CHAPTER 2 : LITERATURE REVIEW

2.1 General

Foam concrete is also known as lightweight cellular concrete, whose density varies from 400 to 1850 kg/m³ with an irregular pattern of air voids entrained in the mixture by the foaming agent. Foam concrete is acknowledged for its excellent flowability, low cement usage, and high thermal and sound insulation [4]. However, foam concrete is generally a feasible and practical alternative solution to construction sector issues such as partition walls in buildings, grade filling, Engineered Material Arresting System (EMAS) at airport runway end safety area (RESA), and the road embankment filling process due to its self-flowability and easy handling from manufacturing plant to site [40–43]

Concrete is the second most used substance globally, behind water. Concrete is used worldwide to construct infrastructure facilities like buildings and roads due to its reasonable cost, performance, and ease of construction. Concrete comprises cement, fine aggregates, coarse aggregates, and water. More than 70% of the weight of concrete consists of aggregates. A significant quantity of natural aggregates is being used for the manufacture of concrete. By 2027, there is expected to be a substantial demand for virgin aggregates, estimated to range between 2 and 10.3 billion [49,50]. As to India's 12th five-year plan, the projected demand for concrete is estimated to reach around 1 billion tons by 2027. The depletion and scarcity of virgin aggregates provide a significant sustainability challenge for the infrastructure industry, requiring urgent action. According to the Indian government organization, Indian cities generate over 150 million tons of construction and demolition (C&D) trash annually. Despite the substantial volume of construction and demolition debris produced, our maximum capacity is limited to 6500 tons per day, representing a mere one percent. In the absence of effective management and utilization strategies for construction and demolition (C&D) waste, a substantial quantity of primary aggregate is wasted as it is disposed of in landfills rather than being repurposed and recycled in future infrastructure endeavors. These have culminated in detrimental environmental consequences such as global warming, pollution, soil erosion, etc. It is also a challenge for scientists and researchers to devise sustainable building materials and structures. Researchers search for new eco-friendly alternatives to natural resources that can be used to make sustainable infrastructures. Better applications can be made using industrial byproducts and stone waste like granite, marble, limestone, sandstone, Kota stone, and quartz stone instead of fine or coarse aggregate either partially or wholly [38,49,50].

Foaming concrete uses waste materials and by-products from various sources to partially or completely replace cement or aggregate. Fly ash (FA) and bottom ash (BA) can react with other materials and are fine enough to be used instead of cement in concrete. Moreover, materials such as rice husk ash (RHA), waste glass (WG), and silica fume (SF) possess high amorphous silica content, making them suitable as cement replacement materials. Conversely, larger-sized waste materials with low pozzolanic reactivity, such as crumb rubber and construction and demolition waste (CDW), are predominantly utilized as fine aggregate substitutes in foamed concrete [19,22,35,51]

2.2 Material Components and Preparation

The fundamental constituents of foam concrete include (1) water, (2) OPC, (3) foaming agent, and (4) fine aggregates. The latest research and findings regarding these components are outlined as follows:

Water: The water requirement for constituent materials is influenced by the composition, consistency, and stability of the mortar body. Lower water content results in a denser mixture, which can lead to bubble bursting. Conversely, higher water content renders the mixture too fluid to retain bubbles, leading to their separation from the mixture. The American Concrete Institute (ACI) advises that the water used in mixing should be fresh, clean, and potable. In some cases, the mixed water can be replaced with water from city supplies that works just as well, as long as the strength of FC (foam concrete) mixes reaches 90% during the specified curing time.

OPC: Cement serves as the predominant binder in construction applications. Ordinary Portland cement (33, 43 & 53 grade) [52,53].

Foaming agent: The foaming agent plays a crucial role in determining the foam concrete density by regulating the bubble generation rate within the cement paste. Among the various options, resin-based foaming agents were among the first to be utilized in foam concrete applications. Currently, advancements in synthetic protein and natural protein are being made in the field of materials science and engineering [52,53].

Fine aggregates: Natural River sand with a 1.18 mm passing were used. Prior to casting, the sand particle undergoes thorough oven-drying process at a temperature of 105º C for a duration of 24 hours in order to eliminate any moisture content. The CD-RFA was acquired via diverse construction activities, such as building demolition, concrete pavement repair, and project upkeep. The CD-RFA acquired has an age of less than 6 months according to the plant knowledge database, with a layer of dust covering the whole perimeter. Therefore, it was subjected to ordinary washing and drying techniques for a duration of 24 h. The oven was kept at a constant temperature of 100–105 °C. Following the physical treatment, the CD-RFA underwent microstructural examination, including XRF, XRD, and SEM analysis, to assess the composition and pore structure matrix of the recycled materials obtained. The recycled fine aggregates stated earlier were sorted into suitable binary gradation, with a range of 1.18 mm. The CD-RFA was utilized without any additional processing to create FC mixes. The physical properties of the Natural River Sand were analysed in line with IS 2386 [54,55].

2.3 Proportioning and Preparation of FC mixes

Nehdi et al. [56] frequently employ a trial-and-error methodology to obtain foam concrete with specified qualities. McCormick [57] provided a rational proportioning approach based on solid volume calculations for a specific mix proportion and density. The design aid of ACI 523-R14 [58] correlates plastic density with compressive strength, enabling the selection of cement amount and water-cement ratio for specified strength and density. ASTM C 796-25 [59] delineates a calculating technique for determining the foam volume necessary to produce a cement slurry with a specified water-cement ratio and target density. The mix design equations proposed by Nambiar and Ramamurthy [17] ascertain the constituents of the mixture, including the percentage of foam volume, net water content, cement content, and percentage of fly ash replacement, based on a specified 28-day compressive strength, filler-cement ratio, and fresh density. Most recommended approaches assist in calculating batch amounts when the mix proportions are established. Although the strength of foam concrete is contingent upon its density, at a specific density, the strength can be enhanced by altering the constituent ingredients. Furthermore, at a specified density, the volume of foam required is contingent upon the component materials [13,60]. Therefore, for specified strength and density requirements, the mix design method must ascertain the batch quantities.

FC is typically produced using the pre-foaming or mix-foaming methods. Most conventional mixers, such as inclined drums and pan mixers utilized for concrete or mortar, are suitable for FC production. The type of mixer, mixing proportions, and mixing sequence for FC are contingent upon the implementation of the aforementioned two approaches. The three principal processes utilizing these two methods are delineated below: Pre-foaming Technique. The foam and base mixture are made separately. Thoroughly combine the foam and base mixture. In Mix-Foaming Technique, surfactants or foaming agents are used with the basic mixture, particularly the cement paste. The foam generates cellular structures in FC using two methods: dry or wet processes. The dry process yields more stable foaming bubbles with diameters less than 1 mm, whereas the wet process produces bubbles ranging from 2 mm to 5 mm in size. The stable foam aids in resisting mortar pressure until the cement hardens, hence facilitating the formation of a dependable pore structure in FC [61]. Although the mixing procedure and FC quality in these two ways may be regulated, the preforming method is deemed preferable to the mix-forming method for the following reasons. The criteria for foaming agents have been lowered. The air content in the mixture closely correlates with the foaming agent content [4,5,38].

