Performance Of High Strength Concrete With High-Volume Fly Ash: A Compressive Study On Tensile And Flexural Strengths

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There has been a growing interest in the use of fly ash as a partial replacement material to Portland cement in concrete because of its environmental advantages and positive effects it has on the properties of the concrete. This research paper aims at determining the strengths of HSC mixtures where high volume of fly ash (HVFA) has been used. This work used the laboratory experimental method to assess the mechanical characteristics of concrete combinations comprising of 50% and 70% fly ash replacement of cement. The findings reveal the potential of high-volume fly ash concrete to offer strength properties which are not only comparable or even superior to conventional concrete, but require a correct proportioning of concrete mixture and appropriate curing regime.

Key Words: high-strength concrete, high-volume fly ash, compressive strength, tensile strength, flexural strength.

1. Introduction

The rising usage of high strength concrete is more probably due to the enhanced height, strength, and stability that is required from buildings in the contemporary world. High-strength concrete conveys high compressive strength, which lets the designer produce relatively thin-cross-section members, enhancing space efficiency and nominal quantity of the materials required [1]. Moreover, due to the initiation of high volumes of fly ash which is a by-product of coal-fired electricity generation facilities, sustainability advantages are gained. Fly ash is a pozzolanic material which can be used as a cementitious material and thus; there is a reduction in the quantities of cement needed leading to decrease in green house emissions from cement production. Use of high-volume fly ash in high-strength concrete also minimize the dump of industrial waste in landfills and improve circular economy hence reducing the environmental impacts on construction [2]. In the context of the present review, high strength concrete means the concrete with a compressive strength normally ranging between 50 and 80 MPa, normally produced with specific admixtures, high quality aggregates and other materials, special concrete designs and production technologies. On the other hand, high-volume fly ash points to concrete mixes in which fly ash derived from coal-fired power plants eliminates at least 30 % cementitious material [3]. The use of high fly ash content in the high strength concrete improves the sustainability of the material portion employed and also has a profound effect on the mechanical characteristics namely tensile and flexural strengths which are essential for structures.

Tensile strength and flexural strength particularly have a great impact in the application of concrete for structures. Tensile strength, which is the capacity of a material to withstand pulling forces in order not to rupture, is crucial for items like beams, slabs, and columns in that they bend as well as resist tension. Conversely, flexural strength depicts the capability of the concrete in resisting bending forces and it is very essential in determination of some of the components of structures that bear loads [4,5]. They affect the load bearing, serviceability and safety of a structure or any part of it. Several literatures concluded that one has to ensure tensile and flexural strengths by proper selection of kernel width and other parameters for more extents of reinforcement in concrete structures due to the physical requirement of the strength for more appropriate structural applications including tall buildings, long span bridges and other infrastructural structures. Due to the significance of mechanical properties on structure performance, durability, and economy of concrete structures, it is important to select the right type of concrete that will perform equally well in all these aspects [6].

Thus, this review intends to provide an exhaustive evaluation of the behaviour of high-strength concrete with a high percentage of fly ash addition. It focuses on several key objectives: first, determining the influence of differences in fly ash replacement ratio on the development of tensile and flexural strengths, in terms of: fly ash type, w/b ratio, curing conditions. Second, on the understanding of the microstructural characteristics due to the incorporation of high-volume fly ash and their relationship with the mechanical performance parameters. Third, based on meaningful discussions to engineer practicum, the issues of the mix design of HSC and difficulties of applying high-volume fly ash will be considered. Last but not least, recognizing areas of knowledge shortage and the future research roadmap for the improved usage of large volumes of fly ash in this context.

2. Influence of Fly Ash on Concrete Properties

It is deemed necessary to first give an overview of fly ash in concrete before elaborating on each of the strengths. Fly ash is a fine-particle, fluffy, powdery substance collected from the combustion of coal in thermal power plants. They have chemical and physical beneficial characteristics that can affect the concrete’s performance in one way or the other. Fly ash is chemically a pozzolanic material: it reacts with calcium hydroxide (a byproduct of of cement hydration) to form more C-S-H gel, the main glue of concrete [7]. This pozzolanic activity can improve the later age strength and durability of the concrete though it could also result to a lesser rate of strength development in the initial stages [8,9].

