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A REVIEW ON CELLULAR CONCRETE A DIFFERENTDEVELOPMENTS FOR APPLICATIONINCONSTRUCTION

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A B S T R A C T

In the last years the use of cellular concretes has been extended, due to the rise in the ratio strength/ weight reached, as well as the development of new cementitious raw materials, foaming agents and fillers for specific applications of cellular concrete. However, the knowhow of this form of lightweight concrete is still under construction. This article presents a complete review with the main aspects that influence the application of cellular concrete: raw materials, production methods and expected proper- ties based on density. The aim of this review is to show how the use of new and alternative raw materials for cellular concrete could permit modifications on the physical and mechanical properties for construction applications. The difficulties found in the industrial production of foamed concrete in processes like mixing,transporting and pumping needs to be solved for enhancing the potential of foamed concreteasa structural construction material.

Introduction andbackground

Cellular concrete is a type of lightweight concrete. American Institute of Concrete (ACI) in 523 defines the cellular lightweight concrete as ‘‘a mixture of cement, water and preformed foam”. The purpose of the foam is to supply a production mechanism of a high ratio of air cells that when they are mixed with cement produce a porous solid [1]. Alternative binding materials are included with an air content above 10% and a density below 50 lb/ft^3[2]. The main advantages of cellular concrete compared to conventional Portland cement concrete are weight reduction (up to 80%); excellent acoustic and thermal isolation; high resistance to fire; lower costs in raw materials, easier pumping and application; and finally it does not need compacting, vibration orleveling.

The materials used to make it are the same used for concrete of normal use, except the chemical agents that produce the air cells. It can be considered that there are two main groups of cellular concrete: aerated and/or foamed concrete and microspores. The difference between both groups is defined by the porous system they have and the average size of the pores. In aerated concretethe porosity is formed through the inclusion of air or foaming agents giving as a result a big quantity of macroscopic bubbles. In the microspore’s a lime mortar is used which is highly diluted and allowstheairtogoinwhenthesettingprocessstarts.

Although initially lightweight concrete was restricted to the use of low-weight volcanic rocks, it is considered that the Romans were the creators of the cellular concrete concept. The first cement-based cellular concrete was patented in 1923 by Axel Eriksson. This concrete is known as Ytong[3]. In 1934 the Siporex is patented is Switzerland and it is elaborated through a vapor curing process invented by Eklund. Foamed concretes are used in the Soviet Union since 1938 where manufacturing processes introduced by Kudriashoff were used even though their usage was restricted to non-structural elements. It was in 1950 when aerated concrete was introduced into the United Kingdom for load-bearing elements using the coal slag from thermoelectric plants. By 1970, cellular concrete was successfully applied as a cementing agent in oil wells and as a filler in excavation [4]. The first large-scale project involving cellular concrete was in 1980 in Scotland in the Falkirk railway tunnel, with an amount of about 4500 m^3 of concrete with a density of 1100 kg/m^3[5]. Now, Siporex, Ytong, Duros, Hebel and H+H have been the most important company's world- wide that make cellularconcrete.

In the late 50s foaming agents based on hydrolyzed proteins hit the market, those allowed to improve the air cells stability to main- tain an acceptable control in the density. Around 1990 synthetic foaming agents were created which conducted to highly stable air cells with an extended life in the concrete plastic state, which became in concretes with higher durability [1]. In the last twenty years, the improvement in the production of superplasticizers and the creation of hybrid foaming agents (a mixture of protein and synthetic agents), has allowed the use of foamed concrete on a larger scale and big efforts had been made to study the characteristics and mechanical behavior with the ideal of using cellular concrete main construction applications. Another improvement of significance has been the development of equipment for foam production.

