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Review Article

An overview of the impact of using glass powder on mechanical, durability properties in self-compacting concrete

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ABSTRACT

Color, texture, and shape alternatives of glass, chemical similarity, and close reactions with cement has made it preferred in the construction industry. Studies reveal that the use of glass in concrete after grinding to micron size provides improvements in strength and durability parameters by increasing pozzolanic reactivity. Besides, research studies have also shown that glass powder not only contributes positively to strength and durability properties but also reduces the amount of cement used, energy and cost losses. This paper presents current studies on waste glass powder, one of the by-products used in self-compacting concrete. Information was given about the physical and chemical properties of glass powder used in related studies. In addition, the effect of glass powder in self-compacting concrete on fresh, strength, and durability properties were investigated in detail. Inferences were made in line with the information in the literature and suggestions were made about what can be done in future studies.

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1. INTRODUCTION

Advances in the field of chemistry and the advancement of polymer technology have led to the discovery of highly impressive fluids. These plasticizers, which have high water-cutting properties, also increase the workability of concrete. With this effect provided by the fluids, the researchers demand that the concrete be placed without the need for any compression during the placement of the concrete. This situation has led to the emergence of a notice called Self-Compacting Concrete (SCC). SCC has very important advantages such as fast construction time, reduction in labor costs, facilitating surface smoothing, providing the opportunity to obtain a void-free and smooth surface, providing impermeability, flowing consistency, not requiring placement and compaction, and increasing the workability, preserving time-related loss of consistency. It is also used in mineral additives as well as chemical additives such as superplasticizers, viscosity-increasing, air-entraining additives in SCC production. These additives must have pozzolanic properties and comply with the relevant standards before use [1]. There are many studies on the usage of pozzolanic materials such as fly ash (FA), silica fume (SF), granulated blast furnace slag (GBFS) from mineral admixtures or by-products separately or in combination in SCC. In studies, both mechanical and durability performances of

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this type of additives were examined and their suitability in concrete was investigated and good results were obtained. In addition to these types of additives, the usability of waste glass aggregate or waste glass powder (WGP) in concrete has been discussed recently. Glass, which has similar properties to cement in terms of physical, chemical, and mechanical structure, can make a positive contribution to the environment as it can reduce cement consumption when used in concrete after grinding to micron size WGP. Using it in this form in concrete not only improves its mechanical and durability properties but also provides environmental and economic benefits [2–7].

The theme of sustainability has taken an important place in the concrete industry in recent years. It is aimed to ensure sustainability in the concrete sector with options such as reducing the amount of cement used, using recycled aggregate, and adding treated water to the concrete mixing water. The environmental impact assessment, which includes the social consequences of potential permanent or temporary effects on the environment and alternative solutions, needs to be analyzed. Environmental impacts related to the production of a product are evaluated, from the extraction of the raw material to its final disposal. This concept, which covers the entire life cycle assessment (LCA), is also called the cradle-to-grave approach. When concrete LCA studies are evaluated, it is known that it is negative in terms of production, transportation, placement, CO_2 emission, energy consumption, cost, and many other factors. The use of industrial wastes in concrete becomes a sustainable and smart solution to limit these effects and create a positive effect. At this point, the use of glass, one of the industrial wastes, protects the environment by reducing the consumption of natural materials, CO_2 emissions, and energy consumption. However, with the wide usage area of glass, the emergence of high amounts of waste glass is a serious problem. Every year, $2x10^{13}$ kg of solid waste is produced in the world and 7% of this waste is glass waste. Storage problems can be solved by creating new areas where waste glass can be used. By expanding the recycling possibilities of waste glass, which is a material currently used in recycling, the waste storage costs and the number of required facilities can decrease, and this can also be reflected in the production costs as a decrease.

In this review study, the effect of the utilization of WGP, which is one of the industrial wastes, on the mechanical and durability properties of SCC is discussed. In the studies carried out so far, many researches have been carried out on the integration of different industrial and agricultural wastes, especially into normal concrete. Since SCC is more difficult than normal concrete in terms of added materials, placement, flow, and different methods and meeting special project requirements, studies are limited. In this study, the main aim is to present the current studies on the inclusion of WGP in SCC, to give information about the methods used, to express the missing aspects of the studies, and to draw attention to the need for more studies to be added for the limited literature on this subject.