Great importance of fly ash is mainly from physical characteristic such as fine particle sizes and spherical shape, small particle size, close particle packing and low porosity that can enter the concrete mix hence enhance its work ability, packing density, reduced porosity and mechanical properties [10]. From the chemical point of view fly ash is a pozzolanic material in which silica and alumina are the elements that are capable to react with CH the calcium hydroxide formed in the cement hydration stage. This pozzolanic reaction leads to the creation of more C-S-H gel that is accountable for the strength and durability of concrete. Therefore, fly ash composition depending on the kind of coal burnt and the proportion of SiO2 to CaO can differ, thus the reactivity of fly ash in concrete may also differ [11].

Pile-wise, Fly ash is fine in particle size, highly spherical in shape, and is generally low in specific gravity. Due to the fact that the particle size of fly ash is usually smaller than that of cement, it is able to conform to the shape of the pores to be filled in the concrete matrix and there by enhance the packing density and hence minimize on the porosity of the hardened concrete. The rounded nature of fly ash particles can also improve the easy flowing and or the flowability of the fresh concrete mixture. Further, the specific gravity of fly ash is lesser than cement; therefore, this helps in achieving the decrease in the overall weight of concrete which is advantageous in some cases [12]. Many investigators have researched on the use of high-strength concrete containing fly ash and many have pointed out the benefits and concerns. The main advantage of fly ash production is the possible decrease of the cement content, which can result in both financial and environmental gains [13,14]. Since cement making industry is an energy intensive and high carbon emission industry, using fly ash which is a waste product as substitution for cement in concrete manufacturing is considered sustainable [15].

Table.1. Presents the literature Summary: Influence of Fly Ash on Concrete Properties.

Fly Ash Type	**Fly Ash Replacement (%)**	**Concrete Property Studied**	**Findings**
Class F	20	Compressive Strength	Increase in strength at early ages, slight decrease at later ages compared to control.
Class C	30	Workability	Improved workability due to spherical particles filling voids.
Class F	40	Durability	Reduced permeability and chloride ion penetration.
Class C	50	Flexural Strength	Enhanced flexural strength, especially in long-term performance.

Fly Ash Type	Fly Ash Replacement (%)	Concrete Property Studied	Findings
Blend of F+C	25	Heat of Hydration	Lower heat of hydration, beneficial for mass concrete applications.

3. Tensile Strength of High-Strength Concrete with High-Volume Fly Ash

Tensile strength is one of the fundamental mechanical properties that determines the ability of concrete to crack and fail under tensile stresses. Increased incorporation of fly ash affects tensile strength in both the short as well as in the long run when high volumes of fly ash is used. In the short term, the strength development caused by pozzolanic fly ash is relatively slower and thus in comparison with the OPC concrete, the tensile strength at early ages will be lower [9]. Cement hydration is the initial process that creates strength in concrete, but Ft has proved to achieve high tensile strength compared to concrete with fly ash at the later age depending on the formation of calcium silicate hydrate. Possibility to substitute up to 50% of cement oversaturated by fly ash does not reduce the tensile strength and at the concentration increment provokes further tension strength increase, depending on the fly ash and mixture design [4,16].

It means that the use of large amounts of fly ash, characterized by the implementation of deposits in excess of 30% of the cementing material, exerts considerable influence on the characteristics of high-strength concrete. It is indicated that higher content of fly ash has the potential reducing the required cement content in the concrete mixture hence making the product cheaper and more sustainable [14]. Moreover, fly ash can improve the pore characteristic of concreting and provide the improved durability of concrete in long-term concrete structures through the pozzolanic activity like better resistance towards chloride ions and lesser possibility of occurrence of alkali silica reactions. In addition to the impact on the solutions' strength enhancement, other important mechanical characteristics of concrete can be affected by fly ash inclusion, such as the decrease in heat of hydration, increased resistance to sulphate attack and ASR, and the promotion of long-term concrete durability. These extra advantages make fly ash to be a good supplementary cementitious material in high-strength concrete [17].

