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An Exhaustive Review on The Development of The Role of Cementitious Supplementary Cementitious Material in Ductile Engineered Cementitious Composite (ECC)

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Abstract

In recent years, worldwide, a newly developed composite with an assurance of high ductility and high matrix toughness named as Engineered Cementitious Composites (ECC) is started. It is a known fact that the manufacturing of ECC uses a higher amount of fly ash, contributing to sustainable development and reduction of carbon footprint. In this paper, a review of ECC with supplementary cementitious materials such as fly ash has been studied. ECC looks similar to ordinary Portland cement-based concrete, except that it can deform (or bend) under strain. Conventional concrete's lack of durability and failure under strain, both stemming from brittle behaviour, have been a pushing factor in the development of ECC. ECC has exclusive properties, such as tensile properties, ductile properties, durability properties higher than other types of fibre reinforced concrete. Different trail mixes of ECC with fly ash, fly ash cenosphere and various authors have used calcium content of fly ash. The results have been assessed based on the properties of ECC in the presence of fly ash. This paper presents an exhaustive review of ECC by incorporating fly ash as a cementitious material. The reports consider the effect of fly ash fineness and fly ash content on various properties of concrete. Also, the effect on strength and other parameters studied at high-temperature conditions.

Keywords: Sustainable Development, Cementitious Composites, fly ash Cenosphere, High ductility, Fly ash, Fineness, Calcium Content.

1. Introduction

Concrete is most extensively utilized structural material on the earth; in the past century on modern infrastructures, it plays a significant role. With the quick evolution of modernized society, long-span bridges, dams and high-rise buildings so on, were rising throughout the world, which needs the concrete to attribute high performance in various perspectives [1]. High-performance concrete featured with the characteristics of high compressive and high ductility. It can be utilized in the development of longer spans, highway bridges and diminishing the number of girders required, consequently letting down the total cost. High strength concrete usually has a higher modulus of elasticity in comparison with conventional concrete, which reduces the structural member deflection and increases the deflection. Also, less prone to shrinkage and smaller ultimate creep strain in high strength concrete would result in a lower loss of pre-stress in steel; thus, in the pre-stressed structure members, it is used frequently. More brittleness is usually companion with the increased strength of high strength concrete. Short steel fiber at a dose of 1-4% by volume fraction included in ultra-high-performance concrete (UHPC) to overcome that problem [2,3,4,5,6].

The addition of steel fiber permits ultra-high-performance concrete having a slight strain-hardening phenomenon with tensile strain capacity of around 0.5% [3,5,7]. Tension-softening behaviour observed with the spalling of the matrix surrounding steel fibers in the post-peak-stress stage [8]. The ductility of high strength concrete needs to be improved to assure the structural resiliency to ensure the safety of infrastructures under extreme loading. It may absorb the energy generated during a significant event like an earthquake; therefore, the chance of building collapse and the requirement for frequent repairs is greatly diminished [9]. Conventional concrete brittleness overcome by the high-ductility concretes, High-ductility concrete avoids failure of concrete structures under disasters such as bomb blast, consequently resulting in buildings safer.

Engineered cementitious composites invented in the 1990s. ECC designed based on micromechanics theory, high-ductility concrete and has a tensile strain capacity of over 3% with moderate fiber fraction under 2% by volume. Different from the usual brittle fracture in conventional concrete or tension-softening behaviour in fiber reinforced concrete (FRC) when undergoing tensile loads, ECC after linear stage exhibit metal-like strain-hardening behavior. However, multiple micro-cracks generally with crack width controlled to around 60 mm develop in ECC [23], or even 20 mm with an adequately designed matrix [10-16]. ECC

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imparts high ductility, primarily due to little crack width [13]. The ductility of ECC is on the order of several hundred times that of conventional concrete or fiber reinforced concrete. Due to its high tensile ductility and durability, ECC is attractive in a variety of civil engineering application. As an example, used to pavement, structural slabs, high-rise buildings and also used in structural repairs and retrofits [17]. In ECC only fine sand is allowed to be applied to obtain better strain capacity and multiple cracking. It demands higher cement content due to coarse aggregate elimination in comparison with conventional concrete.