2. LITERATURE SURVEY ON THE USAGE OF WGP IN CONCRETE

Raju and Kumar [8] stated that there was a decrease in consistency and density with the increase in the use of WGP in concrete. The increase in surface area due to the fineness of WGP affected this result. In the studies conducted by Elaqra et al. [9] and Rahma et al. [10], the increase in the content of WGP, increases slump. The reason for this is that as the amount of hydrated cement decreases, less water is required for hydration which results in the increase in consistency. Another reason for this is that WGP is transparent, it has smooth surface texture, low water absorption, and a low specific surface compared to cement. Studies on the effects of hardened concrete have shown that there is a decrease in the compressive and flexural strengths at the initial gain, while an increase in the final strength. It has been determined that the interfacial transition zones (ITZ) intensifies with the acceleration of the pozzolanic reaction in later ages. When the strength at later ages were examined in the studies, it was observed that the use of WGP at 0–20% by volume or weight as cement or aggregate substitute resulted in positive results on the strength [10–14]. It has been understood from the studies that the increase in flexural strength improves the interface region and slows down the crack propagation rate thanks to the fineness of WGP. The contribution of WGP to mechanical properties is realized by showing better reactivity, being a finer-grained material, and having more surface area than cement [3, 15–21]. In addition, the WGP used in concrete also contributes to the durability parameter since the concrete has low porosity and moisture content, lower absorption rates (surface water retention), a decrease in alkali-silica reaction (ASR), and chloride depth decrease in drying shrinkage, increase in resistance to sulfate, electrical and corrosion, along with strength [3, 10, 14, 18, 22–24]. Corrosion is one of the most serious problems affecting reinforced concrete structures and it should be tried to inhibit damage or to keep it at a minimum even if the damage cannot be prevented. Resistance to corrosion in reinforced concrete is possible by increasing the pH values of WGP. The increment in pH value has been associated the color of glass as well as with the rise in the amount of WGP. It has been found that green glass is richer in calcium alumina than white glass, and silica does not dissolve easily in voids [25].

3. SELF-COMPACTING CONCRETE

SCC is a special type of concrete with a very fluid consistency, which can settle with its weight, even under harsh conditions (with dense reinforcement and deep sections), compressible without requiring any internal and external vibration, and maintains its cohesion without causing problems such as segregation and bleeding. Its differences from plain concrete is that it has all or some of the chemical additives, viscosity enhancing additives, and a very high amount of inert or pozzolanic mineral additives are used in this concrete. In addition, with SCC, high quality finishing is obtained in terms of architecture and aesthetics in reinforced concrete structures compared to conventional concrete. However, more knowledge and experience are required in determining the components and mixing ratios of SCC compared to conventional concrete. Although SCC is classified according to its workability properties, it must also meet certain mechanical performance criteria. The expected mechanical performance of SCC depends on the following conditions;

- Selection of material types and ratios suitable for the desired performance (mixture optimization),
- Minimization of the change in material types and ratios during the production phase (using homogeneous materials, reducing the problems that may arise from raw material variability),
- Considering the effect of ambient conditions on SCC, both in the design of the mixture and in the production phase.
- Continuously control of fresh concrete quality with selected tests during the production phase, immediate intervention in the mixture that does not provide the desired properties.

If the above criteria are met, it is possible to obtain the highest mechanical performance from SCC. This condition is also valid for normal concretes. However, the sensitivity to these criteria is higher in SCC and it is much more difficult to correct the mistakes to be made compared to normal concrete production [26–28].

3.1. History of SCC

Thanks to the development of the ready mixed concrete sector in the world, other sectors that provide raw materials to the sector have also developed. One of the most important of these is the additive sector. Concrete additives are mainly used to improve and develop the properties of concrete and especially in the production of concrete that is more resistant to environmental conditions. Before the use of chemical additives in concrete, a high water/cement (w/c) ratio was used in the concrete mix to increase the workability of the concrete. However, it reduces the quality of the concrete. In the early 1970s, plasticizers or superplasticizers were used to increase the workability of concrete at a low w/c ratio. In 1986, research on self-leveling and compacting concrete was started at the University of Tokyo, and thus the first steps of SCC design were taken. After the ACI Workshop in Bangkok in 1994, many researchers started to work on SCC. Usage of SCC in Swedish highway structures in 1990 is the first example in Europe. In 1996, with the publication of the papers on SCC at ACI Autumn Congress in New Orleans, SCC became more used in the United States and Canada. After 1997, European Union started studies aiming to increase the use of SCC. In 2005, European Precast Concrete Manufacturers Association (BIBM), European Cement Association (CEMBUREU), European Ready Mixed Concrete Association (ERMCO), European Concrete Admixture Manufacturers Federation (EFCA), European Federation of Special Construction Chemicals and Concrete Systems (EFNARC) have prepared a common specification by coming together [26–28].