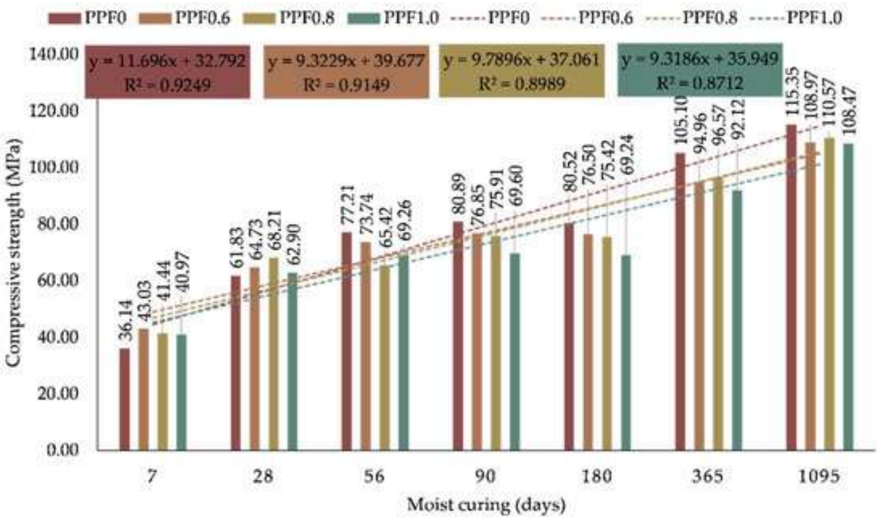

Fig.1. Compressive strength test results for immersion curing.

Figure 1 represents the concrete samples Immersion curing and the compressive strengths of the samples were measured at 7, 28, 56, 90, 180, 365, and 1095 days. It was identified that there are four different samples namely PPF0, PPF0. 6, PPF0. 8, and PPF1. In general, the obtained values 0 correspond to various concrete mixture composition. It is clearly observed that compressive strength is in direct proportion with the curing time and all samples exhibit an improved compressive strength with time. These are the specific compressive strength values which are indicated at the concerned time intervals with the help of marks for various samples. For instance, as it can be viewed, in the case of PPF0 the compressive strength increases gradually from 31. As such the setting of the mortar was determined independently of the compressive strength, ranging from about 23 MPa at 7 days to 107 MPa at 90 days. The soil pressure was analysed at the fifteen months which is equivalent to 1095 days and is equal to 15 MPa. PPF0. It illustrates that 31 is raised to 6. 83 MPa to 115. From 2007 to 2012, the interest expenses has increase by 57 MPa. PPF0. 8 starts at 36. 98 MPa and it goes up to 105. 97 MPa, while PPF1. Consequently, the value of 0 delivers the similar final strength that is 105. These results are 68.5 MPa at 298 days and 97 MPa at 1095 days.

However, the use of the figure helps in depicting the extent to which the strength of concrete grows with time through the cure period to show that curing periods improve the strength of concrete samples. Some works in the literature discourse on the tensile strength of high strength concrete incorporating high volume fly ash are useful in this study. Literature surveys have revealed that, generally, use of high volume of fly ash, generally referred as the percentage of fly ash greater than 30 % of total cementitious material, affects the tensile strength development of high strength concrete [18]. This is specifically brought by the type of fly ash used and the components that makes up the entire compound used in the mixture. It can be observed that fly ashes containing more silicon dioxide and lesser calcium oxide demonstrate more pozzolanic activity that in term produced more C-S-H gel and improves the tensile strength. Regarding the other factors that affects the properties of fly ash, the fineness of the fly ash and the increase in specific surface area is also important because fine fly ash particles can pack closely together leading to a lower porosity of the concrete matrix, which will enhance the tensile strength [19].

