporation of other types supplementary cementitious materials (SCM) into SCC, no significant effect on the compressive strength of

SCC was observed up to 20% LSP as presented in Fig. 5. However, after 20% there is a decrease in the compressive strength of the SCC. Therefore, it is essential that when incorporating LSP into SCC, the optimum level for both fresh and hardened properties should be selected. Also, the limited application of this type of material in SCC calls for more research and development dedicated to this area.

2.3 Sawdust ash

Sawdust ash (SA) is obtained from the combustion of sawdust that is generated as a waste product by the furniture industry. Sawdusts are smaller particles produced during various finishing processes in the furniture industry such as cutting, milling and shaving. Due to the high production of various products from wood all over the world, there is a correspondingly high amount of sawdust being generated. A larger amount of the sawdust is being used by the furniture and other industries to generate energy by burning the sawdust. However, after the combustion of the sawdust, the remaining material is the SA which is mostly dumped openly or in landfills. In order to find a valuable use of this waste product, they can be incorporated into concrete as partial replacement of OPC. Extensive work done by Elinwa et al. [36] showed that it is viable to incorporate SA into SCC. Their study indicates an increase in flow time with increasing content of SA as presented in Fig. 6. But the slump at 5 and 10% SA gave a similar flow of about 7 s, whereas a flow time of 4 and 18 s was obtained at 0 and about 20% SA levels, respectively [36]. However, a contrasting behaviour was observed in the spread, as the spread decreases with increasing levels of SA.

The compressive strength of SCC incorporating SA was found to increase with increasing content of SA till 10% as presented in Fig. 7. After 10% SA, there was a significant decrease in the compressive strength which continues with increasing content of SA. The increase in

Fig. 6 Effect of SA level on the flow time and spread of SCC (data from [36])

the compressive strength can be as a result of the possible pozzolanic reaction of the SA. And the reduction after 10% might be as a result of the significant dilution of the cementitious content. This trend was observed at all ages of the SCC, and 10% can be concluded to be the optimum amount of SA to be incorporated into SCC. An increase in compressive strength with age as presented also indicates the progression of the hydration reaction with time. The microstructure analysis done by the authors also verified this claim. However, more studies on the application of SA are still needed to be able to increase the confidence in the use of this material in SCC.

Fig. 5 Compressive strength and ultrasound pulse velocity of SCC incorporating different types of SCMs (data from [35])

Fig. 7 Effect of SA levels on the compressive strength of SCC (data from [36])

2.4 Silica fume

Silica fume (SF) is a by-product of the ferrosilicon alloy industry, and this material has been used extensively as partial replacement of OPC in CC. The incorporation of SF into SCC has been reported to reduce the flow time of the mixture [37, 38]. And the amount of superplasticizer required to achieve a flowable mixture is higher with SCC incorporating SF compared to those of MK despite the two materials having similar fineness. The study by Lu et al. [39] also agreed with the decrease in the slump of the SCC with the incorporation of SF, which further reduces with increasing SF content as presented in Fig. 8. However, it will be observed from Fig. 8 that there was no significant difference in the slump for SF content ranging between 2 and 8%. The addition of SF into SCC was also found to result in an increase in the air content of the mixtures, which increased with higher content of SF [39]. About 3% higher air content was reported for 16% SF compared to that of the control without SF. Therefore, the impact of SF on the workability and air content of the SCC must be taken into consideration when selecting an optimum level for the SF.

Mohamed [40] determined the effect of SF on the mechanical properties of SCC at 10, 15 and 20% replacement of OPC. It was reported that the compressive strength of the SCC increased with the incorporation of SF up to 15% replacement of OPC, after which a decrease was observed. This was also true for different curing regimes (i.e. air and underwater) examined. However, samples air cured gave the highest strengths at all levels

of SF compared to those cured in water [40]. The strengths observed for different levels of SF were also greater than those of SCC incorporating the same levels of FA as presented in Fig. 9. And when SF and FA were used as binary blend replacement of OPC, the strengths recorded were still lower too when SF was used solely. The observation of strength increase at 10% SF is also similar to that of Akcay and Tasdemir [37] where they reported a significant increase in strength compared to the control with the incorporation of SF at 10%. Mastali and Dalvand [38] were able to improve the mechanical properties and impact resistance of SCC by the incorporation of SF and recycled