Although the first scientific research in cellular concrete was made by Valore in 1954, recently, it exists a growing worldwide interest for understand the performance of cellular concretes focused in some lines:

The assessment of all kind of additives: pozzolanic like fly ashes, residues from sugar cane, microsilica and slags, reinforcement like natural and synthetic fibers; and fillers like polystyrene [6] Determination of physical properties like hydration heat [7], resistance to temperature variations [8], microstructure [9], pore distribution and size [10] and rheological behavior [11,12]. Evaluation of mechanical properties [13–15] and their numeric modeling[16, 17].

New Applications of cellular concrete based ontheir density.

This review examines the most determining aspects that have allowed the development of new technologies related to cellular concrete highlighting the use of different active additions and fillers to improve performance.

Aerated or foamed concreteframework

Overview

Inaeratedconcrete,themixturepresentsahomogenousstructurethatcontainssmallairbubblesnotcommunicatedbetween them, which size, in already cured elements, ithasdiameterbetween 0.1 and 1.0 mm being their form nearlyspherical.Thesecells structure determines the physical properties ofthematerial,the light weight, low thermal conductivity, high resistancetofire,lowcompressivestrengthandlowresistancetofreezingduetothesizeanddistributionofpores[2].Thereareseveralmethodstoaccomplishtheporosityincellularconcretes:chemicalagentsthatincludetheairinthemortar,foamingagentsthatareaddedtothemixtureorvacuumcuringthatmanagestocreateporesduetotheinternalstrainsgeneratedinthepaste.Whicheverthe productionmethod, in the case of aerated concretes, the issue is howtotrapairanddistributeituniformlythroughthemass.Withpreformedfoam,thefoammustbeverystablesothatitdoesnotdissolve.Inthewayofmixing,theadditivemusttrapair(encapsulate)and make it distribute uniformly. That is why the necessityofapermanent injector during the mortar production. Thecuringofcellular concrete can be accomplished in normalconditions,withvapororautoclaved.Aschemethatrepresentsthediversewaysofcellularconcreteproductionis showedinFig.1.Themosteffectivemethodformakingcellularconcreteistheonethatusesfoam-ingagentsbecausethecompressivestrengthsobtainedarehigher.AccordingtoFig.1,theproductionofastablecellularconcretemixture depends upon many factors such as: thefoamingagent,thefoamproductionmethodandmixturedesign[18].Intheinmixingmethod,foamingagentisaddedtoamixerthatcreatesbubblesduetoitshighrotatingspeed.Thismethodiseasytoper-form,standardizedandwidelyused.However,itcanproduceabigvolume of damaged bubbles which compromises theamountofincludedair.Inthepreformedfoammethod,itrequirestheuseofcompressedairequipmenttocreatethebubblesthatlateronaregoingtobeaddedtothemortartocreatethecellstructure[4].Thepreformedfoammightbedryorwet.Thedryfoamisquitestable and generates bubbles with sizes below 1 mmwhichfacilitatestheuniformmixingandpumping.Ontheotherside,thewetfoamproducesbubblesbetweentwoandfivemmbutsomehowislessstablecomparedtodryfoam.Thepreformedfoamisanexpensiveoperationcomparedtoinmixingmethod,butcreatesamoreefficient foam with better quality. The preformed foammethodisthemoreextendedoneduetosomecomparativeadvantageswiththeinmixingmethod:lowfoamingagentconsumptionandadirectrelationbetweentheamountofagentusedandtheincludedair content in the mixture [18].

The cellular concrete is used in two ways. Precasting for walls panels, slabs and construction bricks. To produce high quality elements with precasting fabrication, it is required to maintain a constant ambient temperature and any curing system might be used. The other way is on site casting which process is used for structural