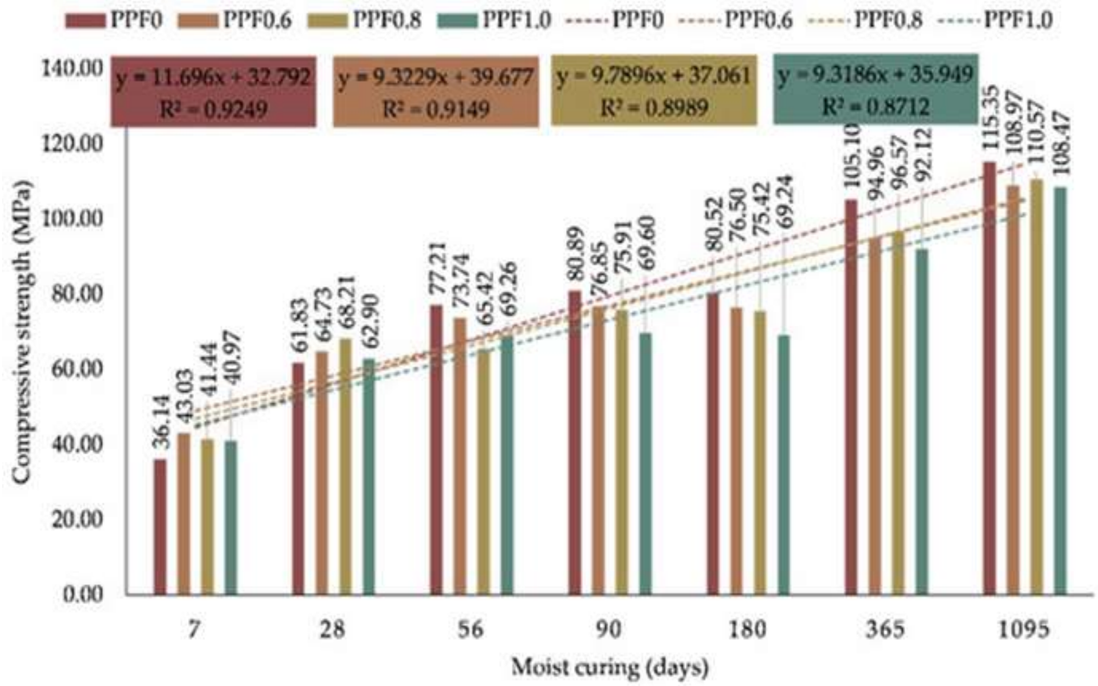

Fig.2. Compressive strength test results for moist curing.

Figure 2 displays the compressive strength test on the samples of concrete for moist curing for the time period of 7, 28, 56, 90, 180, 365, and 1095 days. On this graph, the y-axis denotes the Compressive Strength in Mega Pascal (MPa) while the x-axis shows the Moist curing Time in Days. As for the samples, the initial ones are labelled as PPF0, the ones in between as PPF0. 6, PPF0. 8, and PPF1. They both relate to different concrete mixture proportions, 0, respectively. As illustrated in the Figure 2, the values of the compressive strength for all samples rise with the increase of the curing time that proves the positive effect of moist curing. For instance, in case of PPF0 the compressive strength increases from 36. The concrete strength varied from 14 MPa at 7 days to 115. 35 MPa at 1095 days. Similarly, PPF0. 6 has risen from forty percent to a extent of One percent as indicated in figure 2 below. 44 MPa to 115. 57 MPa, PPF0. 8 starts at 41. 9 It can reach up to 0.09 MPa and increases up to 1.08. 47 MPa, and PPF1. 0 begins at 40. The fracture strength of the STM LN 101 was reached 97 MPa, as well as 108. The CSM of reinforced concrete was found to be 16 MPa at 7 days and 47 MPa at 1095 days.

Figure 2 indicates sample curing time and compressive strength and these are expressed as trends, equations and R^2 values. These trend lines in fact give an insight to the ratio at which strength enhanced over time, with the equations illustrating how much strength picked up in that particular unit of time. Specifically, the equations for the samples are as follows: The linear regression equation was established as follows: Y = 11. 696x + 32. 792, R^2 = 0. 9249; PPF0. Limited which the company has 6 (y = 9. 3229x + 39. 677, R^2 = 0. 9149), PPF0. The values of reached parameters are as follows: S: 8 (y = 9. 7896x + 37. 061, R^2 = 0. 8989) and PPF1. 0 (y = 9. 3186x + 35. 949, R = 0. 8712). In turn, the figure is desirable to illustrate the notable influence of moist curing on the increase of the compressive strength of concrete and that long curing periods are beneficial for the further strength increase of concrete samples.

Another factor, which influences the tensile strength of high-strength concrete with high volume fly ash inclusion is the water to binder ratio. Cautious decrease of the water-to-binder ratio results in improved mechanical properties of concrete and denser microstructure, which restricts micro-cracking. In the same way, the conditions of curing affect the strength gaining rate and the ultimate tensile strength achieved[20]. Literature reviews have deemed that the use of high-volume fly ash the concrete slow down the initial tensile strength gains relative to normal fly ash concrete. However, inevitably the reaction of the pozzolanic active materials will cause further formation of C-S-H gel, and consequently increase tensile strength gradually and accordingly vie for conventional high strength concrete mixtures[21].