Fig. 9 Effect of SF and FA on the compressive strength of SCC (data from [40])

Fig. 8 Effect of different levels of SF on the slump of SCC (data from [39])

steel fibres. And the similar trend was also observed in terms of the split tensile and flexural strength of SCC incorporating SF. Also, Yazici [41] was able to produce a high strength SCC using high-volume FA and 10% SF. Their SCC exhibited enhanced durability in terms of chloride permeability and freeze–thaw when compared to that of CC. SF was also found to significantly enhance the carbonation resistance of SCC incorporating different levels of RCA as replacement of NA when used to replace 10% of OPC [34]. This enhanced durability can be associated with high quality of SCC compared to that of CC and the pore refinement ability of SF. Therefore, the use of SF at 10% can be deemed the optimum for use in SCC. This replacement level of OPC with SF is also similar to several recommendations made for CC [42, 43].

Despite the numerous advantages of incorporating SF into SCC, its use in high strength SCC was found to increase the autogenous shrinkage of the samples, which was more significant at a higher water-to-cement ratio and later ages [37]. The observed autogenous shrinkage was also higher compared to high strength SCC made with MK of the same proportion. This detrimental effect might be as a result of high fineness of the cementitious content and the availability of excess water in the mixture.

2.5 Fly ash

Fly ash (FA) is obtained as a waste product from the power production which utilizes coal as a source of fuel. Due to the abundance of many coal power plants still in service all over the world, there is a significant high production of this material in several parts of the world. FA has been extensively used in different types of concrete due to its pozzolanic reaction and pore-filling ability. Fly ash can be classified as either type C or F depending on its calcium content which gives it determines the way it reacts with other compounds. As SCC is a cementitious composite, FA can be used as partial replacement of OPC. However, it should be noted that the incorporation of any material into the composite will influence its fresh and hardened properties. A significant increase in the slump of about 60 mm was observed when FA was used as a partial replacement for OPC in SCC [44]. And more increase in the slump was observed with increasing fly ash content. Compared to other types of materials used as partial replacement of OPC, FA was found to give the highest slump [44]. This high slump resulting from the incorporation of FA has been attributed to the ability of the FA to disperse cement particles more due to its spherical shape. Despite the improvement of the slump with the incorporation of FA into SCC, no improvement was observed in terms of its compressive strength [44] as presented in Fig. 5. At 15% and 25% FA, the compressive strength observed was close

to that of the control. But at 35% FA, a significant decrease in strength was also observed at 28 days. Khatib [45] also reported a decrease in the strength of SCC with the incorporation of FA at different levels as partial replacement of OPC compared to that of the control. A similar trend in strength reduction was also reported by Guneyisi et al. [46] and Sahmaran et al. [47]. The ultrasound pulse velocity (UPV) results also show a similar trend to that of the compressive strength at all FA content as observed in Fig. 5. However, when using FA as a partial replacement of OPC in SCC, its effect on the early strength should also be taken into consideration especially when a high FA content is used. This is paramount as the pozzolanic reaction from the FA takes a long time compared to that of the hydration reaction. Therefore, a combination of FA with other SCMs such as MK, SF and SL might be necessary to achieve the early strength desired in some applications. But it is of importance to also note that these combinations will also affect other properties of the SCC such as workability and mechanical properties.