The cement quantity can be greater of 1000 kg/m^3 for general ECC. Every ton of cement delivered produces an equivalent measure of carbon dioxide, liable for 5% of worldwide greenhouse gas emission created by human activities [18-21]. Therefore, because of global sustainable development, according to the Concrete Centre, the amount of embodied CO_2(ECO_2) of concrete is a component of the cement content in the mix designs. The ECO_2 effect of concrete around 100 kg CO_2 for each ton. For sustainable concrete development, the embodied CO_2 of concrete considered. Portland cement is the essential constituent in concrete production from the ECO_2 viewpoint. In the production of Portland cement, a large amount of CO_2 is liberated. Portland cement can be partly replaced with Supplementary Cementitious Materials (SCMs, such as fly ash, ground granulated blast furnace slag, silica fume, rice husk ash and so on) to reduce the embodied CO_2 of concrete. Over the last few decades, the SCMs have been used extensively in the production of concrete.

In sustainability dimension of concrete, the use of SCM is more critical consideration similarly, as with expanded use of SCM, we are hoping to lessen the considerable volume of CO_2 emissions, consequently moderating the ecological effect of concrete production [22]. It is imperative to develop green ECC by incorporating mineral admixtures to replace cement partially. Recent studies have shown that fly ash has been a necessary ingredient for engineered cementitious composites (ECCs) to improve mechanical properties and reduce drying shrinkage of ECC [18].

This paper reviews and critically analyses the latest advancements in fly ash utilization in cement-based composites. The properties of fly ash are presented and also evaluated mechanical properties, and temperature effect of fly ash incorporated ECC reviewed comprehensively. Finally, based on the available research output, possible future applications of fly ash are pointed out.

2. Background on Supplementary Cementitious Materials (SCMs)

Generally, SCMs falls into one of the two categories: self-cementing or pozzolanic [23]. Self-cementing materials react similarly to Portland cement; through which, the resultant mixtures harden during an irreversible hydration reaction when mixed with water. A pozzolan is a material, primarily siliceous in composition, which on its own does not have cementitious properties in the presence of water. Pozzolan hydrates and exhibits cementitious properties when it exposed to water and calcium.

SCM, which are mostly siliceous, when adequately incorporated into a cement mixture, provide some notable benefits. Reduction in the heat of hydration caused by the replacement of Portland cement with available SCMs [23].

According to Kamile et al., [24], the use of coal combustion by-products such as fly ash as a mineral admixture in the production of cementitious composites became necessary. It offers environmental advantages in processing cement (reduces the energy investment and CO_2 release). Moreover, with ecological effects, better fiber dispersion homogeneity in the fresh state can be obtained when fly ash is partially replaced with cement in ECC production. Fly ash replacement reduces the interface chemical bond strength the fiber and matrix phase, facilitates fiber pull-out, and decrease the fracture toughness of matrix. However, the physical and chemical properties of fly ash may greatly vary depending on the source of burning coal at the power plant. Due to this reason, the beneficial role of fly ash in ductile Engineered Cementitious Composite (ECC) should be reviewed [16,25,26].

3. Fly ash as SCM

Fly ash is a result of the combustion of pulverized coal in thermal power plants. The dust collection system expels fly ash, as a fine particulate residue, from the burning gases before they released into the environment. Most of fly ash particles are solid spheres, and some are hallowed cenosphere [25]. Fly ash has usually sorted into two groups Class C (high-calcium fly ash) and Class F (low calcium fly ash) according to ASTM C 618[20, 23, 24, 36]. The Canadian Standards Association (CSA 1982) ranked fly ash based on the Cao content [36]. Low calcium fly formed by burning of bituminous coal or anthracite; and high calcium fly ash formed by burning sub-bituminous coal or lignite[24,37].Class F has named as pozzolan, which contains silicate glass, modified iron and aluminium [23].SEM micrographs show that most of class C fly ash particles have an irregular and hallow shape (Fig.2), while most of class F fly ash particles have the spherical and smooth shape (Fig.1)[20].

The difference in fuel source that creates class F fly ash provides a material that has a different chemical composition. Still, it has similar physical characteristics as Class C fly ash. Therefore, many of the effects that are due to physical characteristics (as opposed to chemical reactions) are identical to that of Class C fly ash [23].