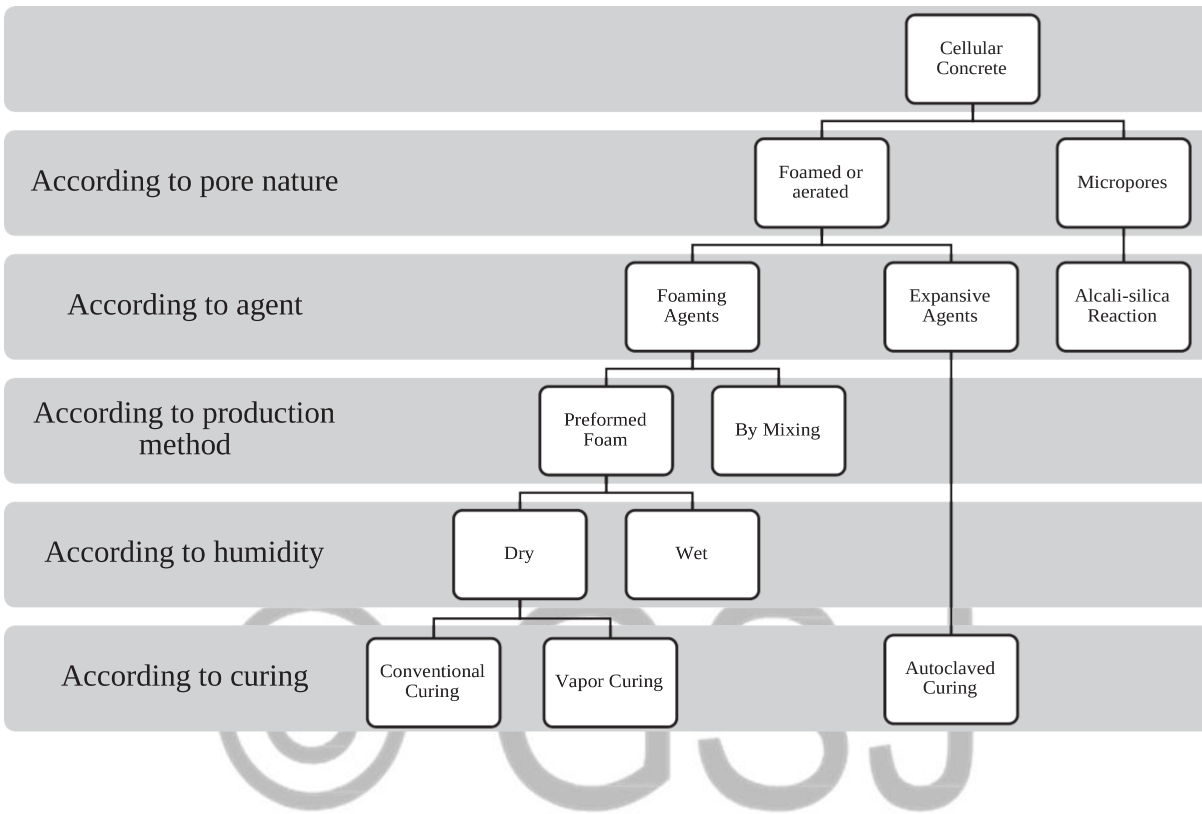

Fig. 1. Lightweight Cellular Concrete Classification.

and secondary elements. This elements can be cured with air and water spraying or vapor. With any utilized procedure, cellular concrete with very low density might be obtained from 320 kg/m^3 when there are not added aggregates to 1600 kg/m^3 when there are aggregates [2]. Foamed concrete is ideal to be cast on site, because it is easy to add the foam directly and it is easy to pump, workable and self-leveling. The amount of air that may be included varies between 30 and 60% in volume when structural elements are made, but it might be 70 to 85% in concretes cast on site intendedonlyforthermalisolation,orassecondaryelements.

The mixture design process is made by trial and error. However, some methods to determine the mixture materials proportions have been developed (water content, foam and cement). McCormick proposed a design method that relates the solids volume proportions with an objective density. Based on this work the ACI 523-1975 relates the plastic density and compression strength, using the cement content and the W/C ratio that may be chosen for a desired density. ASTM C796-93 gives a method to calculate the volume of required preformed foam to make the cement paste if the ratio W/C and the desired density are known [4]. Kearsley proposed a set of equations (density and foam volume) which is written in terms of the mixture composition, that allowthefoamvolumeandcementcontentcalculation[19,3].