Pre-formed foaming is favored over the mix-forming approach for the following reasons: i) reduced foaming agent necessity and ii) a direct correlation between the quantity of foaming agent utilized and the air content of the mixture [5,15,22,52,53,61,62]. The most prevalent forms of mixers, such as tilt drum or pan mixers utilized for concrete or mortar, are appropriate for foam concrete. The selection of a mixer and the sequences for batching and mixing foam concrete are contingent upon the pre-formed foam method or the mix-foaming method. The batching sequence for the manufacturing of foam concrete using premade foam was documented as follows. The requisite volume of premade foam is incorporated into the base mix and thereafter blended for a minimum of two minutes to achieve consistent foam dispersion

[52,53,63,64]. The compressive strength, drying shrinkage, and absorption characteristics are directly influenced by the curing process and time.

2.4 Properties of foam concrete

2.4.1 Fresh state characteristics

2.4.1.1 Consistency

The workability and flow properties of foam concrete contribute to its uniformity. These qualities significantly influence the FC mixes pumpability, compatibility, and finish quality. Various studies have examined how consistency varies with different mixing ratios, foam kinds, and additives [5,17,61]. Amran et al. [4] stated that increasing the water-to-cement ratio enhances the foam concrete consistency; however, it may also reduce stability due to increased foam collapse and segregation. Jones and McCarthy [65]emphasized the significance of stable pre-formed foam and regulated viscosity to maintain uniform consistency. A flow spread of 200 mm to 240 mm is deemed optimal for most applications. Falliano et al. [66,67] noted that the kind and quantity of foaming agents significantly influenced uniformity. Synthetic foams provide superior flow uniformity compared to protein-based foams. Furthermore, the incorporation of supplemental cementitious materials (SCMs) such as fly ash and silica fume has been shown to enhance the homogeneity of the mix by improving its cohesiveness [17,52,63,64]. Mydin et al. [68,69]conducted recent study indicating that the incorporation of nanomaterials, such as nano silica, alters the rheology of foam concrete, facilitating consistency management and minimizing bleeding. Chandni TJ and Anand KB [70] discovered that recycled aggregates influence consistency, necessitating the application of superplasticizers to maintain flow. Liu Z et al. [71] have demonstrated that the dilution ratio of the foaming ingredient directly influences consistency. Increased dilution ratios result in greater volumes and reduced density, hence exacerbating inconsistency due to the presence of more pores. To achieve optimal consistency in foam concrete, it is essential to meticulously control the mix design parameters, foam characteristics, and types of additives to ensure structural integrity and ease of on-site application.

2.4.1.2 Stability

Jones et al. [72] investigated the factors contributing to the stability of fresh foamed concrete. It was determined that at extremely low densities < 500 kg/m³, instability is nearly inevitable due to the coalescence and enlargement of bubbles. The ratio of bubble-to-solid area and the interactions between cement particles and air bubbles are crucial for mix stability. Feneuil et al. [73] developed a theoretical stability criterion linking bubble radius to the yield stress of cement paste. It was shown that substantial bubbles and low yield-stress paste induce ripening and drainage during the setting process, resulting in foam collapse. Boddepalli et al. [74] conducted a study on 3D-printable foam concrete, revealing that surfactant solution viscosity exceeding 5 mPas and low surface tension below 31 mN/m are crucial for maintaining foam stability during extrusion and buildability, even in mixtures with a density ranging from 1000 to 1300 kg/m³. A comparable study altered the temperature of the foam preparation to enhance the foam's stability. This indicates that modifying the surfactant temperature during foam production can significantly enhance the durability of the newly produced foam concrete mix. Zhou & Su [75], indicated that the durability issues of hardened foam concrete, including its resistance to freeze-thaw cycles and sulfates, are associated with the stability of its pore structure. They also stated that incorporating additives into foam stability enhances the pore structure's density, hence improving the concrete's long-term performance. Fu et al. [76] conducted a comprehensive assessment of foam concrete properties and determined that stability during mixing is crucial for achieving a uniform pore structure, constant density, and reliable strength and shrinkage characteristics.

2.4.1.3 Workability

The workability of foam concrete can be visually evaluated by measuring its viscosity. The traditional slump cone approach is unsuitable for lower-density foam concretes, according to BS EN 12350-8 [77] . The research indicates that the workability of foam concrete is influenced by various factors, including the kind of foam, binder, admixture, and aggregate. A balanced mix design is essential for optimal workability, as it maintains foam stability, minimizes segregation, and ensures pumpability and placement. Researchers have extensively examined the feasibility of foam concrete in recent years. This is a significant component that influences its placement and compaction. Jones and McCarthy [65] were among the initial scholars to emphasize the significance of novel traits. The consistency and stability of the foam primarily dictate the workability of foam concrete. It was said that foam concrete mixtures with a water-to-cement ratio of 0.6 to 0.65 exhibited optimal flowability without segregation. Kearsley and Wainwright [78] noted that increasing water content enhances foam fluidity; nevertheless, excessive water might destabilize it, compromising its ability to maintain a consistent structure. Nambiar and Ramamurthy [79] examined the impact of fly ash. They discovered that substituting a portion of the cement with these components enhances the fluidity of the concrete, as the spherical particles reduce internal friction. Pasupathy et al. [80] noted that recycled fine aggregates (RFAs) derived from construction and demolition debris increased the difficulty of work due to their high-water absorption capacity. This issue could be resolved by incorporating superplasticizers. Abd Elrahman [81] discovered that substituting of nanosilica improved the homogeneity of the foamed concrete in the fresh state, since it acted as foam stabilizers. Consequently, the required dosage of viscosity-enhancing admixtures decreased with rising nanosilica content. Liu et al. [71] demonstrated that the incorporation of nano-silica enhances adhesion and fluidity by functioning as micro-fillers and water retainers. Cui et al. [82] utilized HPMC (hydroxypropyl methyl cellulose) was the most suitable for SUHPC (sprayable ultra-high performance concrete) , and the field sprayed thickness could be up to 50 mm when the dosage of HPMC was 0.7‰, which meets the mechanical requirements of repair or lining. A functional relationship between slump-flow, static and oscillatory rheological parameters was revealed and established a simple functional model, beneficial to comprehensively understand the rheological behaviors of SUHPC materials.

2.4.2 Hardened properties

2.4.2.1 Drying shrinkage

The extent of shrinkage during the drying process significantly influences the long-term strength and stability of foam concrete. In the past two decades, extensive study has been conducted to elucidate the underlying mechanisms and contributing elements. Jones and McCarthy [83] conducted extensive research on the engineering properties of foamed concrete. It was noted that drying shrinkage escalates with a decrease in density and a rise in the water-to-cement (w/c) ratio. This illustrates how the volume of water and the dimensions of the pores influence the degree of shrinkage. Chindaprasirt et al. [84] conducted a comprehensive study on foamed concrete, emphasizing the influence of mix composition on shrinkage, particularly regarding the quantity of paste and the type of foam utilized. Their findings indicate that shrinkage can be mitigated by utilizing an appropriate amount of foaming agents and incorporating fly ash, rice husk ash and palm oil fuel ash. Roslan et al. [85] investigated the shrinkage of foamed concrete with differing densities and cement-sand ratios along with polypropylene fiber. They discovered that an increased amount of fly ash results in less shrinkage due to the pozzolanic nature of fly ash and lime which reduces the number of pores and provide uniform distribution in FC mixes admixed with lime and fly ash as OPC replacement. Jung et al. [86] examined the impacts of recycled fine aggregates (RFA) and discovered that drying shrinkage of FC mixes admixed with recycled aggregates observed at early stage and higher the water absorption of FC mixes higher will be the drying shrinkage..