3.1. Physical and Chemical properties of fly ash

The properties of fly ash presented in Tables-1,2 and 3.

Table-1. Physical properties of Fly ash [26-27]

Physical properties	Class C fly ash	Class F fly ash
Blaine's fineness(cm^2/g)	285-306	290-335
Specific gravity	1.84	2.34

Table-2 Chemical properties of Class C Fly ash

Oxides	Cao	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
Mustafa Sahmaran et al.,[27]	15.50	46.97	11.86	7.98	6.51	3.47	3.23	2.33
Mucteba Uysal et al. [26]	15.1	46.38	13.9	8.26	6.68	4.26	2.78	2.13

Table-3 Chemical properties of Class F Fly ash

Oxides	Cao	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
Mustafa Sahmaran et al. [27]	3.48	60.78	21.08	5.48	1.71	0.34	1.95	0.74
Mucteba Uysal et al. [26]	1.55	58.58	23.4	6.97	2.76	0.45	4.11	0.46

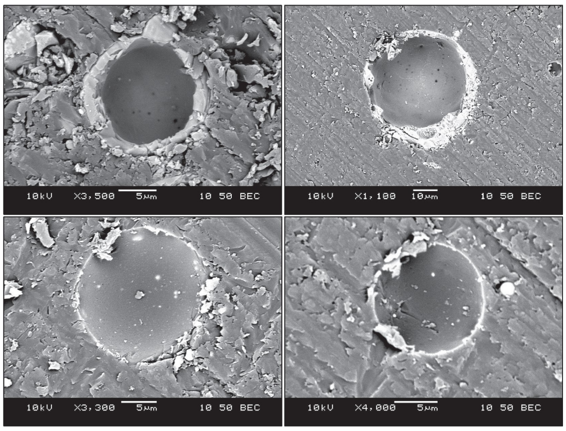

Fig. 1.SEM micrographs of class F fly ash [28].

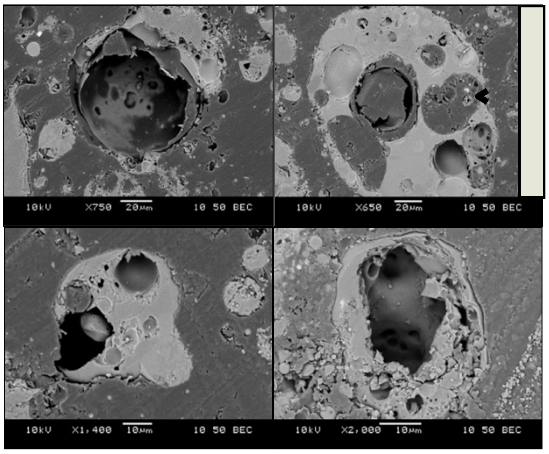

Fig. 2. SEM micrographs of class C fly ash [28].

From the above, it is clear that Class C has high lime content compared to Class F. Following figures represents the shape of particles of fly ash.

4.Performance of ECC with fly ash based on Compressive strength

The effect of fineness, lime content, fly ash shape, class of fly ash, time and temperature on compressive strength of ECC have been studied from the review.

4.1. Effect of fineness of fly ash incorporated ECC on compressive strength [16]

The fineness of fly ash extensively investigated by Li-Kan et al., FA-1 processed by planetary ball factory machine for 4 min,10min and 15min, respectively. At that point the samples were separated into group A, B and C. The particulate surface areas of group A, B and C are 646.9 m^2/kg, 750.4 m^2/kg and 850.1 m^2/kg and thus concluded that increasing in grinding time increases the specific surface area.

According to ASTM C618 requirements, four kinds of fly ash originated from different power plants, Class F fly ash (FA-1, FA-2, FA-3) and Class C fly ash (FA-4). It is well-known that under the same hydration conditions, finer fly ash can be more beneficial to improve the compressive strength of concrete material.

As a comparison of group A with group C, the compressive strength decreases as the fineness of fly ash increases. Calcium ion of the matrix reduced, so the matrix could not be completely hydrated due to the activity of fly ash not stimulated fully, which decreases the degree of hydration of the matrix. Meanwhile, the formation of C-S-H gel and the strength of the matrix reduced due to the low calcium-content fly ash. The physical appearances and chemical properties of fly ash deteriorated due to a series of energy loss caused by friction and rolling of fly ash during mechanical grinding. Although the particle size also smaller, the ability and activity of its hydration became much worse. The fineness of fly ash has a more significant effect on the compressive performance of ECC.