Materials used in cellular concretemanufacture

Binder

The most important binders in cellular concretes manufacture are Portland cement, calcium and sulphoaluminate cements [3]. Other materials, generally residues from other industries that may be used to replace, partly, the cement are the microsilica, fly ashes and lime, and demolition and construction waste. The pur- pose of each one of these materials can be different, they might improve consistency and long term resistance or simply lower productioncosts.

Some experimental developments available that consider replacement of some portion of the cement are focused on assessing the use of fly ashes that are known for their pozzolanic activity, because they help the hydration process [20]. The use of fly ashes allowed a reduction in 50% the amount of cement needed per cubic meter and 40% of the hydration temperature [7], as well asan increase in compressive strength at early ages due to the reduction of bubble size [21]. The above mentioned implies light densities that vary between 1100 and 1500 kg/m^3[22] and lower compression and flexion strengths at 28 days of curing [23]. A microstructure analysis shows the potential use of fly ashes, especially for elements that should be cast. Fly ashes have been used as an alternative to sulphoaluminate and other quick-setting cementitious materials, accompanied by hydrogen peroxide, cellulose and dispersants, accomplishing a concrete of ultralow densities between 100 and 300 kg/m^3, with a pore size between 2 and 4 mm, of low thermal conductivity and higher durability compared to sulphoaluminate mixtures[23].

Another part of the studies has been focused on the assessment of blast furnace slags to replace up to 30% in weight of cement. The use of this waste material showed improvement in compression and flexion strength [24] and aids to avoid cracking when the particle size used is ultrafine[25].

A residue from the manufacture of phosphoric acid, known as phosphogypsum, was also used together with a small portion of Portland cement to produce cellular concretes. It was shown that only a portion of this material acts as a cementing material stimulating the production of calcium silicate and ettringite improving the compressive strength[26].

On the other hand, a significant percentage of the experimental reports are associated to the use of mineral mixtures either as alternative binders or as replacement of Portland cement. The mixture of blast furnace slag + fly ash + microsilica (23%, 15% and 12% of cement weight) allows cellular concretes with compressive strengths between 1.1 and 23.7 MPa. Besides, an addition of super- plasticizers takes the compressive strength up to 44.1 MPa w

Table 1

Function	Type of additive	Dosification Bin Aggregates	Physical propertie		Mechanical properties 28 days				Additional informa	Refer
		POC: Binder	Dry D [kg/m	Porosit Sorptiv mm]	Shrin [%]	Therm condu [W/ml	Com Strer [MPa	Flex Strer [MPa		
Cement replac	Fly ash	1:3		2.5 mr	0.37		5.5			[9]
	Class F									
	Fly ash	1:1	1150	29%			19			[40]
	Class F		1000	31%			9			
			650	34%			4			
	Fly ash	1:0.25	1000				1.4			[7]
	Fly ash	1:1.5	1000–	<10%	0.06–		3.7–(		Structural blocks	[22]
			1300-				10–1			
	Fly ash	Replacement 0.3	800	56%			3.92			[21]
	Fly ash	1:0.3	1590		150–		12.1		Different curing conditions.	[53]
	Class F				micro					
	Fly ash + peroxide	1:0.4	100–3	80.3–7		0.043–	0.12			[54]
	Fly ash Class F + bl furnace	0:5	1889-	12–25.			38.3-	5.01-	Self –consolidating	[30]
	slag + hydrogen p	1:9							Slump 260–280 mm	
	Fly ash + blast furn slag + silica fume	1:20	1020-			0.24–(	4.2–4		Massive casting in and of filling casting	[27]
	Fly ash + silica fun	1:1.5	1280-			0.498-	19–4	1.4–		[28]
		1:2.5								
	Blast furnace slag	Replacement 0.3	1300				2.2–(	6.1–:		[24]
	Blast furnace slag	1:6	153–3	6.6–8.3		0.05–(	0.57		Reinforcement witl	[25]
									polypropylene fibe	
	Sugarcane filter ca	Replacement 0, 0 0.1, 0.15, 0.20	1100 1000	14–30%	—800 micro	0.878-	1.7–: 1.5–:	0.7– 0.6–	Spread: 45 ± 5% Casting/finishing sh and	[23]
			900				1.2–:	0.5–	surface	
Aggregate	Laterite	Sand replacemen	800–1			0.17–(	40–5			[46]
Replacement/F		10, 15%								
	Laterite	Sand replacemen	Functi				4–12		Spread [mm]: 580–(	[55]
		10, 20, 30, 40, 50	curing							
			metho							
	Palm oil fuel ash	Sand replacemen	1000			0.65–(	3.28-	1.36	Elasticity module [(	[41]
		0.1–0.2							0.37–0.093	
	Waste Clay Brick	Coarse replacem	1631-	15.98–			25.9			[42]
		25, 50, 75, 100%								
	Clay brick	Coarse replacem 25, 50, 75, 100%	750–5	65–72%		; 40%	3.0–:		Autoclaved fabrica with aluminum	[43]
	Soil	100% Sand	780–1			0.2–0.5	4–42			[47]
		replacement								
	Plastic waste	0, 2.5, 5, 0, 20%	1950-	8.2–20		1.467-	29.9-	4.5–	Compressive and f	[44]
	PE		2050-	7.7–17		1.467-	31.9-	4.5–	strength increases v age	
	PVC		1950-	7.8–16		1.467-	30.8-	4.1–		
	PE + PVC									
	Recycled waste	1:1	1253-	13.3–3			5.28-		Superplasticizer PC SNF	[56]
	Glass	1:0.33	773–1	19.5–4			1.53-		increases compress	
	Plastic (PP)								strength	