2.4.2.2 Density

There are two ways to determine the density of foamed concrete mixtures: fresh state and hardened state. It is advised that the range of fresh and dry density values be kept to between 100 and 120 kg/m³ [87]. The actual fresh mix density is frequently measured by adding the foam concrete to a pre-weighed standard container with a given volume and weighing the mixture. It is possible to evaluate the difference between both the achieved and designed densities. For high-density foam concrete mixes (i.e., 1600 kg/m³), the maximum tolerance for dry density is limited to 50 kg/m³, with a potential variance of up to 100 kg/m³. The density of foam concrete significantly influences its strength and durability. Foam concrete typically exhibits a lower density compared to conventional concrete, rendering it suitable for applications where weight is not a critical factor [68,79]. The literature indicates that the density of foam concrete, in its fresh, dry, or bulk states, is influenced by the quantity of foam, the water-to-cement ratio, the curing process, and the composition of the mix. Density control is crucial not only for mechanical strength but also for thermal insulation and workability. This is a crucial design consideration for lightweight concrete applications [17,52,53,61].

2.4.2.3 Air-void system

The existence of air voids in foam concrete is a critical consideration as it influences other essential characteristics such as permeability, porosity, and pore size distribution, therefore affecting the strength and longevity of the foam concrete. The air void structure in foam concrete is very important for its mechanical and durability performance, especially because it has a unique cellular matrix [28]. Jones and McCarthy [72,83] gave us important information about how pore size distribution and connectivity affect things. They stressed that a uniform void structure greatly improves strength and thermal insulation. Hilal et al. [88,89]found that incorporation of Nano silica into the mixture with foam bubbles and this way was found as an effective way in gaining better properties than the way with adding them with mixing water. Compared to foamed concrete mixes made with natural fine sand, a homogenous pore structure in terms of pores size distribution, circularity and spacing Silica sand was created with using silica sand. Li et al. [71,90]found that Appropriate fiber mass fraction can play a role of refining small pores and separating large pores, improve the structural compactness, reduce the pore collapse phenomenon and optimize the pore structure of FRFC (Fibre reinforced foamed concrete). As fiber mass fraction of fibers increased to 2%, the agglomeration induced the macrospores were connected and the air pores collapsed in the hardened FC.

2.4.2.4 Compressive strength

Multiple variables such as density, constituent composition, aggregates, admixtures, water content, foaming agents, curing, and porosity influence the compressive strength of foam concrete. Enhanced compressive strength was achieved by combining fine sand with consistently distributed pores, in contrast to coarse sand with randomly distributed pores [24,34]. Several investigations have been conducted on the compressive strength of foam concrete, examining a diverse array of mix designs and curing conditions. This lightweight material is recognized for its excellent thermal insulation properties and low density [22]. Higher densities usually indicate greater compressive strength. This is because denser mixes contain fewer air voids and a more continuous cementitious matrix, making them more capable of supporting loads

[38,52,52,83,91]. Furthermore, the foaming agent stability and manufacturing process are critical. Stable and evenly dispersed foam ensures that the material remains consistent and that its strength rises steadily [92]. Compressive strength has a significant impact on thermal conductivity, water absorption, and durability of foam concrete mixes. However, making the mix stronger may reduce its ability to insulate against heat, as denser mixes often have higher thermal conductivity [66,93]. Furthermore, high-strength foam concrete may not absorb sound as well as lightweight concrete, which is one of the reasons it appeals. Adding mineral admixture such as fly ash, silica fume, rice husk ash and ground granulated blast furnace slag has showed promise in boosting compressive strength while maintaining or improving other relevant qualities like as heat resistance and microstructural characteristics [17,91]. These components promote the pozzolanic process, which makes the matrix denser, stronger, and more lasting. However, in order to maximize the strength, gain while also improving thermal and acoustic performance, the mix must be carefully planned and optimized. Higher strength often indicates greater durability and less permeability, but it must be balanced with other desired properties such as thermal insulation and soundproofing, depending on how the foam concrete mix will be utilized [89].

2.4.2.5 Flexural and split tensile strengths

In recent years, foam concrete has gained significant traction as a building material due to its lightweight nature and eco-friendly properties. Extensive studies have been conducted on its compressive strength; however, understanding its flexural and split tensile strength remains crucial for analyzing its behavior under various loading conditions. According to Jones and McCarthy [83,94], foam concrete exhibits lower tensile and flexural strengths compared to regular concrete due to its cellular structure. Nonetheless, these strengths can be improved through the appropriate selection of mix designs and additives. The findings indicated that the split tensile strength of foam concrete varied from 0.8 to 2.4 MPa for densities ranging from 800 to 1600 kg/m^3. This indicates a direct correlation between density and mechanical performance [83].

Amran et al. [4] reviewed the various mix components and curing conditions that influence the properties of foam concrete. The findings indicate that increasing the cement content while reducing the water proportion enhances flexural performance. The findings indicated that the flexural strength of medium-density mixtures typically ranges from 1 to 3 MPa. Incorporating fibers such as polypropylene or glass fibers enhances the foam concrete flexibility and improves its resistance to cracking. Hilal et al. [88,95] discovered that incorporating fibers into foam concrete significantly enhances its tensile strength. The explanation provided indicates that the fibers act as a bridge over microcracks, thereby decelerating the propagation of fractures. Kearsley and Wainwright [78] conducted a study that compared split tensile strength to compressive strength, revealing that split tensile strength is approximately 8–12% of compressive strength, while flexural strength is around 15–20%. This indicates that strategies to enhance strength should be targeted appropriately. Nambiar and Ramamurthy [17] investigated the potential of using fly ash as a partial substitute for cement. The study revealed that substituting as much as 60% of the cement with fly ash could enhance the material's strength in both tension and bending, attributed to improved particle packing and the occurrence of the pozzolanic reaction. However, after that point, the strength began to decline. Ramamurthy and Nambiar [13] discussed the impact of the curing method and age on the outcomes. It was observed that specimens subjected to wet curing for a duration of 28 days exhibited tensile and flexural strengths that were 20–30% greater compared to those that underwent air curing. Split tensile and flexural strengths of foam concrete are significantly influenced by the mixed design, curing methods, and the incorporation of additional cementitious materials or fibers. The findings hold significant relevance for applications such as load-bearing wall panels or precast components, where tensile and flexural resistance are critical considerations [94].