4.2. Effect of Cao content of fly ash incorporated ECC on compressive strength [16]

From the studies of Li-li Kan et al., the potential of fly ash lies in its compaction effect, namely hydration activity. Therefore, the development of the early strength of cement-based materials prepared by high calcium-content fly ash should be faster than that of low calcium-content fly ash. Meanwhile, cement-based systems with high calcium-content fly ash will produce more C-S-H gels after hydration for a long time and be filled with cement hydration products so that the matrix strength will be significantly improved. In conclusion, the calcium content of fly ash can affect the compressive performance of cement-based materials. The compressive strength will become better with the increment in calcium content and age.

4.3. Effect of fly ash cenosphere (FAC) with iron ore tailings (IOTs) aggregate incorporated ECC on compressive strength [30]

According to Xiaoyan Huang et al., the compressive strength of Green Lightweight Engineered Cementitious Composites (GLECC) mixtures decrease with increase in fly ash/cement (FA/C) ratio for all levels of IOTs replacement with FAC, due to the reduction in strong primary hydration products at 28 days due to the reduced amount of cement. For each level of FA/C ratio, the increase in FAC (Fig.3,4) content by increasing IOTs replacement results only in marginal (at most 10%) decrease in compressive strength. With total IOTs aggregate replaced by fly ash cenosphere, the 28-days compressive strength of GLECC mixtures reduced with FA/C ratio of 4.4 as compared with FA/C ratio of 2.2.

4.4 Effect of class C and F fly ash incorporated ECC on compressive strength [26]

Mucteba Uysal et al. studied the Performance of class C and F fly ash., at 28 days the compressive strength of Class C fly ash additive concrete including different amounts of fly ash generally higher than that of

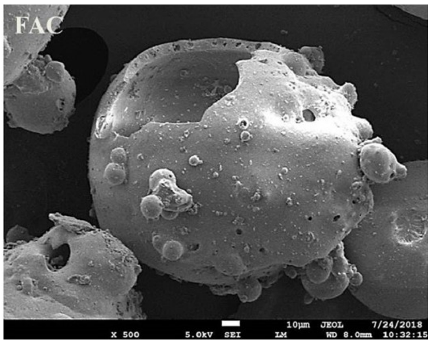

Fig.3. SEM image of Fly ash Cenosphere (FAC) [1].

conventional concrete. Moreover, the long-term strength as detected at 90 days, the compressive strength developed of Class C fly ash additive mixtures also found to have higher strength values than conventional concrete. Fly ash additive concrete mixtures including different amounts of Class F fly ash generally exhibited lower compressive strength than that of conventional concrete at 28 days and 90 days. The compressive strength of Class F fly ash mixes decreased when the fly ash content increased. The use of Class C fly ash instead of class F with the same cement dosage and fly ash percentage generally caused to higher compressive strength. As Class C fly ash, contains higher calcium amount, the compressive strength results are higher in early ages compared to Class F fly ash. 10% cement reduction by adding Class C fly ash improves compressive strength, and this improvement increases with fly ash percentage. When cement is reduced by 17%, Class C and Class F fly ash additive specimens show similar behaviour; compressive strength decreases with decreasing of the cement dosage and increases with adding fly ash when cement dosage is constant. Generally, the addition of Class C fly ash increased the compressive strength of concrete mixes. The slight compressive strength improved slightly due to pozzolanic reaction. Since fly ash is pozzolanic, the addition of fly ash should also increase concrete compressive strength through the pozzolanic response. Pozzolanic means it will react with calcium hydroxide and water to form a compound with cementing properties.

C-S-H is the major contributor to concrete strength, among the two products of cement hydration are calcium silicates hydrate (C-S-H) and calcium hydroxide (CH). Supplementary cementitious materials such as fly ash contain amorphous silica (S) which with calcium hydroxide (CH) to form additional C-S-H, thereby improving strength.