The split cylinder test is a technique that is employed to determine the tensile stress of the concrete and hence estimate their Strength. Nevertheless, rates of increase in the proportion of fly-ash beyond about 30 per cent of the total cementitious content are said to retard the initial tensile strength development compared to that of ‘normal’ high-strength concrete. This is due to the circumstance that fly ash is pozzolanic material which takes a finite period of time to undergo additional secondary hydration reactions to form further C-S-H gel. Reactions such as these may proceed over time and produce more C-S-H, which in turn increases the tensile strength permanently. HPC using high volume fly ash could be similar or even superior to normal HSC when the consequences such as type of fly ash, ratio of water/binder, and curing system are considered[22,23] . The nature and content of fly ash that is used can appreciably affect the tensile strength gain. Ash fly with high silicon dioxide and low calcium oxide is likely to be highly pozzolanic and thus, be capable of producing higher amounts of C-S-H gel and tensile strength. Moreover, the characteristic of fineness of the fly ash and the particle size distribution also affects the packing density and porosity of the concrete matrix to any degree contributing to the tensile capability [24]. High-strength concrete containing high volume of fly ash: effect of water to binder ratio and curing conditions on tensile strength. Downward changes in the ratio can help develop a closer packing at the micro level and an associated decrease in the danger of micro-cracking The effects of favourable curing conditions which include an improved and enhanced rate and a correspondingly higher maximum strength can also be realized. Also, in high volume fly ash the rate may decrease at first and then gain strength due to the reactions of POZZOLAN. Tensile strength is tested by direct tensile as well as split-cylinder tests.

Flexural Strength

Another aspect of research carried out on high strength concrete particularly containing high volume fly ash is the flexural strength. Scientists have used different techniques including 4 point bending test and the third point bending test to determine the flexural strength of the concrete mixtures in question. These test methods are informative of the behaviour of the material under the structural loading as specified, since the flexural strength is one of the most important parameters in the design of members that are prone to bending stress[25]. Literatures review has revealed that several papers have analysed the impact of the degree of fly ash replacement on the enhancement of flexural strength of high-strength concrete. In general, it has been ascertained that high volumes of Integrated Fly Ash higher than 30% of the Cementitious material will affect the development of the later age flexural strength. Just as with the facts presented for the tensile strength behaviour, the early stage of the increase in flexural strength may be less steep with high-volume fly ash concrete than with conventional high-strength mixes. Thus, fly ash can cause a gradual increase in the flexural strength of the material due to pozzolanic reactions, and the designed characteristics can correspond to or exceed the characteristics of high-strength concrete[26].

Other parameters have also been studied in connection with high strength concrete with high volume fly ash; the properties of the aggregates and the provision of fiber reinforcement. Further, because the toughness of concrete after cracking, fibre reinforcement such as steel or synthetic fibre will improve the flexural strength and energy dissipation of the material[27].

4. Microstructural Considerations

The microstructure of high strength concrete is altered by high volume fly ash, in terms of the changes in pore structure, hydration products, and contact zone. It carries out additional pozzolanic reactions that develop new C-S-H gel which is the major binder in green concrete. This gel enhances the capacity of filling the pores, reduces the porosity of the microstructure, and enhances the ITZ between aggregates and cementitious paste [9]. Pozzolanic responses of fly ash allow more volume of calcium silicate hydrate (C-S-H) gel to be created and this gel could further pack up the pores thereby increasing in microstructural density. This enhancement of the pore network maybe helpful in attaining better tensile and flexural strengths of high strength fly ash concrete due to the reduction of micro crack and improves mechanical properties [28].

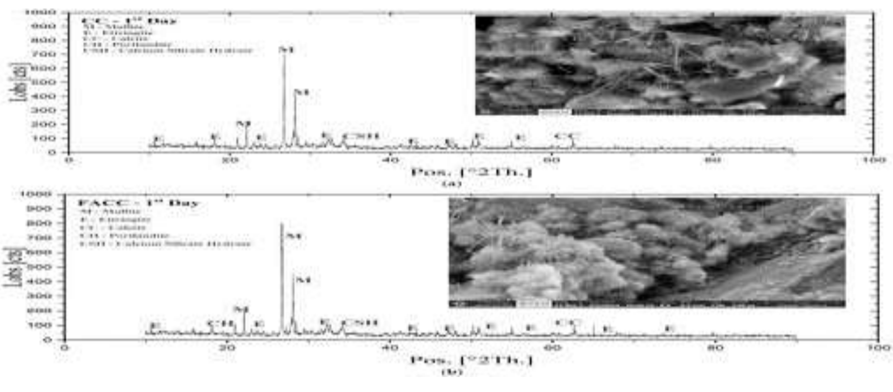

Fig.3. XRD and SEM (a) CC (b) FACC on the First Day of Testing.