2.4.2.6 Modulus of elasticity

The modulus of elasticity (E) of foam concrete is a crucial mechanical characteristic that influences its deformation behavior when subjected to stress. The influence of density, mix composition, and pore structure on this property is significant. Jones and McCarthy [83] found that the modulus of elasticity of foam concrete increases almost linearly with density, ranging from 1 GPa for 600 kg/m³ to more than 8 GPa for densities exceeding 1600 kg/m³. This indicates a notable connection between the rigidity and density of a structure. Kearsley and Wainwright [78] discovered that foam concrete exhibiting higher cement content and a finer pore structure demonstrated increased stiffness. This indicates that optimizing the mix may enhance elastic performance. Amran et al. [96] findings support the notion that substituting cement with alternative materials such as fly ash or GGBS can alter the elastic modulus; however, this frequently results in a compromise on strength and stiffness. Nambiar and Ramamurthy [17] discovered that foam concrete exhibits a significantly lower elastic modulus compared to conventional concrete with equivalent compressive strength. This occurs due to the presence of air pockets trapped within the foam concrete and the existence of weaker interfacial zones. However, they emphasized that enhancing the stability of foam and incorporating finer fillers such as silica fume can contribute to increasing E values. Chen and Liu [97] demonstrated through experiments and regression modeling that one can estimate the modulus of elasticity in foam concrete by utilizing empirical relationships that incorporate compressive strength and density. This aligns with research conducted by Hilal et al. [88], who developed a predictive model tailored for low-density concrete.

Zhang et al. [98] examined the influence of foaming agent concentration on pore connectivity and stiffness. Excessive dilution, such as a ratio of 1:40 or greater, results in increased porosity and reduced elasticity due to the thinning of cell walls and the enlargement of the average pore size. Microstructural research employing SEM imaging further validated these findings and highlighted the critical significance of pore shape. The findings indicate that foam concrete offers advantages in weight reduction and thermal insulation; however, its elasticity modulus is notably influenced by the mix parameters and density. This indicates that structural applications require a particular methodology for effective implementation.

2.4.3 Durability properties

The capacity of concrete to resist external factors that may lead to deterioration and reduce its lifespan is known as the durability characteristic of foamed concrete.

2.4.3.1 Water absorption and permeability

Water absorption of FC mixes is directly related to its pore structure, which includes porosity, pore connectivity, and dry density. These factors depend on the mix design, the water-cement ratio, and the curing process [99]. Kearsley and Wainwright [93] stated that foamed concrete water absorption is mostly unaffected by foam content, ash type, or fly ash ratio, but is strongly affected by dry density. Water-vapor permeability increases with porosity and is more affected by the fly ash/cement ratio at lower densities. The permeability trends are the same for mixtures with and without foam. Jierula et al. [100] investigated at densities ranging from 600 to 1,200 kg/m^3 at different W/C ratios. They found that water absorption decreases significantly with increasing density. Lower density (600 kg/m^3) showed about 45.9% higher absorption compared to 1,200 kg/m^3, while the 800–1,000 kg/m^3 densities had moderate rates (11.1% to 20.3%). They also found that when the density was set at 800 kg/m^3, the water absorption showed a nonmonotonic trend with the W/C ratio. Cai et al. [101] investigated that with the increase of density, the volume water absorption of lightweight foam concrete decreases gradually. The water absorption decreases at first and then increases with the fly ash content increasing, and the critical value of fly ash is 40%. Gencel et al. [102] studied the production of sustainable foamed concrete admixed with rice husk ash and found that large, interconnected voids cause moisture movement. This is because foamed concrete doesn't compact, so these macro-void pathways control how much water it can hold and how easily it can pass through. Controlling the microstructure, choosing the right ingredients, and optimizing the admixture were all found to be important for reducing permeability.

2.4.3.2 Sorptivity and porosity

The sorptivity of a medium is its ability to absorb a liquid by capillary action. Sorptivity influences the longevity of foamed concrete, primarily determined by the type of mineral admixtures, the foaming agent, density, permeability characteristics, and curing conditions [100,103,104]. The variables influence water transmission regarding bubble size (or porosity), tortuosity, distribution uniformity, and continuity characteristics. “Utilizing the theory of unsaturated flow and assessing the capillary rise absorption rate in relatively homogeneous concrete, such as foamed concrete, one can calculate the sorptivity” [99]. The permissible sorptivity fluctuation is influenced by the air content in the foam concrete, ranging from 4 to 8% [104]. Foam concrete exhibits distinctive porosity and sorptivity characteristics, which fundamentally influence its durability, moisture transport behavior, and long-term performance. The porosity in foam concrete is strongly governed by dry density, while being largely insensitive to fly ash type or content. Their extensive investigations revealed that porosity increases as density decreases, and that water-vapour permeability rises with both porosity and ash content.

Notably, foam concrete absorbs roughly twice the volume of water per m^3 compared to conventional concrete, yet this absorption correlates poorly with entrained air volume or binder substitution—underscoring that pore volume connectivity, not just porosity, governs sorption performance [4,5,105]. Sorptivity—the capillary-driven rate of moisture uptake—was shown to be intricately tied to pore structure: higher porosity and increased pore connectivity led to steeper sorptivity curves. Using vacuum saturation techniques, both absorption and sorptivity across mixes with varying fly ash content up to 75%, demonstrating that increased ash content exacerbates capillary transport only indirectly through its effect on pore interconnectivity and weaker matrix interfaces. Gencel et al. [106] evaluated foam concrete mixes incorporating expanded perlite and waste glass sand. They reported that apparent porosity, sorptivity, and water absorption are closely interrelated: a foam concrete containing expanded perlite showed high porosity but moderate sorptivity, while substitution with fine waste glass reduced pore connectivity and thus lowered sorptivity and absorption coefficients significantly improving durability traits despite high void volume. Rudziewicz et al. [107] studied 3D-printed foam concrete using protein-based and synthetic foaming agents, with or without stabilizers. They compared porosity and sorptivity in both 3D-printed and cast specimens and found that protein-based foaming agents with stabilizers yielded smaller, and more uniform pores, while synthetic based foaming agent without stabiliser produce less stable foam. The orientation (vertical vs horizontal) also affected sorptivity, reflecting anisotropic pore channels in printed samples. This research demonstrates how foam stability and pore uniformity control moisture uptake rates by capillary suction.

2.4.3.3 Resistance to aggressive environment

In aggressive situations like acid, sulfate, chloride, etc., foam concrete might function poorly. The erosion resistance of foam concrete depends on its properties, including porosity, pore size, dispersion, shape, and content [52,53,75].