4. SCC APPLICATIONS

- It can be used in all kinds of reinforced concrete productions, but due to its high cost, it is used in structures and prefabricated elements, panels, and floors where concrete settlement is difficult.
- It is used in reinforcement productions due to the problems experienced in the placement of concrete and facilitates the strengthening process.
- Unlike the geometrically frequently used molds, it can be used in unusual molds, in very densely reinforced structures, where it is not possible to use vibrators.

5. WASTE-GLASS

Glass is not affected by water and neutral liquids under normal conditions. The solubility rate of amorphous silica in water at 25°C is 0.012%, but this rate increases as the temperature increases. As a result, non-ionized monomeric silica is formed. Although the resistance of glass to acids is generally high, hydrofluoric acid and phosphoric acid at high temperatures affect silica glass. This effect of hydrofluoric acid on glass is used in the glass industry for polishing glass and etching glass for various purposes. To produce glass resistance against water and humid environments, limestone (CaO) must be added to the glass. Limestone or limestone-added glass products are both resistant to humid environments, water and exhibit stable behavior without losing their qualities. The molecular structure of glass, which has an amorphous structure, is irregular and does not have a certain freezing and melting temperature. It softens as heat is given, melts at an uncertain temperature, and has no upper temperature limiting the melting process. The density of the glass varies between 2.20 g/cm^3 and 8.00 g/cm^3. When it is desired to increase this density, some oxides such as ZnO, BaO, and PbO can be added to the mixture. According to the Mohr hardness scale, the hardness of normal glass is between 5 and 6, that is, between apatite and feldspar. Since materials softer than this hardness cannot scratch the glass, the glass does not lose its transparency and brightness for many years. Abrasion resistance also depends on the raw materials in the glass. SiO_2 and B_2O_3 increase this resistance, while Na_2O, CaO, and PbO decrease it [29–34].

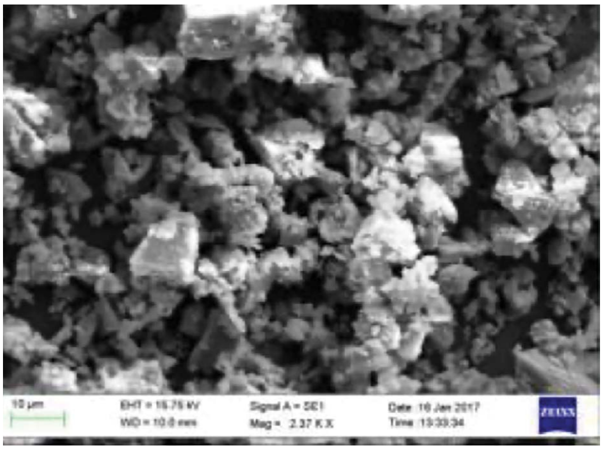

Figure 1. SEM image of WGP [40].

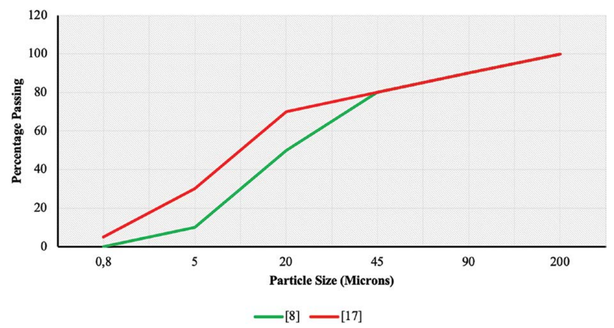

Figure 2. Sieve analysis of WGP.

5.1. Waste Glass Powder

WGP is a building material with an amorphous structure and a high degree of silica content, with a density of 2.6 g/cm^3, obtained by being brought to micron dimensions after certain processes such as after the collection, separation, and sieving of waste glasses, after certain processes. In addition to its low conductivity and moisture-absorbing properties, it also has high hardness. For this powder to show binding properties, the particle size must be less than 0.075 mm. The powder in these levels is sieved through the sieve and made ready for use and can be used as an alternative binder replacement of cement [35–37].

The physical properties of WGP, which has lower specific gravity and bulk density than cement, are given in Table 1, information on its chemical properties are given in Table 2, and SEM image is given in Figure 1.