2.6 Slag

The metal industry produced several tons of slag (SL) annually as a waste product, and a significant amount of this waste is already being consumed in the production of cement and CC. Similar to CC, SL can be incorporated into SCC as partial replacement of OPC due to its pozzolanic behaviour. The incorporation of SL into SCC can be used to achieve a significant increase in the slump. An increase of about 10 mm was observed when 20% SL was used as a partial replacement of OPC in SCC [44]. More increase of about 30 mm was also observed by increasing the content of SL to 40%. However, a decrease of about 10 mm was observed when the content of SL was increased to 60%. This decrease in the slump at higher replacement level might be as a result of too much fine in the mixture which makes the mixture sticky and reduces the workability. Similar to the trend observed for the slump, a decrease in strength was observed when the content of SL was increased from 40 to 60% as shown in Fig. 5. But there is no significant difference between the compressive strength at 20 and 40% compared to the control without SL. Compared to other types of SCM, the use of SL as partial replacement of OPC has been found to result in higher resistance to sulphate attack [44]. This higher resistance has been attributed to SL refining the pore structure of the SCC and formation of more calcium silicate hydrates (CSH), thereby limiting the ingress of sulphate ions into the matrix. A possibility of segregation and low flowability was observed by García-Taengua et al. [48] when up to 50% OPC was replaced solely by SL in SCC. However, the use of

limestone powder alongside the SL has been found to be able to curb this segregation.

2.7 Glass waste

Glass has been a common material used by humans for various applications for several centuries. But the use of this material in large quantities also means there is a corresponding waste that ensues at the end life of materials made with glass. This waste can be generally referred to as glass waste, and it can be 100% recyclable when proper procedures are followed. Glass wastes (GW) are obtained from the disposal of various waste materials such as bottles and containers. However, only a small percentage of glasses are being recycled to produce new ones, while there still exists a large amount of GW disposed into the environment improperly. The reason for the improper disposal of glass wastes into the environment is due to the high cost associated with its recycling. GW can be incorporated into concrete as either replacement of fine aggregate or OPC depending on its size. The use of GW as 100% aggregate has been carried out by Meyer and Baxter [49]. Their study showed the viability of producing a structural grade concrete using GW as aggregates alongside 20% MK as partial replacement of OPC. However, the high silica in glass has made it susceptible to a type of alkali–aggregate reaction called alkali–silica reaction (ASR). This type of reaction occurs as a result of the interaction between the high alkali in the pore system with the certain types of silica present in some aggregates. However, this reaction can be prevented when GW is used as an aggregate by incorporating SCM such as fly ash as a partial replacement of the OPC [50, 51]. In terms of mechanical property, a decrease in the strength of SCC was observed when GW was incorporated as aggregate [52]. Increasing the content of the GW was also found to reduce the compressive strength of the SCC further. This trend of a decrease in the mechanical properties of SCC incorporating GW is also similar to that of Ali and Al-Tersawy [53], where they observed a decrease in strength with an increase in the GW content. This decrease in mechanical properties can be associated with the increase in air content of the SCC which leads to ease of collapse of the voids. However, an increase in slump ensues with the incorporation of GW into SCC, with more increase in the slump with increasing GW content [53]. But the chloride ion permeability of the SCC was found to decrease when compared to the controlled samples with no GW. On the positive side, incorporation of GW into SCC has also been found to result in lower drying shrinkage, and more decrease in drying shrinkage was observed with increasing GW content [52]. Ali and Al-Tersawy [53] reported weak cohesion between the GW and the cement paste due to the smooth surface

of the GW. And this weak cohesion might be responsible for the lower mechanical properties observed.

When the GW is processed into a very fine size (i.e. powder), it can be used as a partial replacement of OPC in SCC. Shi and Wu [54] incorporated glass powder as a partial replacement of OPC to produce a lightweight SCC. They observed improved durability in terms of chloride migration resistance and enhanced mechanical property in terms of compressive strength of the SCC compared to those incorporating FA. However, the incorporation of the glass powders was found to increase drying shrinkage and shorten the setting time of the SCC. These detrimental properties might be as a result of the high fineness of the glass powder. As mentioned earlier, the use of glass is associated with ASR in concrete due to its high silica content and high alkali of the pore. However, no deteriorating effect in terms of ASR was observed when clay was used as a coarse aggregate alongside glass powder as partial replacement of OPC in SCC [54]. The use of air entrainer alongside the glass powder was also found to be non-effective as no significant increase in air content was observed with the admixture. The incorporation of glass powder was also found to increase the setting times of the SCC due to the contribution of the alkali in the glass powder to the hastening of the hydration reaction. When incorporating GW into SCC as aggregate or replacement of OPC, it is essential to incorporate other types of SCMs with it to ensure there is no durability threat that ensues from its use especially in terms of ASR.