2.4.3.3.1 Resistance to chloride environment

Foam concrete performance under hydrochloric acid (HCl) exposure is critically influenced by its inherent porosity, density, and mixture composition, which govern acid ingress and material deterioration. A comprehensive review by Zhou & Su [75] highlights acid attack as a major durability concern for traditional OPC foam concrete, where mass loss under 5% HCl increases as dry density decreases, owing to elevated porosity and greater exposed contact area facilitating acid diffusion. Specifically, low-density mixes demonstrate significantly more degradation than higher-density versions, consistent with their more open pore structure and higher permeability. Amendments to the foam concrete mixture—including fiber reinforcement, pozzolanic replacements, or GFC (geopolymer foam concrete)—substantially enhance acid resistance. The addition of basalt fiber reduces mass loss under 5% HCl attack, as the fiber creates a more acid-resistant network within the matrix and reinforces structural integrity against dissolution of binder phases. Similarly, replacing part of cement with processed spent bleaching earth or fly ash improves erosion resistance under aggressive HCl exposure: the pozzolanic reactions reduce free calcium hydroxide—and therefore vulnerable phases—resulting in lower mass loss compared to pure OPC foam concrete. OPC based foam concrete—without admixtures or fibers—exposed to 5% HCl solutions shows a clear inverse relationship between density and acid-induced deterioration: as density drops (and porosity rises), mass and strength losses amplify, due to increased acid diffusion paths and surface contact area. However, acid dosing time and cycle number also matter: an experimental study on dry–wet cycling under acidic conditions (pH 3 or pH 5) revealed progressive mass reduction, compressive strength degradation, pore expansion and internal cracking, with severity increasing under lower pH and more cycles. After 15 cycles in pH 3 HCl, extensive microstructural damage and strength loss occurred, demonstrating that cyclic acid exposure accelerates internal pore coalescence and structural breakdown [75]. Bagheri & Rastegar [108] investigated that chloride diffusion increases as foam content increases in FC mixes. Foam concrete under repeated HCl immersion cycles exhibits visible surface deterioration, color change, pore expansion, and cracking—with compressive strength decreasing exponentially as acid exposure accumulates. This supports earlier assertions regarding density dependency and adds the insight that chemical erosion alters microstructure, promoting pore growth and aggregate–matrix separation.

2.4.3.3.2 Resistance to sulphate environment

The resistance of foam concrete to sulfuric acid (H_2SO_4) is influenced by its OPC chemistry, porosity, density, and microstructure. Conventional OPC-based foam concrete typically demonstrates inadequate durability in sulfate-rich acidic environments [4,5,76]. A comprehensive durability review by Zhou & Su [75] indicates that acid resistance, including sulfate resistance, is a relatively weak performance metric for typical foam concrete materials (OPC, GFC, SAC, MPC, LC^3). This limitation is primarily attributed to their higher porosity and permeable microstructure, which allow for aggressive ion ingress and subsequent chemical degradation. Geopolymers (GFC) and admixture-enhanced mixes exhibit enhanced sulfate tolerance due to lower calcium hydroxide content and the presence of more chemically stable binder phases, such as N-A-S-H gel. Research on foam concrete subjected to continuous or cyclic immersion in sulfuric acid indicates that foam concretes with higher porosity and lower density experienced increased erosion, gypsum formation, cracking, and a reduction in strength. Accelerated durability tests utilizing alternating immersion and drying in 0.5% H_2SO_4 over several weeks demonstrated that even mixtures modified with silica fume and high-sulfate resisting cement experienced considerable surface degradation, dimensional alterations, and integrity loss—especially in regions where calcium silicate hydrate (C–S–H) was prone to conversion into gypsum and ettringite formation. The tests, although not exclusively focused on foam, demonstrate chemical mechanisms that are generally relevant to porous cementitious materials such as foam concrete. Phosphogypsum based foam concrete performs better than OPC based foam concrete in the presence of acid base salt solution. This is because OPC based foam concrete contains more cement minerals, and hydrated products contain more active minerals, which are more susceptible to erosion by acid base salt solution [109].

2.5 Literature review on recycled waste admixed in FC mixes

2.5.1 Fly ash and bottom ash as OPC and natural river sand replacement

Sari et al. [110] explored the synergistic application of fly ash (FA) and bottom ash (BA) in aerated concrete, employing a density-driven mix design approach. In the research conducted, fly ash was utilized as a substitute for cement at levels ranging from 0 to 30%, whereas bottom ash served as a replacement for sand at proportions of 0 to 50%, across four specified target densities (1000–1800 kg/m³). The findings indicated that the addition of 15% FA without BA in the 1000 kg/m³ mixture yielded the highest performance index, achieving a compressive strength of 15 MPa at 28 days. Nonetheless, the addition of BA typically resulted in heightened water absorption and diminished compressive strength because of its porous and less reactive characteristics. Fly ash demonstrated superior effectiveness in enhancing strength compared to bottom ash.

Although bottom ash contributed to a reduction in overall density, it required meticulous proportioning to prevent any compromises in durability. The research highlighted that the integration of FA and BA has the potential to produce sustainable and structurally sound foam concretes when optimized appropriately.

Jones et al. [26] investigated the creation of ultra-lightweight foam concretes by utilizing a high volume of fly ash along with a partial addition of calcium sulfoaluminate cement, resulting in densities reaching as low as 150 kg/m³. The incorporation of fly ash effectively lowered the density while simultaneously boosting foam stability, refining pore structures, and enhancing the long-term performance of the concrete. The research showed that replacing up to 70% with fly ash facilitated the creation of consistent cell walls and minimized the carbon footprint, rendering it appropriate for insulating and non-structural uses. Their study demonstrated that fly ash serves as a valuable supplementary component that enhances the sustainability aspects of foam concrete while preserving essential mechanical characteristics.

Malaiškienė and Vaičienė [111] investigated the impact of integrating silica fly ash and wood-derived bottom ash within conventional concrete, emphasizing hydration behavior, strength, and durability. They replaced as much as 30% of the cement and fine aggregate with FA and BA, observing that hydration was postponed by approximately 5 hours, yet the ultimate compressive strength experienced only a reduction of around 6%. The findings, while not exclusively centered on foam concrete, demonstrate that blended ash systems can provide both mechanical stability and environmental advantages. The integration of FA and BA yielded satisfactory porosity levels, enhanced freeze-thaw durability, and better environmental performance, endorsing their use in lightweight concrete mixes.

Haddadian et al. [112] assessed the effectiveness of coal bottom ash as a substitute for fine aggregate in foam concrete, observing that although CBA decreased the dry density of the concrete, it resulted in a reduction in compressive strength. The research indicated that bottom ash, characterized by its coarse texture and reduced pozzolanic activity, led to higher water absorption and adversely impacted foam stability. Nonetheless, the incorporation of fly ash in limited amounts helped to alleviate the adverse impacts of CBA, allowing for the attainment of satisfactory strength and workability levels. The findings indicated that using bottom ash by itself might not yield the best results for foam concrete. However, when combined with fly ash, it can enhance eco-friendly, low-density mixtures

Haddadian et al. [113] carried out an extensive investigation into the incorporation of coal bottom ash (CBA) as partial replacement of OPC and natural river sand replacement in lightweight concrete. Their findings showed that incorporating CBA enhanced the flow properties and longevity of foam concrete. FC mixes which were water-cured had a higher density than ambient-cured specimens, with an average difference of about 150 kg/m^3. However, substituting 20% of OPC weight with CBA did not affect FC mixes density. The UPV values of FC mixes admixed with CBA and cured at ambient condition were lower than those which were water-cured. This might be due to lesser available water for pozzolanic reaction during hydration of mixes and finally contributed to had larger air voids.