The replacement of waste glass, which has a high SiO_2 content, with cement, also affects the pozzolanic reactivity index. As the waste glass reacts with calcium hydroxide and consumes cement hydrates, the pore structure is filled with calcium silicate hydrate gels and a denser matrix structure is formed. It was determined that grinding the glass into 45–75 µm glass powder and using it replacement of cement up to 30% increased the pozzolanic reactivity index as well as the strength index. It was observed that another parameter increasing the pozzolanic activity apart from the fineness was the curing temperature. As the curing temperature increased, the pozzolanic reactivity index increased [5, 10, 38, 39].

Table 1. Physical properties of WGP

Physical properties	Ref.				
	[8]	[41]	[42]	[17]	[24]
Specific gravity	2.58	2.43	2.22	2.53	2.68
Bulk density (kg/m^3)	2.58	2.53	–	–	–
Fineness (%)	–	3.4	–	–	–

Table 2. Chemical properties of WGP

Component	Ref.					
	[8]	[12]	[43]	[24]	[17]	[44]
SiO_2	72.5	72.61	70.22	70	72.08	71.4
Al_2O_3	0.4	1.38	1.64	1.2	2.19	2.54
Fe_2O_3	0.2		0.52	0.65	0.22	0.37
CaO	9.7	11.42	11.13	8.7	10.45	11.2
MgO	3.3	0.79	–	3.7	0.72	1.6
Na_2O	13.7	12.85	15.29	16	13.71	12.25
K_2O	0.1	0.43	–	0.35	0.16	0.36
SO_3	–	–	–	<0.05	–	0.16
CI	–	–	–	<0.005	–	0.04
TiO_2	–	–	–	–	–	0.1
Cr_2O_3	–	–	–	–	–	0.01
LOI	0.36	–	0.8	0.92	–	0.82

6. EFFECT OF WGP USE ON FRESH AND HARDENED CONCRETE PROPERTIES IN SCC

Prasetyo et al. [45] investigated the tensile strength and porosity of SCC to which WGP (5–30%) was incorporated in various proportions as replacement of cement. Good results were obtained in terms of tensile strength at the ratio of 5% WGP, and the optimum value was determined at the ratio of 5.5% WGP. For the porosity values, better results were obtained than the reference concrete at the ratio of WGP between 5–10%. A decrease in properties was observed for WGP percentages higher than these ratios.

Noorzyafiqi et al. [46] examined properties such as flow, specific gravity, and compressive strength in SCC with partial replacement of WGP for 14 days. In the study, the mixture was made using a 5–30% WGP, 0.35 w/c ratio, and 1% superplasticizer. The research results showed that the flow, specific gravity, and compressive strength increased with the addition of 5–20% WGP in SCC, while the properties decreased at 25% and 30% WGP ratios.

In the study conducted by Khudair et al. [47], in which WGP was added to SCC and its effects on rheological properties and compressive, splitting tensile and flexural strengths were analyzed, WGP was used at the ratio of 0–40% replacement of cement, and five different mixtures were designed. In the experimental study, compressive strengths were realized on the 7th, 28th, and 56th days, and splitting tensile and bending strength were performed only on the 28th day. The research was not only limited to this but also included the evaluation of CO_2 emission and production cost in terms of sustainability with the statistical optimization model. The results demonstrated that the rheological properties (Slump flow, T500, L-box, and Segregation test) and compressive, splitting tensile and flexural strength increased by 30% with the usage of WGP, the maximum compressive and splitting tensile strength were increased by 10% with the use of WGP and the highest bending strength was attained by using 20% WGP.

Yücel [40] constituted SCC by using WGP replacement of FA and assessed the fresh, mechanical, and durability effects of WGP on SCC. In the study, SCC's were produced with 550 kg/m^3 binder content, 0.32 water/binder (w/b) ratio, and a constant slump diameter of 700±10 mm. The reference mixture was designed by using 20% of the total binder amount of FA, while the other mixtures were prepared by using 5–20% WGP replacement of FA. The results showed that increasing WGP amount decreased slump diameter, height ratio in L-box, while T500 (mm) slump flow time and discharge time in V-funnel increased compared to reference mixtures. In addition, with the increase in the amount of WGP used replacement of FA, compressive, flexural, and splitting strength results on the 28th and 56th days increased, and these strengths increased as the curing time increased. The best results regarding mechanical properties were found in mixtures designed using 20% WGP replacement of FA. Capillary water permeability and rapid chloride permeability decreased with increasing WGP and curing time. From here, it can be seen that the durability properties improve with the increase in the amount of WGP as replacement of FA.