2.8 Basalt powder

Similar to limestone powder, high amount of basalt powder (BP) is produced as a waste product in basalt quarries. The high quantity of this powder produced in the quarry is a serious health and environmental hazard if not properly disposed of Felekoglu [55]. Therefore, their use in concrete, especially SCC, will create an economical avenue to manage the waste efficiently while adding to its value. When BP was used as a partial replacement of OPC in SCC, no significant effect of the compressive strength was observed when BP up to 10% replacement of OPC. However, a further increase above 10% resulted in a decrease in the compressive strength as presented in Fig. 5. A similar trend in the slump was observed above 10% BP. No significant change in the slump was observed at 10% BP. But at 20% BP, an increase of about 10 mm was observed compared to the control without BP [44]. This increase in the slump can be attributed to the large quantity of fine particles with a higher surface area. The strength observed for all mixtures incorporating BP was found to increase with age which indicates continuous hydration and pozzolanic reaction. More research is still needed in the incorporation of BP in

SCC and other types of cementitious composite especially on its durability in an alkali environment.

2.9 Marble powder

One of the most used materials for decorative purposes is marble. However, the production of marble produces a huge amount of marble powder (MP) as waste during its production [56]. With about 50% of the raw materials mined to produce marble being marble powder, its disposal as waste is a financial threat to the producers. In addition, the average size of marble powder is about 200 μm , and the disposal of this type of material into the environment can lead to a consequential contamination of both water and air. Therefore, finding ways to utilize this large amount of waste generated from marble production will ensure that profit is being maximized while protecting the environment. The use of MP as partial replacement of 10% OPC in SCC has been reported to give similar strength compared to those made with 100% OPC [35]. It can be observed from Fig. 5 that no significant effect on the strength of SCC was observed when MP was used as a partial replacement of OPC at 10 and 20%. However, when the level of MP was increased to 30%, a decrease in the compressive strength of about 5 MPa was observed at 28 days. Based on the lower difference in the compressive strength observed at all levels up to 30%, the effect on compressive strength at these levels can be deemed insignificant. This insignificant effect of MP on the compressive strength of SCC might be as a result of the pozzolanic and pore-filling ability of the MP which complements the OPC replacement. The UPV results also confirmed these effects, as there was only a slight decrease in the velocity of 30%, whereas the UPV at 10 and 20% were similar to that of the control [35]. However, to be more proactive in the incorporation of this material into SCC, it can be used as 10% replacement of OPC. Though it was mentioned that no significant difference in the compressive strength between all replacement levels, 10% MP was deemed optimum as it resulted in compressive strength similar or higher to that of the as shown in Fig. 10. But in comparison to other waste materials such as BP and LP, MP was able to result in a higher strength due to its ability to function as a nucleation area for early hydration products which further increase the rate of the reaction [44].

The incorporation of MP as partial replacement of OPC has been found to increase the slump of the SCC mixture [44]. And the slump observed for 10–20% MP gives similar slump of about 710 mm which is higher compared to that of the control which is about 690 mm. However, when the percentage of MP was increased to 30%, a decrease in the slump of about 700 mm was observed. As the difference in the slump between 10 and 30% replacement of OPC

Fig. 10 Effect of MP content and age on compressive strength of SCC (data from [35])

with MP is about 10 mm, this effect can also be deemed insignificant. In comparison to other types of materials used as a partial replacement for OPC (i.e. FA, SL, LP and BP), MP was found to have a lower slump [44]. However, the observed slump values were still within the range that can be used to classify the concrete as SCC. Similar to BP, this type of waste is less explored and more research and development in this area is imminent.