4.5. Effect on compressive strength of ECC as a function of replacement ratio of fly ash and time [31,32]

Pipat Termkhajornkit et al., [31], demonstrated that the dependence of compressive strength as a function of replacement ration of fly ash and time. The compressive strength decreased when cement replaced by fly ash. However, the increase in compressive strength after 28 days is notable. The rise of compressive strength after 28 days is mainly due to the hydration of fly ash.

Alaa M.Rashad et al. found that significant reduction in the compressive strength may occur when 70% from Portland cement has substituted with fly ash. The decline in strength is attributed to the slow pozzolanic reaction of fly ash(low-calcium) and the dominant dilution effect, especially during the early ages, with only a few arts if the fly ash participating in the reaction.

4.6. Effect on Specimen size with temperature exposure on the Residual compressive strength of fly ash incorporated ECC [33]

Tahir Kemal Erdem et al. studied the residual properties of ECC subjected to elevated temperature with size effect. The increase of temperature up to 400^{0}C residual compressive strength variations are steady with the pore structure variation the total intruded porosity and percent of pore size between in the range of 50 nm, and 500 nm increased. The increase in porosity up to 400^{0}C is no doubt because of little channels created in ECC by melting PVA fibers. After exposure to 600^{0}C, the primary sources of weakening in compressive strength may be credited both to the physical change of the transformation of the matrix and changes of hydration products. The temperature raised to 600°C, causing serious increment in the microstructure of its matrix and the loss of property of binding.

The percent reduction in compressive strength classified in three patterns of strength loss, 23–400°C, 400–600°C and 600–800°C. From 23 to 400^{0}C, the reduction in compressive strength is around 20% for all specimen dimensions. Between 400°C and 600°C, the average loss in compressive strength is significantly higher in contrast with a range of 23-400^{0}C and reach 50%. ECC specimens showed severe determination beyond 600^{0}C, most probably, due to the decomposition of hydration gels. Usually, as mentioned earlier, deterioration of the cement-based composite is altering because specimen size is directly related to the heat and moisture transport through the structure. The larger structures store more energy, and as the specimen gets bigger, the deterioration and risk of thermal spalling get higher. Therefore, within the range of specimen sizes studied, ECC accepted as the size effect independent of thermal exposure. However, ECC tends to change from ductile to brittle when increasing the exposed temperature level.

4.7. Effect of temperature exposure on the compressive strength of high-volume fly ash incorporated ECC [17]

Jiangtao Yu et al., extensively investigated the macro-mechanical properties of ECC with high-volume fly ash after sub-elevated temperature exposures of 50°C,100°C and 200°C. The compressive strength of ECC remained almost unchanged after temperature exposures of 50°C and 100°C but declined after temperature exposure at 200°C.

4.8. Effect of temperature exposure on the Residual compressive strength of fly ash incorporated ECC [34]

Yu Ke-Quan et al. found that high-temperature exposure influenced the residual compressive strength of the self-Hardening Cementitious Composite (SHCC) samples. However, the variation percent in compressive strength characterized in four particular phases of strength loss,20-200^{0}C, 200-400^{0}C, 400-600^{0}C and temperatures no more than 200^{0}C appeared to help the strength increment, the mean compressive strength of the 7-day SHCC samples increased by 2% after exposure to 200^0C. The impact of high-temperature exposure on the residual compressive strength is not prominent up to 400^0C, where the mean compressive strength of the 7-days SHCC samples diminished by 28%. Heating up to. 400^0C created a generally low amount of cracking, which did not cause immediate loss of carrying capacity in compression because the slightly cracked concrete could function as a highly redundant structure. Beyond 400^0C, the compressive strength of the 7-days samples dropped. As indicated by the variation of the residual compressive strength, temperature of 600^0C and above considered as the critical temperature range for the SHCC strength loss. Residual compressive strength variations are steady with the pore structure variation. The increase in porosity up to 400^0C leads to the formation of small channels created in the SHCC by melting PVA fibers. After exposure to 600^0C, the primary sources of deterioration in the compressive strength credited to both the physical changes of the matrix and chemical transformation of the hydration products. The temperature increased to 600^0C, the decomposition of the significant hydrate, causing an extreme increment in the microstructure of its matrix and loss of property of binding.