Summary of binder/filler replacemen

Table 1 (*continued*)

Function	Type of additive	Dosification Aggregates Binders/Physical properties				Mechanical properties 28 days			Additional information	Reference
		POC: Binder	Dry Density [kg/m^3]	Porosity/ Sorptivity [%, mm]	Shrinkage [%]	Thermal conductivity [W/mk]	Compressive Strength [MPa]	Flexural Strength [MPa]		
Mix cement and filler	Portland cement + Alumina	1:0.16	332–489	75–90%			0.7–2.5		Elasticity module [GPa]: 0.7–	[45]
replacement	Cement + Silica fume	(10%SF + 6%HAC)							2.5	
	EPS (as aggregate)	Replacement 75.5–								
	PP + latex fibers	86%								
		0.1%PP + 0.2% Latex								
	Salt waste + zeolite (as binder)	Replacement 0.1	650	76.4%			2.7		Pore size [mm]: 0.16–0.21	[33]
	Fly ash + PP fibers	1 kg/m^3								
	Silica fume (as binder) + soil	Replacement 0.05–0.2	758–790	18–40%		0.155–0.195	4–8		Finer pores	[57]
	(filler)									
	Quick lime (as binder) + soil	Replacement 0.05–	1047–1650			0.2–0.73	4–28		Broken foam	[57]
	(filler)	0.15								
	Fly ash	1:3	800–900				3.91–8.44		Non autoclaved structural	[50]
	Poly-Olefin	0–0.55 volume					5.94–6.58		masonry block	
	Microfibers fibrillated	fraction (0–5 kg/m^3)								
	Macrofibers									
	Silica powder	3:1	903				5.9			[48]
	Red sand	2:1	800				2.0			
	Kaolin	3:1	1065				5.6			
		2.5:1	650				0.5			
		3:1	800				1.2			
	Silica fume	Replacement 0.05–	821–855			0.166–0.19	3.8–7.5			[47]
	Soil	0.15								
		Sand replacement								
		100%								
Foam replacement	Food additives: methyl cellulose	0.15	140–630	92%		0.11	Very low		Ultrahigh porosity Glass fiber	[49]
	and iota carageenan gum (for								addition: 18 lm diameter	
	foam)									
	Bentonite	Foam replacement 0%,	300	36.8%, 39.3%		0.085–0.059	0.9–0.4			[58]
		10%, 20%, 30%, 40%,	600	24.4% 30.3%		0.153–0.127	4.8–3.0			
		50%								
ULCC admixtures	Silica fume	12:1	1450				52–63.3	2.6–5.0	Elastic Module:16.5 GPa	[51]
	Chemical admixtures	3%							Chemical admixture to	
	PVA fibers Cenospheres	0.5, 0.9, 0.2%							reduce shrinkage Cenospheres: 10 to 300 mm	