2.10 Rubber waste

As urbanization evolves significantly coupled with an increase in the population, there is a corresponding increase in the use of automobiles which makes use of rubber tires. And due to the replacement of these tires with time after deterioration, a large amount of these rubber tires is being dumped in the environment where they consume space and contaminate the environment. For example, about 37 million rubber tires were estimated to be produced in the United Kingdom in 2002 only, and this number is expected to rise due to the reasons mentioned earlier [57]. In more populated countries like the USA, approximately 275 million rubber tires are produced as waste per year [58]. Considering the significant increase in the number of automobiles and consequentially rubber tire waste that will be generated in the coming years, a need for action is required to find ways to manage these wastes effectively. Some of the ways in which rubber wastes (RW) are used are in the marine industry where they are used as shock absorbers for various marine infrastructures. However, only a minute amount of these RW is being used for this purpose, and this application is only secluded to certain parts of the world. Other ways in which RW can be managed are by burning them, but this method is not sustainable as it contributes a significant amount of carbon dioxide into the environment. The use of RW

in concrete is one of the main sustainable ways in which these wastes can be managed and ensure sustainability of the materials. In addition, as conventional SCC does not exhibit high ductility, the incorporation of RW can be used to enhance the ductility of the SCC. Several types of rubber wastes can be incorporated into SCC as a replacement for aggregate (i.e. both fine and coarse aggregate). These types range from threaded rubber [59], crumb rubber [60, 61], cryogenic rubber, treated milled rubber [62], etc. Crumb rubbers are mostly used as partial replacement of fine aggregate, while threaded rubbers are mostly used as a replacement of coarse aggregate [63, 64]. The inclusion of rubber waste and glass powder increased strength properties of concrete, and at the same time, workability of the concrete was improved because of lesser water absorption nature of rubber waste and glass powder [65]. A correlation between RW and strength reduction in CC is presented in Fig. 11.

Numerous studies on the use of rubber wastes in concrete have reported a depreciation in the mechanical properties of concrete irrespective of the properties of the rubber used [59, 66–68]. This trend of decrease in these properties also continues with increasing content of RW. The decrease in mechanical properties was also reported when RW is incorporated into concrete as a partial replacement of NA [69]. This decrease in strength has been found to be as a result of debonding of rubber particles from the binder paste when the load is applied [70]. This deterioration further creates more voids that lead to the failure of the SCC. However, the mechanical properties of the SCC obtained were still higher compared to those made with similar CC. But increasing the content of rubber led to a significant decrease in the strength of the SCC. In the same study by Li et al. [70], a reduction in the split and tensile strength with increasing content of rubber was reported. But the amount

of decrease was significantly lower when compared to that of the compressive strength. This trend was also reported for the young modulus of the SCC incorporating RW. However, the use of RW in SCC was found to improve the ductility behaviour of the SCC [71]. These observations also agreed with that of CC incorporating RW compared to the control without RW [72]. Comparing the results from different studies, no direct correlation was found between the RW content and reduction in strength as presented in Fig. 11. Also, Güneysi et al. [73] and Batayneh et al. [74] reported an increase in the strain of the SCC containing RW in contrast to the decreasing compressive and tensile strength of the SCC. The incorporation of chipped RW was also found to improve the impact resistance of SCC during the first crack and failure [75]. However, SCC incorporating RW has a higher crack size compared to those without RW [76]. Possible higher energy absorption of the SCC incorporating RW has been attributed to the higher cracks size. Also, it has been found out the stiffness of SCC incorporating RW is lower when compared to that of the CC incorporating RW. This lower stiffness has been ascribed to the densified microstructure of the SCC compared to CC which results in a compacted microstructure [69].

Slump which is a critical property of SCC is also found to be affected negatively with the incorporation of RW. Reduced workability with the incorporation of RW into SCC has been ascribed to the high friction between RW particles and other components in the concrete [74]. Also, the surface texture has been found to influence the workability of the SCC negatively. This reduction in the slump was also reported by Hernandez and Barluenga [77], Gesoğlu and Güneysi [78], Khatib and Bayomy [79], Albano et al. [80], Wong and Ting [81]. However, the slump of the SCC incorporating RW can be improved by using FA as a partial replacement for OPC and the use of superplasticizers at higher dosages. SCC incorporating RW exhibits higher porosity and water absorption compared to CC [69]. This high porosity has been ascribed to the possibility of high entrapment of air during mixing and the difference in size of RW compared to NFA. And this strongly agrees with several other studies where similar observations were made [74, 77, 82]. As RW is deemed lighter than the conventional aggregate, their use in concrete has been reported to yield a lightweight concrete. Lightweight SCC will create an avenue to use this type of application for applications in areas where it is necessary to reduce the dead load of the structures. But ways to improve the workability and mechanical properties using chemical and mineral admixtures, respectively, must be considered.