5. Performance of ECC with fly ash based on tensile strength

The effect of fineness, lime content, fly ash shape, class of fly ash, time and temperature on tensile strength of ECC have been studied from the review.

5.1 effect of fineness of fly ash incorporated ECC on tensile strength [16]

Li-li Kan et al. found that the overall tensile properties of group B were better than the other two groups, such as A and C.

The tensile strain capacity did not increase with the increase of fineness. When the surface area of group B increased by 100 m^2/kg, compared with the specimens of 7 days, concluded that the rise of fineness did not increase the strain capacity. Additionally, the ductility of medium-fineness-fly ash specimen is the best. Based on the distribution of cracks, concluded that the uniform cracking performance is consistent with the ductility performance. Uniform Cracks distribution obtained with an average fineness of group B, and the number of cracks are more than that the other two groups. Therefore, the effect of fineness of fly ash on the ductility of ECC is merely linear.

5.2. effect of Cao content of fly ash incorporated ECC on tensile strength [16,35]

Li-li Kan et al. stated that difference calcium content had an evident influence on the ultimate tensile stress and tensile strain capacity of ECC. The ultimate tensile stress and tensile strain capacity of ECC influenced by calcium content. The ultimate strain capacity of FA-3 is maximum, followed by FA-2, FA-4 is minimum at the age of 7 days. Consequently, with the increase of calcium content, the early strength of the ECC would not be higher.

According to the Fernendez-jimenez's microanalysis, the development of strength is related to the active Si/Al ratio. There would be a balance between Si and Al which is favourable for quick setting and early strength when the Si/Al ratio close to 1.8. From XRF analysis, the Si/Al ration of FA-2 and FA-3 is 1.527 and 1.273, respectively.

Usually, the cement-based systems with high calcium content have higher matrix strength. Instead, from the test results of Li-li Kan et al., FA-4 exhibits less tensile stress with the highest calcium-content. The reason may be related to the content of SiO_2 in FA. The Ca^{2+} could reduce bond strength of the gel products, and if the content of Si in the gel is low when the alkali is activated, the bond strength of the low-silica gel would be weakened, which would lead to the decrease of the matrix strength. The SiO_2 content of FA-2, FA-3, FA-4 are 42.3%, 51.7%, 35.4% respectively. Among those, the highest is FA-3, and the FA-4 is least.

It is concluded that FA-3 has the best cracking performance and tensile properties at different ages, followed by FA-2 and FA-4 is worst.

5.3. Effect of FA/C ratio, the replacement of IOTs aggregate with fly ash Cenosphere (FAC) incorporated ECC on tensile strength [30]

According to the finding of Xiaoyan Huang et al., tensile strain capacity of GLECC mixtures higher than that of conventional brittle concrete. The FA/C ratio significantly influences the tensile performance of GLECC. The increases in FA/C proportion from 2.2 to 4.4 causes a diminishing in firs cracking strength and ultimate tensile strength. GLECC mixtures with a FA/C proportion of 4.4 displays an increase in tensile strain capacity than those with a FA/C ratio of 2.2. The lower strength performance and higher ductility in GLECC mixtures with a higher content of fly ash are consistent with past research results [36]. The higher fly ash content results in an increase of frictional bond at the interface between PVA fibers and matrix, and a decrease in matrix fracture toughness and interfacial chemical bond [36]. As per the micromechanics design theory of ECC, those effects because of the high substance of fly ash and also beneficial for getting high tensile ductility [37]. At each level of FA/C ratio, matrix fracture toughness decreases with the increases in fly ash cenosphere content, which causes a reduction first cracking strength. Further supporting the influence of IOT replacement with fly ash cenosphere on first crack strength through matrix fracture toughness. Fly ash cenosphere is stable in alkaline solution at ambient temperature. So, both fly ash cenosphere and IOTs regarded as inert fillers in the GLECC mixtures. The decrease in matrix fracture toughness is likely due to the difference in particle shape of IOTs and fly ash cenosphere. The replacement of irregularly shaped IOTs with spherical fly ash cenosphere reduces the porosity of fracture path along with the interface between aggregates and cement paste, which is expected to facilitate crack propagation and, therefore, result in lower fracture toughness and firs cracking strength.