2.5.2 Slag as OPC and natural river and replacement

Awang et al. [38] investigated using unground blast furnace slag (GBS) and ground granulated blast furnace slag(GGBS) as partial OPC replacement in foam concrete. The consistency of FC mixes admixed with GBS was higher than FC mixes having BFS. GBS foam concrete mixes recorded higher strength than the control mix due to fineness of GBS particle. Compressive strength ratios of 81 and 70% respectively, with respect to their corresponding admixed with 30% GBS and 30% GGBS after 28 days of curing. This research provides evidence that GBS can be a good replacement for cement in the production of foam concrete. The utilization of GBS without a grinding process is made possible with the help of a super plasticizer to reduce the water demand of the mix. Such incorporation will not only reduce the cost of foamed concrete but will also enhance the possibility of utilising unground GBS in the production of concrete.

Bazhenova et al. [114] looked at using granular blast furnace slag as a full sand substitute in foam concrete at densities of 900 and 1,700 kg/m³. When BFS completely replaced sand, the total porosity went down, and the pore structure got denser. This made the compressive strength and elastic modulus better. They also showed that the theoretical porosity (using models) and the measured values were quite close, which supports the idea that slag could be a useful fine aggregate in foam concretes.

Zhang et al. [115] conducted a systematic investigation on the combined impacts of foam content, fly ash, slag, silica fume, and the water-to-binder ratio. They looked at 39 different mixes. They saw that adding slag made the material stronger and less able to absorb water up to a certain amount, after which the performance dropped. Slag had a big effect on keeping strength in freezing-thaw cycle resistance and pore stability, whereas silica fume did better at refining pores on a smaller scale.

Vishavkarma et al. [63] studied the application of slag and fly ash as OPC substitution in FC mixes and compared the results with conventional concrete grade of M25. FC mixtures admixed with fly ash and slag resulted in the reduced the amount of unhydrated cement grains in the matrices along with decrement in large-sized capillary pores by 90.4%-95.8% and increased the gel pores by 33%- 94% and decreased the macro-porosity by 15%-27% compared to OPC based FC mixture.

2.5.3 Silica fume as OPC

Anusree & Gopakumar [116] performed an experiment where they added silica fume (5–20%) and fly ash to foam concrete mixes with different amounts of foam (2–5%) and densities (600 to 1450 kg/m³). They discovered that adding silica fume increased compressive strength by up to 50%, made the material easier to work with, and improved the pore structure. Even at lower densities, compressive strength reached up to 13 MPa with 10% silica fume.

Zhang et al. [115] varied the amount of foam, fly ash, slag, silica fume, and w/c ratio in 39 combinations. They said that silica fume had the biggest effect on compressive strength, water absorption, and pore stability compared to other admixtures. Moderate amounts of silica fume made the correlation between density and strength better and made the material more resistant to freezing and thawing. Too much silica fume, on the other hand, made the material less effective since it changed the balance between porosity and water absorption.

Gökçe et al.[117] demonstrated the application of silica fume and fly ash in foamed concrete mixes. The reduction in compressive strength of FC admixed with high fly as was higher. But compressive strength of FC mixes admixed with silica fume was observed to be 4.4 times higher at same foaming agent concentration. Compressive strength/thermal conductivity ratios of the silica fume-based FC mixes increased up to 4 times by the increase of foam content. But in case of fly ash-based FC mixes this ratio was reduced up to 38% at high foaming agent concentration.

Wang et al. [118] studied the implication of silica fume as foam stabilizer. FC mixes admixed with silica fume in plastic stage have higher density followed by higher compressive strength and higher compressive strength to density ratio. The compressive strength/density ratios were about 2, 4 and 4 higher than that of control mix, and were about 1, 2 and 2 higher at the ages of 7 days, 14 days, 28 days, respectively. FC mixes admixed with silica fume have more spherical air voids due to the stabilization effect of FC mixes. This clearly shows that the pore structure of FC mixes was stabilized with the help of silica fume and silica fume can be used as foam stabilizer.

Gong et al. [119] investigates the utilization of silica fume and Nano silica in structural foamed concrete mixes. The compressive strength of FC, admixed by Nano silica with 4% had 35.8 MPa strength and silica fume with 15% had 32.8 MPa, respectively. FC flexural and compressive strength of FC mixes are admixed with 4% Nano silica and 15% silica fume had maximum strength but after further addition of both, compressive strength starts decreases. The ultrasonic pulse velocity of FC mixes are directly related to strength. FC mixes having Nanosilica and silica fume had higher velocity as compared to conventional FC mixes due to denseness of FC mixes.

2.5.4 Palm oil fuel ash

Hadi, Awang, and Al-Mulali [120] looked at using fine oil palm ash (FOPA) as a partial replacement for cement in foamed concrete (with a target plastic density of about 1,000 kg/m^3). They used FOPA to replace cement at amounts ranging from 25% to 65%. The concrete mix containing 25% of FOPA did better after 90 days. It had stronger compressive strength, density, and water absorption, and lower sorptivity than the control mix. However, it did shrink a little more as it dried. The strength and durability advantages at modest replacement levels point to the best FOPA content for long-lasting foam concrete construction.

Al-Mulali et al. [121] 2015 did another investigation with solely sieved oil palm ash (OPA) and replaced 25% to 65% of the OPC. The 25% OPA mix had higher compressive, tensile, and flexural strength than the control throughout 28–56 days, which shows that pozzolanic reactions were still happening even if there wasn't much processing. But increasing levels of replacement made the strength weaker. This study shows that low-cost, lightly processed POFA can be used as a substitute for cement in dense foam concrete.

Patah et al. [122] demonstrated the 100 µm POFA as a partial cement substitute (10–20%) in sustainable foamed concrete with different amounts of foam agent. The study found that the best way to replace 10% of POFA with foam agent and water in a 1:60 ratio was to get the best strength and durability. Strength stayed about the same as the control at 20% substitution of POFA in FC mixes. The strong link between porosity and compressive strength supports POFA involvement in refining microstructure.

Bayagoob et al. [123] looked at lightweight concrete that had 10–20% POFA with silica fume and 0–100% palm oil clinker (POC) as fine aggregate substitution. They observed that adding POFA made LWC less permeable, absorbed less chloride and water, and helped keep compressive strength at high temperatures. Results show that POFA makes things last longer, especially when used wisely with other cementitious materials, even though they aren't foam specific.

Jose et al. [124] studied foamed concrete with POFA and red gypsum as a replacement for OPC and sand, respectively in low-density mixes. Their results showed that adding POFA to the mix enhanced compressive strength and lowered dry density and water absorption. This made foamed concrete blocks that are environmentally friendly and may be used for non-load-bearing masonry.

2.5.5 Rice husk ash

Agboola and Shabi et al. [95] explored the properties of foamed concrete incorporating up to 30% RHA as a substitute for cement along with kenaf fibre, targeting a design density of 1600 kg/m^3. Their analysis assessed compressive strength, sorptivity, water absorption, as well as tensile and flexural performance over a curing period of 7 to 90 days. Kenaf fibre has significant effect on the foamed concrete properties, as the percentage fibre is increased, the density of the foamed concrete is reduced, which makes the specimen lighter in weight. The highest split tensile strength of foamed concrete at 28 days was 2.41 N/mm^2, at 0.5% kenaf fibre addition. The density of the foamed concrete has an impact on the sorption performance of the concrete. Water absorption is higher in concrete produced with higher percentage of kenaf fibre. Kenaf fibre foamed concrete show high absorption and sorptivity rate as compared to the control concrete with optimum addition at 0.5%.