Fig. 11 Correlation between RW level and strength reduction in CC (data from [59, 66–68])

2.11 Rice husk ash

During the production of rice, a huge amount of rice husk is produced as a waste product. A large percentage of this waste is used by the agricultural and other industries as a source of energy by burning it. After the combustion of the rice husk at temperatures around 650 °C, Rice husk ash (RHA) is obtained as a residue, and this residue is mostly deposited in open spaces and landfills where they consume a large amount of space and pose a contamination threat to the environment. Significant use of RHA has evolved in CC as supplementary cementitious material (SCM) to replace OPC which is associated with high cost, energy and carbon emission. Since OPC is also used as a binder in SCC, RHA can be incorporated to replace OPC to enhance its properties, reduce overall cost, and reduce the negative environmental impact of OPC and RHA. The incorporation of RHA as partial replacement of OPC has been found to reduce the workability of the SCC which further reduces with increasing levels of RHA [83–85]. The use of RHA more than 10% by mass of the binder in SCC has been found to reduce the workability of SCC below the recommend levels which is detrimental to the application of SCC [84]. Reduction of about 100 mm compared to that of the control was observed at 15% RHA, while at 5% RHA, only about 40 mm reduction in slump ensued. This reduction at higher levels of RHA has been attributed to the high surface area of the RHA. These observations about the reduction in the slump with increasing RHA content also agreed with that of Moloei et al. [86]. The incorporation of RHA into SCC has been found to result in the need to incorporate superplasticizer to achieve desirable slump [87]. The amount of superplasticizer needed also increases with the increase in the RHA content. For example, in order to obtain a slump of about 750 mm, Rukzon and Chindarasirt [87] used 3, 5, 6 and 7% for 0, 20, 30 and 40% RHA, respectively. The need to increase the amount of superplasticizer with RHA level is associated with the cellular structure and specific surface of RHA particles. This observation was also agreed to earlier studies by the authors [88].

The resulting compressive strength from different studies that incorporated RHA into SCC is presented in Table 1. As mentioned earlier, it can be observed from Table 1 that the compressive strength of the mixtures reduces with increasing content of RW and a higher difference in strength is more evident at a water-to-cement ratio of 0.50. The study by Rukzon and Chindaprasirt [87] also agreed with this observation as they reported a decrease in the compressive strength of the SCC with the incorporation of RHA. The observed strengths are lower compared to those of the control without RHA but are still above 25 MPa which shows that can be used for structural

Table 1 28th-day compressive strength of SCC incorporating different levels of RHA

Ref.	w/c	% of RHA	Compressive
[84]	0.55	0	41
		5	43
		10	48
		15	51
		20	44
		25	42
		30	37
[88]	0.46	0	28
		20	27
		30	25
		40	22
[89]	0.41	0	38
		10	40
		15	44
		20	39
[86]	0.50	0	53.4
		5	57.7
		10	54.8
		15	50.3
		20	47.5
[90]	0.50	0	48.5
		5	42.9
		15	40.9
		20	33.5

applications. In contrary, Kannan and Ganesan [84] only observed a decrease in compressive strength after 15% replacement of OPC with RHA. However, they were able to enhance the compressive strength of the SCC by using both RHA and MK as binary replacement of OPC up to 35%. Gill and Siddique [91] were also able to enhance the mechanical properties of SCC incorporating RHA by adding MK. The ability of MK to enhance the mechanical properties of the SCC can be attributed to its higher pozzolanic and pore refinement capability, and the acceleration of early age strength of the SCC [92]. On the other hand, Ahmadi et al. [93] showed that the incorporation of RHA between 10 and 20% resulted in an increase in strength at later ages due to the pozzolanic reaction. However, the compressive strength recorded at early ages is lower which is similar to other studies. On the contrary, Memon et al. [94] and Rahman et al. [90] reported an increase in the compressive strength of SCC up to 15% replacement of OPC with RHA. Higher strength reported in these studies has been attributed to the enhanced workability which ensures proper compaction of the mixtures. A similar trend was also reported by Chopra et al. [89] for compressive strength and split tensile strength of the SCC where there