Rehman et al. [48] analyzed the effect of WGP and granulated steel slag (GSS) as replacement of cement and fine aggregate on the fresh and hardened properties of SCC. In the study, 20%, 30%, and 40% WGP were added as replacement of cement, and 40%, 60%, and 80% GSS was added as replacement of fine aggregate. The effects of fresh concrete properties on workability, density, and air content, and hardened concrete properties on compressive strength, splitting tensile strength, bending strength, and modulus of elasticity were researched. Although the results showed that workability decreased with the usage of GSS, workability increased with the WGP additive. However, compressive, splitting tensile, flexural strength, and modulus of elasticity decreased due to the increase in WGP content and stability of steel slag aggregates. The best results of the study regarding compressive, splitting tensile and flexural strengths were found with the use of 20% WGP and 80% GSS.

Tariq et al. [49] surveyed the effect of WGP additive on durability properties in SCC. In the work, the mixtures were prepared with 20%, 30%, and 40% WGP additive and 0.4 w/b ratio replacement of cement. Oxygen permeability, electrical resistivity, porosity, and chloride diffusion from the durability properties were measured at curing period of 3 to 545 days. The results of the study indicated that the usage of FA and WGP together increased the compressive strength, as well as decreased the porosity, oxygen and chloride permeability, and drying shrinkage (up to 180 days). Mechanical and durability properties of SCC evidenced the best values at 20–30% WGP replacement level. Thanks to the small size glass particles, the microstructure is denser and results in improved particle packaging, which creates lower particles. In addition, the service life in terms of corrosion initiation time was tried to be determined by using the Life 365 software in the study. A threshold concentration of chlorides of 0.05% and 0.1% by mass of the concrete was used to be realistic for mixes at different ratios. Regardless of the ratios, a significant advantage was observed in the mixtures containing WGP in terms of time to the onset of corrosion compared to mixtures containing only FA, an increase of about 2 to 3.5 times in service life is determined.

7. CONCLUSIONS AND RECOMMENDATIONS

Literature information on the usage of WGP as cement or fine aggregate replacement in SCC was evaluated. The results showed that up to 30% usage of WGP increased slump flow, J-ring flow, L-box, T500, V-funnel values, and reduced segregation in SCC. It can be stated that this is due to the decrease in the amount of hydrated cement and the increase in WGP, and as a result, the need for more water and the increase in consistency. However, it was emphasized that a high amount of WGP adversely affected the slump results and reduced the consistency. This is expressed by the decrease in the Ca(OH)2 content with the increase of the fineness and surface area of the WGP, thus limiting the area through which the water passes. Additionally, it was stated that the addition of WGP to SCC increases compressive, flexural, and tensile strengths, decreases permeability, oxygen, and chloride penetration, and increases electrical and sulfate resistance. It was also pointed out that WGP, one of the different by-products used in SCC, has great potential for sustainable development [50–54].

Concrete pouring, placing and compaction is a difficult task for ready mixed concrete producers and consumers. Quality workmanship and strict control are required to ensure adequate compaction and homogeneity of the poured concrete to ensure the section is filled correctly. For the advantages of SCC to be seen clearly, its design must be done correctly and it must comply with the specified standards. Since SCC has a very fluid consistency, the formwork systems to be used should be carefully selected and the formwork supports should be smooth and sufficient. The utilization of SCC is increasing day by day in the world, and it is rapidly taking the place of traditional concrete in many application areas. It has advantages such as reducing labor costs as a result of ease of placement. It can provide great convenience especially in complex molds, narrow and tightly reinforced sections, high shear walls where placement and compression are difficult, in the production of large-surface floors, and the applications in the prefabricated sectors [26].

The number of studies on the durability properties of WGP added to SCC can be increased. In particular, the number of studies on the effect of corrosion is limited and experimental studies have not been found much. The effect of WGP added to SCC on reinforcement corrosion and mechanical properties in reinforced concrete structural systems can be examined experimentally and compared with numerical analyses. In addition, by including different industrial and agricultural wastes in the SCC mixtures to be made, it may be possible to compare the results, determine the most appropriate waste type and rate, and compare the pros and cons. Another shortcoming of the studies is the deprivation of LCA, focusing only on the effect of WGP added to SCC on its mechanical and endurance properties. Studies on LCA's should be appreciated more, as the gain in the service life of the structure to be strengthened with different industrial and agricultural wastes which can benefit both the country's economy and help in the reduction of energy losses.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The author declared that this study has received no financial support.

PEER-REVIEW

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