The microstructure is briefly described for concrete and with specific reference to the Interfacial Transition Zone between the cement paste matrix and the aggregate. To assess the performance of fly ash concrete (FAC), microstructure analysis required High-Resolution Scanning Electron Microscopy (HRSEM) with a Thermo Scientific Apreo S model to examine the core samples, or the tested specimens, needed to be impregnated with ethanol solution on the specimen's surfaces. Furthermore, it should be noted that some of the polished samples were sputter coated with an electron beam for the purpose of desiccation, that is, to evacuate the samples. Figure 3 is the photomicrography of CC and FACC at 1, 7, 14, and 28 day for each group.

It is also noteworthy that the products formed by the hydration of fly ash in the material are rather different from those in high-strength concrete. Stoichiometric reaction with CH that is generated during the initial stage of cement hydration, fly ash particles contribute to the creation of additional C-S-H gel. This secondary C-S-H gel is comparatively denser as well as presents superior binding properties to the first C-S-H gel which is produced by cement's hydration only. They arise from improvements in the load-carrying capacity, and crack-resisting capacity of the concrete resulting from increased C-S-H content and fine control of its location within the concrete matrix [29,30]. A high-volume fly ash contributes to the durability of high strength concrete; and the tensile as well as flexural strengths are also augmented. In addition, its pozzolanic component decreases permeability and, therefore, its resistance to sulphate attack, as well as deterioration by chlorides. This decrease in permeability helps to enhance performance and service life of the structures in the long run. Fly ash also reduces the possible presence of expansion due to alkali-silica reaction (ASR), hence promotes sustainability and durability of structures[31].

5. Durability Aspects

It is important to note that the incorporation of high-volume fly ash in high-strength concrete can also provide improved property of durability apart from the increase in tensile and flexural strengths [32]. Fly ash as a pozzolanic material enhances the stand of the concrete when it come to the issues of durability as it fixes some issues like sulphate attack and chloride infiltration. The increase in the density of the microstructure and the improvement of the pore structure due to pozzolanic reactions of fly ash has influence on the reduction in permeability of the concrete and thus the resistance against the penetration out aggressive substances. This, thus, enhances durability and serviceability of structures constructed from high strength fly ash concrete since they are protected from the deterioration mechanisms [33, 34]. In addition, it equally reduces the threat of Alkali Silica Reaction which is another durability factor that affects concrete. Since fly ash can also get engaged in the pozzolanic reactions, the alkalis may get used up and cannot trigger more of the undesirable ASR expansion and cracking. All in all it can be said that high volume fly ash serves as an improvement in durability in high strength concrete if incorporated then the structures become more sustainable and resistant to environmental factors and hence it increases their service life [35]. This can go a long way in ensuring that structures would have more durability and can withstand adverse environmental conditions hence increasing its service life. Moreover, with the addition of fly ash, it is also possible to reduce the probability of occurrence of alkali silica reaction another issue that affects the durability of concrete. From the pozzolanic reactions which may occur with the fly ash, the available alkalis can be consumed hence decreasing the possibility of expansive ASR reactions leading to cracking [36].

Table 1. Durability Aspects of Performance of High Strength Concrete with High-Volume Fly Ash.

Fly Ash Type	**Fly Ash Replacement (%)**	**Durability Aspect Studied**	**Findings**
Class F	50	Chloride Ion Penetration	Significant reduction in chloride ion penetration compared to control concrete.
Class C	40	Sulphate Resistance	Enhanced sulphate resistance, lower expansion, and better durability performance.
Class F	60	Alkali-Silica Reaction (ASR)	Marked reduction in ASR expansion, improving long-term stability.
Class C	45	Freeze-Thaw Resistance	Improved freeze-thaw resistance due to reduced permeability and denser microstructure.
Class F	50	Carbonation Resistance	Similar carbonation depth compared to control, indicating maintained performance.
Class F	55	Water Absorption	Lower water absorption rates, indicating reduced porosity and enhanced durability.