was an increase till 15% RHA. Moloei et al. [86] reported an increase in mechanical properties (i.e. compressive, split tensile and modulus of elasticity) up to 5% RHA. When the content of RHA was increased past 5%, there was a corresponding decrease in the mechanical properties which continues with increasing content of RHA. The contradictory reports by various studies can be might be as a result of the RHA used obtained from different sources. The source of the rice husk alongside the method of combustion of the rice husk has been found to significantly affect the resulting properties of the RHA [20]. Despite contradictory results on the effect of RHA level on mechanical properties of RHA, it is generally accepted that the mechanical properties of SCC incorporating RHA increased with age. This increase in mechanical properties with age will be as a result of the progression of the pozzolanic reaction which leads to further densification of the microstructure. Figure 12 shows the effect of RHA content and age on the porosity of SCC.

The use of RHA as a partial replacement of OPC has been reported to increase the porosity of the SCC, which further increases with increasing the content of RHA [87]. However, there is a decrease in porosity with the age of the SCC as presented in Fig. 12. Reduction in the porosities has been ascribed to the formation of more reaction products with time which further densified the microstructure of the SCC. Safiddin et al. [95] reported lower porosity when RHA is incorporated into self-compacting high-performance concrete. This lower porosity can be attributed to the lower water-to-cement ratio used, the microfilling ability of the RHA and its pozzolanic reaction. In terms of chloride permeability, RHA was found to improve the resistance of SCC to chloride ion penetration due to the reason mentioned earlier [87]. More reduction in the chloride penetration was observed with increasing content of RHA and age of the SCC. The incorporation of RHA has also been found to enhance the resistance of SCC

Fig. 12 Effect of RHA content and age on the porosity of SCC (data from [87])

to hydrochloric acid compared to the control [86]. Similar resistance to the sulphate attack was also observed for SCC incorporating RHA, and this was found to be better compared to SCC incorporating MK as partial replacement of OPC. Chopra et al. [89] also reported a reduction in chloride permeability of SCC up to 20% RHA, after which the chloride penetration increased. However, the chloride permeability at 20% RHA is still less than that of the control without RHA. Therefore, when incorporating RHA into SCC to obtained desired properties, it is paramount that the optimum replacement level in terms of excellent fresh and hardened properties should be determined.

2.12 Brick waste

After concrete waste, brick waste (BW) is the next most produced construction and demolition wastes. Brick wastes are generated as a result of the intentional and non-intentional demolition of structures made with bricks. A large percentage of brick waste being generated is as a result of rapid urbanization which results in replacement of these old bricks structures with new ones made with new bricks or different building materials. The generation of these wastes in large quantities has called a need to find a useful application of these wastes in new constructions due to large space consumption that ensues from their disposal. Incorporating BW into concrete is one of the most cost-effective ways to manage these wastes, and their use in a special type of concrete such as SCC is not an exception. Depending on the crushed size of the BW, it can be incorporated into concrete as partial replacement of OPC or/and aggregate. BW has been found to be a possible replacement of OPC due to its pozzolanic reaction which can be maximized to improve the strength of cementitious composite [96, 97]. However, the BW is susceptible to reduce the workability of the mixture when it is used above 25% [97]. Sun et al. [98] used BW to replace OPC and FA in SCC, and they studied how it affects the fresh and hardened properties of the SCC. In contrast to the effects of other wastes incorporated into SCC and CC, Sun et al. [98] observed similar or higher compressive strength in SCC incorporating different levels of BW compared to that of the control. However, the highest compressive strength was observed only for 10% replacement of OPC. The strength improvement of SCC with the incorporation of BW has been attributed to the pozzolanic and internal curing capability of the BW. The incorporation of BW into the SCC also resulted in a reduction in the autogenous shrinkage, and 5% BW gave the highest reduction of about 30% reduction in autogenous shrinkage compared to the control. The reduction in autogenous shrinkage with the incorporation of BW was ascribed mainly to the internal curing capability of the BW. They also observed

no significant change in the slump for OPC replacement level up to 5%. Though quite a number of studies have explored the use of BW in CC, there is still limited study on the use of BW in SCC. Therefore, more research and development are still needed in this area. Development of SCC incorporating BW will contribute to achieving excellent mechanical and durability properties while conserving the environment.