Abdulazeez et al. [125] develop a 28 days compressive strength prediction model. This study indicates that by regulating the mixing process, the density, stability, and characteristics of the materials employed in the production of foamed concrete can be used to forecast strength.

Rizwan Khan et al. [126] investigated foamed concrete with RHA (rice husk ash) substituting fine aggregate at proportions ranging from 0 to 20%, aiming for a density of 1300 kg/m^3. From 28 to 90 days, they assessed compressive and split tensile strength, dry density, and water absorption. The findings indicated that the inclusion of RHA resulted in a slight reduction in density and strength, while also leading to an increase in water absorption, particularly evident at higher replacement levels of 15–20%. This confirmed that using moderate RHA as a substitute for sand is practical, but it should be restricted to maintain durability.

Rum et al. [127] studied the application of RHA as a sand substitute (0–50%) enhanced the compressive strength compared to OPC based foam concrete mixtures. The fine particle structure and high silica content of RHA are emphasized as crucial factors that enhance microstructure and strength, even when used as substitutes for aggregate components.

2.5.6 Ceramic waste tile powder as OPC

El-Nadoury [128] studied that the inclusion of white ceramic tile powder (WCTPs) as OPC positively affects the strength performance at levels of 5, 15, and 20%, and the specimens achieved the highest enhancement of 6.1% with 20% of WCTPs. However, raising the replacement level to 25% and 30% resulted in a drop in strength, causing a loss of 5.6% and 20.3%, respectively. A similar trend of results was observed for flexural and split tensile strength, with specimens containing 20% WTCPs as OPC replacement achieving the highest strength performance among the other ratios. A negative effect was observed with increasing the water-to-cement ratio, and the strength trend decreased with increasing the water content. Specimens prepared with a 0.50 water-to-cement ratio showed a loss in strength between 1.7% to 7.8% at 28 days. A significant loss of strength was observed for specimens prepared with a 0.60 water-to-cement ratio, ranging from a 15.9% to 17.8% loss. For a high-water content (0.50 and 0.60), specimens prepared with a high content of WCTPs (30%) showed a reduced loss of strength of 1.7% and 15.9%, respectively.

Soomro, B. et al. [129] indicate that replacing OPC with 30% of WTCPs leads to an increase in strength from 20.8 MPa to 24.6 MPa. However, the strength trend drops by increasing the level of replacement to 40% and 50%.

Tawfik, T.A. et al. [130] studied the comparison to the strength of control specimens (27.6 MPa), the replacement of OPC by 2, 4, 6, 8, and 10% of WCTPs leads to an enhancement of strength to 28.8, 29.3, 29.7, 29.2, and 28.7 MPa, respectively. A similar trend of results was observed for FS and STS, and all the specimens prepared with WCTPs displayed a better performance than the control specimens.

2.5.7 Quarry dust waste

A substantial portion of the aggregate materials used in construction is sourced from quarrying operations, leading to a considerable amount of quarry waste generated. Lim et al. [131] investigated the substitution of river sand with refined quarry dust (QD) in lightweight foamed concrete (LFC) at densities of approximately 1,300 ± 50 kg/m³. Through the application of 75% and 100% QD replacements at varying water-to-cement (w/c) ratios (0.52–0.58), the study revealed that high-volume QD led to a reduction in slump fluidity while simultaneously increasing compressive strength and improving thermal conductivity in comparison to control mixes that utilized river sand. Interestingly, strength remained stable despite the rise in water-to-cement ratio, probably because of modifications in foam volume. A life-cycle assessment demonstrated a notably reduced environmental impact in terms of energy consumption and greenhouse gas emissions with the inclusion of QD.

Jose et al. [132] conducted an experiment on foam concrete, incorporating 0–100% quarry dust as a substitute for manufactured sand, with densities ranging from 1,000–1,400 kg/m³. The findings indicated that compressive strength improved by approximately 108% relative to the control mix up to 60% replacement of QD with sand. The improvement was linked to more refined particle packing, better stability of foam bubbles, and strengthened cohesion within the microstructure. Strength gains reached their maximum at 70% replacement, beyond which performance diminished due to the elevated water requirements of QD.

Gopalakrishnan et al. [133] explored the synergistic application of fly ash (up to 50%) and quarry dust (0–50%) in the formulation of foam concrete. The findings indicated that the inclusion of 30% quarry dust alongside fly ash resulted in enhanced performance in terms of compressive strength, split tensile strength, and durability measures, such as water absorption and permeability, when compared to traditional foam concrete. The investigation emphasized the collaboration between FA and QD in enhancing performance while minimizing dependence on river sand.

Tharakarama et al. [134] 2017 studied production of foamed concrete blocks concrete where 10–50% of the sand was substituted with QD. Experimental tests demonstrated a 43% enhancement in compressive strength relative to control mixes. The study indicates that QD-filled foam concrete blocks can serve as a viable alternative to conventional bricks, providing both environmental and economic advantages, particularly when incorporating 40–50% QD.

2.5.8 Recycled waste aggregates as natural river sand replacement from C&D plant

Over 70% concrete weight is made up of aggregates. A considerable amount of natural aggregates are utilized in the production of concrete. By 2027, a significant demand for virgin aggregates is anticipated, projected to be between 2 and 10.3 billion. The projected demand for concrete in India's 12th five-year plan is estimated to reach approximately 1 billion tons by 2027. The diminishing availability of virgin aggregates presents a critical sustainability challenge for the infrastructure sector, necessitating immediate attention. As reported by the Indian government organization, Indian cities produce more than 150 million tons of construction and demolition (C&D) waste each year [53]. Considering the significant amount of construction and demolition debris generated, our peak capacity is constrained to 6500 tons per day, accounting for only one percent. Without effective management and utilization strategies for construction and demolition (C&D) waste, a significant amount of primary aggregate is lost as it ends up in landfills instead of being repurposed and recycled for future infrastructure projects. Utilizing construction and demolition waste (CDW) as an aggregate for concrete production presents a practical solution to meet this worldwide demand. The rapid increase in construction and demolition waste, particularly concrete debris and discarded clay brick, is largely attributed to the ongoing demolition of older buildings, the testing of concrete, and the excess or returned concrete from various projects. The removal and management of these wastes lead to environmental challenges. The utilization of construction and demolition waste as recycled concrete aggregate plays a vital role in alleviating environmental and economic impacts [135,136]. Utilizing recycled fine aggregate (0–4 mm) derived from construction and demolition waste as a substitute for natural sand in foam concrete. It was discovered that the partial replacement of CDW resulted in cost-effective, environmentally friendly foam concrete blocks that exhibited satisfactory compressive strength and thermal properties. Significantly, mixtures with as much as 100% CDW fine aggregate demonstrated structural performance on par with traditional blocks, simultaneously decreasing dependence on virgin sand and minimizing embodied CO_2 emissions [137]. The researcher systematically varied the gradation of recycled concrete aggregate, the proportion of recycled concrete aggregate (ranging from 0 to 60%), the water-cement ratio, and the volume of foam. The findings indicated that RCA gradation exerted the most significant effect on early-age compressive strength, whereas foam content demonstrated the minimal influence. The volume of RCA exhibited opposing effects: an increase in RCA led to a decrease in fluidity, density, and strength, while simultaneously enhancing water absorption. The ideal gradation and volume of RCA facilitated a satisfactory equilibrium between sustainability and performance in lightweight systems [138].