335 kg/m^3

excellent workability, which makes this suitable to be cast onsite [27].Asimplemixtureofflyashes+microsilicaimprovestheinterlinkspaste-aggregateandallowsenhancementsinworkabilityand compression strength with densities between 1300 and 1900 kg/ m^3[28]andenhancesthermalisolation[29].Also,studiesthatutilized the mixture lime + microsilica shows that microsilica has great impact in physical properties of cellular concrete based on soils. The addition of microsilica improves the width and uniformity, and gives more rounded form to the pores, which results in a higher thermal isolation y better strength. Additions up to 20% ofmicrosilicadecreasesdensityto800kg/m^3withacompressión strengthof7.5MPa.Lastly,themixtureofflyashes(80%)+Blast furnace slag (20%) (with hydrogen peroxide as foaming agent) hasbeenevaluated,accomplishingtheproductionofcellularcon-cretesof1270kg/m^3[30].Anewtrendisthemanufacturingofcellularconcretesthatdonotcomefrom Portlandcementbutinstead theyusegeopolymers.Thistechnologycombinestheadvantagesof cellularconcretewiththechancetodecreasethecarbonfootprint using a more sustainable material like geopolymers[31]. It has beenreportedtheuseofmixturesoftypeCflyasheswithanalcalineactivator,generallyNaOH,achievingcompressivestrengthsupto 18 MPa at 28 days and at a curing temperature of 60 °C thatcutssuperficial cracks, water absorption and porosity [32]. Other authors showed the difference in form, size and distribution of the pores in a foamed concrete of this kind. The high volumetric contraction between 0.10 and 0.36% (5 to 10 times higher than conventional concrete) is what constitutes their main disadvantage [31]. Cellular concrete also was manufactured using zeolites as bin- der material [33]. A summary of alternative binders or cement replacement are include in Table1.

Foamingagents

Theyareresponsibleforcontrollingdensityandporosityofcellularconcretethroughtheinclusionofairbubbles[3].Hence,foamingagentsrulesthepropertiesinthehardenedstate.Thetendencyofthefoamstocollapseduringthepreparationprocessbringssomechallengesincontrollingthepropertiesofcellularstructures. Consequently, it is critical to improve thestabilityof fresh foams in order to produce high qualitycellularstructuresusingapredictableandreliableapproach[34].Theeffectsofagentconcentration used in the cellular concrete have beenfoundmainlyontheporedistributionandsize,thataffectthefinalstrength[35].Themostcommonlyused foamingagentsaresyntheticand proteinbased,butdetergents,glueresinsandsaponinsmayalsobeused.Thewayofactionofaproteicagentisitsowndegradationthatgeneratesbubbles.Asthebondsoflargermoleculesarebroken, small hydrophobic molecules are formed. Thisprocess notonlyreducessurfacetension,butcreatesinterfacesfortheairbubbles.TheeffectivenessofthiskindofagentsdependsontemperatureandpH[4].Agentsbasedonproteinsallowastrongerporestructure and more closed, providing a stable web ofemptyspaces[3].Syntheticfoamingagentsreducesurfacetensionofthedilution. They are amphiprotic substances andstronglyhydrophilic, theyallowmoreexpansion,hencelowerdensities.However,theycreateacomplexchemicalenvironmentandthereforethecompatibilityofthesurfactantandthecementiscritictoletthedesiredentry of air and the development of the cellmicrostructure[4].The protein based agents perform accordingtocompressivestrength but synthetic agents have an easier handling,arecheaperand require less energy for long term storage [36].Thecombinationofthefoamingagentwithaparticularwater/cementratiois alsoveryimportant.Syntheticfoamingagentsleadtomorestablefoamconcretespecimensthantheonesobtainedwithproteinonesfor a fixed water/cement ratio [37].