2.13 Coal bottom ash

Coal bottom ash (CBA) is one of the waste products obtained from the combustion of coal for power generation. It is imperative to mention that CBA is different from FA, though they are both generated from the same industry. In order to improve the sustainability and cost-effectiveness of SCC, Siddique and Kunal [99] incorporated CBA as partial replacement of fine aggregate alongside FA as partial replacement of OPC. CBA in the range of 10–30% by mass was used to replace fine NA in their study, while the FA was used at a fixed level of 15% to partially replace OPC. Incorporating the CBA into SCC was found to decrease the compressive strength and more decrease in the compressive strength with increasing levels of CBA [99]. This decrease in compressive strength can be ascribed to the introduction of more water into the system to complement the high absorption of the CBA. Nevertheless, the compressive strength of SCC incorporating CBA increases with age as presented in Fig. 13. A similar trend was also observed for the split tensile strength as shown in the figure, where the split tensile strength decreases with increasing levels of CBA but increases with age at all replacement levels.

Introduction of CBA was also found to increase the carbonation depth of the SCC, with more carbon resistance with increasing levels of CBA [99]. A significant weight

loss was also observed when SCC incorporating CBA was subjected to freeze and thaw cycles. And the similar trend of reduced resistance to the detrimental forces in the environment was reported with increasing levels of CBA. Despite higher penetration of chloride ions into SCC containing CBA compared to the control, the charges passed below 1000 coulombs shows that the SCC is durable to an extent. In an earlier study by Siddique et al. [100] where they vary the content of CBA alongside that of FA, a similar trend of decrease in mechanical and durability properties with the incorporation of CBA. Therefore, it is necessary that CBA be incorporated into SCC in lower amounts, and when possible be SCMs such as MK should be incorporated to act as a filler in the mixture.

3 Conclusions and future perspectives

Self-compacting concrete is one of the most significant developments in concrete technology, and more application of this material is imminent. In order to ensure that the concrete industry achieves its sustainability goals with the use of this material, it is imperative to incorporate waste materials as a replacement for both its binder and aggregates. More research is still needed in producing a more sustainable SCC using waste materials, especially by determining the best mix designs to be used. In addition, understanding the long-term effect of these materials on the mechanical and durability property of SCC still needs more dedicated investigations.

This overview has explicitly explored the use of different waste materials in SCC, and the following conclusions were drawn from the study:

- (1) SCC is a more eco-friendly concrete compared to other concrete technologies due to its ability to eliminate both energy consumption and pollution of the environment.
- (2) In order to achieve acceptable workability of SCC, the use of superplasticizer is essential instead of increasing the amount of water. Similar to CC, increasing the water content will lead to a decrease in the strength of the SCC.
- (3) Light density of waste materials incorporated into the SCC will result in SCC with a lightweight SCC which is suitable for several structural construction purposes.
- (4) Materials used to replace OPC are referred to as supplementary cementitious materials (SCM). An increase in slump generally ensues from the incorporation of SCMs into SCC. However, the use of most SCMs at certain lower levels has no significant effect on the compressive strength of concrete, but higher amount of it can have a detrimental effect on the

Fig. 13 Effect of CBA levels on the compressive and splitting tensile strength of SCC (redrawn from [99])

compressive strength. Therefore, proper precaution must be followed to ensure that the level of SCM selected to replace OPC in SCC is beneficial in terms of the resulting fresh and hardened property.

- (5) Generally, incorporation of most waste materials as aggregate results in a decrease in its properties, and this decrease in properties can be neglected due to its enormous advantage in terms of sustainability and cost. Moreover, despite the reduction in properties, the resulting properties still satisfy the requirement for different applications.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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