Shareef et al. [139] focused on the utilization of two categories of construction and demolition waste - thermostone block waste and ceramic waste—as fine aggregates in foam concrete. The study revealed that substituting natural fine aggregates up to a specific threshold (30–40%) resulted in foam concretes exhibiting similar or reduced water absorption when compared to reference mixes. The investigation emphasized the possibilities of using CDW aggregates while ensuring moisture regulation in structural foaming applications.

Yang et al. [140] developed foam concrete utilizing construction and demolition waste residue soil (CDWRS)—comprising crushed soil, brick, and concrete fines—as the aggregate material. The incorporation of water glass and gypsum into their CDWRS mixes resulted in a refined pore structure, improved compressive strength, and potential applicability in sandwich wallboard panels. The study illustrates that CDW residue can effectively serve as the primary raw material for specialized lightweight foam concrete panels, while maintaining minimal impact on thermal insulation performance.

Chandni & Anand [70] evaluated the application of recycled waste fillers, such as CDW fines and crushed masonry, as a partial substitute for sand in foam concrete. The findings indicate that these materials can be utilized in lightweight mixtures without significantly affecting compressive strength or density, while also enhancing capillary absorption and the uniformity of internal pores. The incorporation of CDW filler has the potential to diminish the reliance on natural aggregates, all while maintaining mechanical integrity.

Sunga, A.Y. et al. [141] studied the effect of reclaimed cement on fresh and hardened characteristics of OPC. The findings demonstrated fresh properties and hardened properties of cement paste admixed with reclaimed cement were not affected to 20% of OPC substitution with reclaimed cement.

2.6 Summary

This chapter has sought to provide the reader with a solid foundation regarding the foamed concrete examined in this study. In conclusion, and drawing from the reviewed literature, the subsequent points can be expressed:

- Foamed concrete is a lightweight variant of concrete that exhibits versatility. It comprises either a Portland cement paste or a cement filler matrix (mortar), characterized by a homogeneous pore structure formed by entrained air voids.
- Production of foam concrete can occur through physical methods, utilizing synthetic and natural foaming agents.
- The FC has rapidly gained recognition as construction material for tunnels and underground applications. The material exhibits outstanding self-flowing characteristics, making it suitable for applications such as filling voids, sinkholes, EMAS as RESA materials, decommissioned sewage pipes, and abandoned subway systems. The reduced and controlled self-weight enables it to effectively contribute to load reduction or serve as linear elements in tunnel and metro systems.
- The characteristics of foamed concrete are determined by its density, which is influenced by the type of fine aggregate, aggregate gradation, sand-cement ratio, and the type of foam used. Furthermore, the air void system within foamed concrete may serve as a critical determinant affecting its characteristics.

- The cellular structure of foamed concrete results in minimal water absorption, reduced thermal conductivity, enhanced fire resistance, and effective resistance to aggressive environments.
- While research on foamed concrete has primarily concentrated on examining the usage of different types of synthetic and natural foaming agents and their effect on the characteristics of foamed concrete.

2.7 Need of the study

As indicated in Section 2.6, concrete technologists globally are focused on sustainability. A sustainable concrete mix achieves designated engineering objectives while fulfilling essential human needs, optimizing resource utilization, and conserving or rehabilitating surrounding ecosystems on a broader scale. Sustainability is context-dependent, rendering each concrete mix design strategy unique.

Sustainability is a crucial objective for all industries, including construction and others, under the present circumstances. Various governmental bodies in India, such as MoRTH and NBCC, are actively advocating for the utilization of industrial waste as a viable construction material in both building and road projects, with the aim of encouraging sustainability. Substituting industrial waste materials can effectively decrease the amount of solid waste that has to be managed and disposed of, hence minimizing the environmental impact assessment. This substitution can also lead to a considerable decrease in both energy consumption and pollution levels. Using recycled aggregates (RA) derived from waste materials generated by building, demolition, and road infrastructure projects is a very effective approach to substitute virgin aggregates. Based on certain recommendations and standards, recycled aggregates (RA) can be utilized as a partial replacement for new aggregates after undergoing appropriate processing and satisfying the necessary requirements. Typically, one or more of the following elements are frequently incorporated into best practices for material sustainability:

1) Minimizing the utilization of virgin materials via enhanced mix design and extended durability.

2) Mitigating the effects of material production by enhancing efficiency and decreasing emissions.

It may be recognized that the literature considers foam concrete as having non-structural applications that don't bear loads by admixing foam with cement and sand. For structural applications, sand has been obliterated, and foaming agents are admixed directly with cement. All varieties of foaming agents (synthetic or protein based) have dilution ratio with water as recommended by their manufacturers. In the present experimental pursuit, this dilution ratio is varied once to the lower and once to the higher side of the recommendation to study the changes in the mechanical and durability properties for each. The appropriate dilution ratio of the foaming agent is determined by its specific kind, since each type has a distinct dilution ratio that is most effective. The dosage and dilution ratio of foaming agent significantly affects the dry density and compressive strength of foam concrete. According to Wang and Tang [29], state that changing the dilution ratio of the foaming ingredient can vary the microstructure of the foam, hence impacting its mechanical properties. Consequently, having knowledge of and making adjustments to the dilution ratio is crucial for achieving the desired level of performance. The appropriate dilution ratio of a foaming agent is determined by its specific kind, since each type has a distinct ratio that yields the best results. The dosage and dilution ratio of foaming agent significantly affects the dry density and compressive strength of foam concrete. The dry aggregate consisted of sand replaced with similar fine proportions sourced from construction and demolition waste (CD-RFA). Secondly, sand was replaced previously by investigators with CD-RFA to a maximum of 50%. In the present work, sand is replaced up to 100% by CD-RFA to study its effect on the mechanical and durability properties. Based on the results, the possible usage of foam concrete would be determined, and an optimized dilution ratio is recommended, which stands as the novelty of this work.

As previous studies have investigated the use of ceramic powder as a substitute for cement and aggregates in both conventional and aerated concrete mixtures, there is a paucity of literature addressing its application in foam concrete (FC). Most previous studies have predominantly assessed fresh and mechanical characteristics with synthetic foaming agents only at a 1:20 dilution ratio and ceramic powder obtained from tile polishing [60,142]. Nonetheless, no extensive research has investigated the impact of ceramic waste tile powder (CWTP), sourced from construction and demolition debris, on the mechanical, microstructural, and durability properties of foamed concrete (FC), specifically utilizing a natural protein-based foaming agent at a 1:40 dilution ratio and river sand that passes through a 1.18 mm sieve. The impact of different foam concrete densities (1200–1800 kg/m³) on the performance of CWTP-integrated FC has not been extensively examined.