The development of agents based on highly active syntheticenzymes with biotechnologic origins have enabled the improvement of the foam stability and expedite the pumping of the concrete. The use of new agents provide more freezing resistance and fewer requirements of mixing water without losing slump improving the finished characteristics. A mixture used as a foaming agent is made of aluminum powder and hydrogen peroxyde. Although this mixture is expansive instead of foaming, it can gen- erate linked pores that are smaller than the ones produced by foaming agents, even in conditions of lower density [31]. Oxides and silica nanoparticles also have been used as coadjuvants in the formation of triphasic foams that enhancethe strength in the bubbles boundaries. In this foams, nanoparticles are introduced in the air-water interface through a partial hydrophobing due to the adsorption of surfactants that accomplishes more stable Van- der-Walls interactions. It is possible to produce materials with densities below 100 kg/m^3 with a stable and uniform pore struc- ture and a better strength [38]. She et al. modifying the gasliquid interface by coupling the effects of an organic surfactant and nanoparticles. They added nanosilica and hydroxypropyl methyl- cellulose to reduce coalescence of the bubbles. More homogeneous and finer pore structure is generated with the inclusion of this organic surfactant and nanoparticles[39].

Xanthan gum (with a thickening capacity) also has been utilized as the foam stabilizer to aggregate the liquid film around bubbles. This stabilizing method is shown to significantly enhance the pore size distribution[34]

Water

The amount of water that is required in the manufacturing of cellular concretes depends on a lot of factors: composition of bin- der materials, type of filler and required workability. A low water content generates rigid mixtures and cause the bubbles to break; a high water content provoques thin mixtures that generates segregation of the materials. The W/C ratio varies from 0.4 to 1.25, the latter value is in the case of not using superplasticizer. The concrete strength is mainly ruled by the generated spaces and the evaporable water in the cement, which means that a reduction in W/C ratio is convenient to obtain high strengths. An appropriate combination of superplasticizers and mineral mixtures can reduce the water consumption for certain fluid properties [18]. Based on ACI 523.3R.93 it is recommended that the water to be used for the foamed concrete be fresh and drinking water. Organic elements may have a negative effect on the foaming agents, specifically the protein-based.

Aggregates andfillers

For cellular concretes with nonstructural applications that gen- erally are associated to a very low density, petreous aggregates are not used, but instead fillers are used that reduce the cement consumption without important increases in weight. Structural cellu- lar concrete (densities above 1200 kg/m^3) utilize aggregates of any origin. The most employed filler materials are industrial residues with pozzolanic activity.

Among the most widely used residues to replace natural aggregates are fly ashes. Their use has demonstrated improvement of the mechanic performance with respect to density [9,40] and a reduction on the hydration heat of 24% in the peak temperature [7]. However, the presence of this material in a mixture implies the use of higher W/C ratio which generates an increment in the water absorption of the final product [40] as well as an increment in thermal conductivity and a reduction in Poisson modulus [41]. Others fillers widely used in the production of cellular concrete are construction waste. For the specific case of recycled concrete waste, it has been determined that they do not have a significative effect on the compression strength [20]. Fired ceramic residues have been used in different proportions to replace the aggregate: 25, 50, 75 and 100%, finding an optimum replacement valueof