For each level of FA/C ratio, tensile strain capacity of GLECC mixtures increases with the replacement of IOTs with fly ash cenosphere. The increase in tensile strain capacity attributed to the decrease in matrix fracture toughness and a slight change in fiber bridging capacity as reflected by ultimate tensile strength.

The formation of multiple micro-cracks under tensile load is one of the most distinctive characteristics of ECC. The crack patterns observed in representative GLECC specimens of all mixtures after unloading; both a higher ratio of FA/C and higher content of fly ash cenosphere in GLECC mixtures increase the number of micro-cracks, which contributes towards improving the tensile strain capacity. The average residual crack width for GLECC ranges from 23 to 51nm, depending on the fly ash cenosphere content and FA/C ratio. For each level of FA/C ratio, the replacement of IOTs with fly ash cenosphere leads to a decrease in crack width. This may be due to the lower cracking strengths as a result of a reduction in fracture toughness with the addition of fly ash cenosphere. Also, possible improvement in fiber dispersion, caused by the difference in particle shape of fly ash cenosphere (smooth sphere) and IOTs (irregular shape), may lead to stiffer crack-bridging curve, which may reduce the observed crack widths. Due to the reduction of crack widths, use of fly ash cenosphere in GLECC can potentially assist in reducing the permeability of cracked GLECC, thus promoting the material durability.

5.4. Effect of temperature exposure on the Residual tensile strength of High Volume fly ash(HVFA) incorporated ECC [17]

Jiangtao Yu et al. presented the result of temperature exposure on the composite residual tensile properties.

The axial tensile test indicated High volume fly ash-ECC maintained its unique characteristics of multiple-cracking, strain- hardening and tight crack width control after temperature exposure up to 200°C for one hour. High volume fly ash-ECC exposed to 50°C or 100°C treatment exhibited better residual tensile ductility and strain-hardening behaviour than specimens without temperature exposure but experienced a slight decline after exposure at 200°C exposures.

6.Conclusions

The studies on the development of the role of supplementary cementitious material, primarily fly ash in ductile Engineered cementitious composite (ECC) has been reviewed. Fly ash physical and chemical characteristics of as well as the compressive and tensile performance of the composite with fly ash summarized. The residual compressive and tensile performance of the composite with fly ash subjected to elevated temperature summarized. Based on the review, the following conclusions could be drawn:

1. In reviewing the role of Supplementary Cementitious material in ECC, it becomes clear that the fly ash had imparted its significance in strength, multiple cracking, matrix toughness and Ductility of ECC.
2. The SCM like fly ash would continue to be used to reduce the use of cement in ECC production and to make ECC more sustainable and Environmentally friendly.

The use of fly ash as Portland cement replacement (or) as Supplementary Cementitious Materials (SCM's), has the potential to be beneficial for the built infrastructure as well as the environment when adequately incorporated into ECC.

3. The fineness of fly ash is a more significant effect on the compressive strength and ductility of ECC. The tensile strain capacity did not increase with the increase of fineness. Based on the distribution of cracks, it should be noted that the uniform is cracking performance consistent with the ductility performance. Cracks distribution of group B with average fineness is more uniform.
4. As a comparison, the compressive strength of group A with group C the compressive strength decreased as the fineness of fly ash increased.
5. The experimental results showed that group FA-4 with the highest calcium-content had low tensile stress.
6. Replacing irregular IOTs aggregates with spherical fly ash cenosphere in GLECC improves tensile ductility and reduces crack width at the expense of a marginal reduction in compressive strength.
7.fly ash with the higher calcium-content did not make its tensile properties more significant at different ages.
8. The use of Class C fly ash instead of Class F with the same cement dosage and fly ash percentage generally caused to higher compressive strength. As Class C fly ash, contains higher calcium amount, the compressive strength results are higher in early ages compared to Class F fly ash.
9. When the sample is heated up to 800^0C, the sample size didn't play an essential role in the residual mechanical properties of ECC. In this manner, from the high-temperature deterioration point of view, ECC can be acknowledged as the sample size effect independent.
10. High volume fly ash -ECC exposed to 50°C or 100°C treatment exhibited better residual tensile ductility and strain-hardening behaviour than specimens without temperature exposure but experienced a slight decline after exposure at 200°C exposures.

Disclosures

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