Table 2 summarizes the entire literature related to the service-life characteristics of high-strength concrete containing high volumes of fly ash. There are other significant durability parameters such as, the permeability of chloride ions, resistance to sulphate or sulphate, alkyl silicate or ASR, freeze thaw cycles, carbonation, and water absorption. According to the research carried out, high fly ash had a great effect in enhancing the durability of high strength concrete, with regard to its resistance to aggressive environment, sulphate resistance and freeze thaw resistance.

6. Practical Implications and Recommendations

The reviewed findings suggest several practical implications for engineers and practitioners when incorporating high-volume fly ash in high-strength concrete: The reviewed findings suggest several practical implications for engineers and practitioners when incorporating high-volume fly ash in high-strength concrete:

6.1. Mix Design Considerations:

- The content of replacing fly ash with cement should be adjusted in accordance with the requirements of specific performance properties, considering the enhancement of tensile and flexural strengths, as well as the problems such as the retardation of setting time and the lower values of early age strength.
- Modify the binder composition and incorporate fly ash in the proportions of 30-50% of cement's mass to get the pozzolanic effects necessary but retain adequate strength and workability.
- One has to also take into account the application of certain chemical admixtures, including superplasticizers, in order to retain the concrete workability as well as its flowability, regarding the presence of high fly ash content.
- Modify the total gradation and ratios according to the requirement of finer particle size distribution of fly ash and its effect on the packing factor of the concrete mix.

6.2. Potential Challenges and Limitations:

- It is advisable to track the curing regime and to provide sufficient moisture and temperature conditions for the development of fly ash's pozzolanic activity, which might be slower as compared to cement's hydration.
- Comment on the tendencies to higher or the drying shrinkage and the creep in the high-volume fly ash concrete because of the refined pore structure and the higher volume of hydration products.
- Focus on the effects that fly ash has on concrete's characteristics and performance if its supply is inconsistent and adapt its composition to be constant.
- The long-term durability performance should also be assessed, primarily in relation to various hostile external effects in order to anticipate and monitor the concrete's permanence against deterioration factors for the predicted service life of the structure.

Future Research Directions

- It is also important to detect several blanks and discrepancies concerning the performance of high strength concrete incorporating high volume fly ash. The review should also comparatively analyse the state of knowledge where discrepancies in the findings are discernible.
- Mention concrete areas of requiring further study in order to improve the knowledge of the underlying processes as well as improve the usage of high-volume fly ash in high strength concrete. Some of the research areas may comprise durable concrete structures aspects, fly ash effect on concrete characteristics, effect on concrete strength at early age of concrete structure, and establishing trade-off between strength, workability and sustainability.
- Suggest concrete research questions and suitable research methods which might help in filling the conceptual gaps. These may include cad works, numerical modelling, and analyses in order to enhance the knowledge that one can obtain on the behaviour of high strength fly ash concrete under various environmental and loading stresses.

Conclusion

- The weakness of the paper under review is that it focuses on the enhanced properties of high-strength concrete containing high volume fly ash for tensile and flexural strengths only. Fly ash modification helps to fix the pozzolanic reactions that improve the densification of the microstructure and a related refinement of the pore structure that aids in compensating for such factors that influence the concrete durability, including sulphate attack and chloride penetration. This in turn can enhance the durability of structures that are built with fly ash concretes of high strength which results to increased service life on structures that are subjected to environmental loads.
- It should also be noted that many of the conclusions of the present review have a certain relevance to the modern discourse regarding sustainable construction practices. The sustainability aspect of fly ash application in high strength concrete lies not only in increasing the material strength, mechanical and durability, but also through the reduction of cement content consequently the environmental problem of CO2 emission. This corresponds to the trends of the construction industry to look for environmentally friendly and climate change resilient construction materials.
- This comprehensively presents the significance of improved studies that shall help refine the utilisation of high-volume fly ash in high strength concrete. Areas for further research entailing durability performance of fly ash concrete, the effect of variation in fly ash on the properties of concrete, effect of fly ash usage on early age strength of concrete and strength, workability and sustainability relationship. Filling all of these knowledge gaps will help to create a basis for further popularization and efficient consumption of high-volume fly ash in high-strength concrete, thus advancing toward the creation of efficient and environmentally friendly construction.

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