25% generating a cellular concrete of 1674 kg/m^3 with a compression strength of 25 MPa[42] and with an increase of indirect tensile stregth of 50% [43]. Other materials reported in the production of cellular concrete as fillers are plastic waste of polyethylene, PVC and polystyrene. The use of this kind of waste decrease the compressive strength but improve the performance as an acoustic isolator [44] allowing lightening cellular concrete below 500 kg/m^3[45]. Among the polymer fillers, expanded polystyrene (EPS) stands out for its ability to improve the thermoacoustic insulation properties. Nonetheless, the presence of this filler affects the mechanical performance in a negative way because its presence weakens the interfacial paste-filling bond as a result of the hydrophobic nature of the EPS. According to the content of EPS the density and the fire resistance vary [6]. Also the use of lateritic soils has been reported with an optimus replacing value of 5% [46]. Alternativesasmixturesofsoils+pozzolanas[47],silicapowder

+ red sand + kaolin are the most recently used [48]. The best effects found are the improvement on the uniformity of pore distribution and thermal isolation. The phosphogypsum has been also reported as a filler with some binder capacity [26]. For more information see Table 1.

Fibers andreinforcements

They can be used to improve foamed concrete strength; they may come from natural or synthetic origins. Some utilized fibers are alkali resistant fiber-glass, kenaf, steel, palm fiber and polypropylene fiber. The use of fiber can change the typical behavior of a cellular concrete as it introduces a ductile elastic-plastic region. The volumetric fraction of the fiber reinforcement varies between 0.25 and 0.4 of the mixture [3]. A negative effect of the fiber reinforcement is the porosity decline. The reinforcement with fiber glass has demonstrated being effective just in part because the capability of the fibers to transmit the strengths did not pre- vent the progressive collapse of the cellular structure [49]. Other studies have reported an enhancement in the mechanical proper- ties of foamed concretes reinforced with polypropylene fibers [50]. With the use of those fibers it has been able to produce cellular concretes with 650 kg/m^3 and a compressive strength of

2.7MPaand76.4%oftheporeshaveasizebetween0.2and

1.0 mm [33]. Other fibers used for the reinforcement of cellular concretearetheonesthatcomefrompolyolefin,bothmacroscopic and fibrilated (microfibers). The structural fibers (macroscopic) induce a ductil behavior stopping the cracking propagationwhile the fibrilated fibers work in the micro level fissures. The best experimentalresultsareaccomplishedwithhybridreinforcement but the increase in strength is not proportional with the increase inthereinforcementpercentage:compressivestrengthincrementsupto66.8%andtenacityupto46.7%[

50].Polyvinylalcoholfibers alsohavebeenreportedforultra-lightweightcellularconcretereinforcement avoiding the fragile failure and augmenting tensile strength[51].

Reinforcement with latex microspheres improves the material performance acting as an energy absorption mechanism [52].

Foamed cellular concreteproperties

In the fresh state the mixture of foamed concrete is fluid and with self-compacting rheology. The fresh state properties consistency, stability and workability are strongly influenced by the W/Cratio,theadditivesandthefoamtypeandvolume[59,60].

The mixture consistency is an important factor that affects thestability. This consistency depends mainly on the type of filler [18].In the hardened state the compressive strength with respect todensity is the design property. Porosity is another property thatmust be taken into account because it is associated directly tothe performance of a cellular concrete [9]. Pores have an important

role to enhance the insulation effect, but decreases compressive strength and elastic stiffness [61]. Porosity depends upon the type of foaming agent employed, fillers and the manufacturing process [62]. The air-entraining obviously increases the porosity of con- crete[60]. Fine and close pores resulting in a compact in texture with high strength and low permeability [62]. The pores in a foamed concrete might be generated in different configurations: interlayer (<1 nm), gel (1–10 mm), capillary (>10 mm) and from suction (1–2 mm). The pore connectivity also depends on the formation methods and the type of foaming agents used[31]. Cui and Cahyadi define a critical pore diameter (lc) as the pore diameter above which a connected path could form throughout a sample and added that the smaller the lc, the finer the pore structure. Hilal et al. show that in foamed concrete the critical pore diameter and the pore diameter size (>200 nm) are to be closely related to the permeability [63]. The porosity of the cellular concrete decrease as the growth of curing ages. The reason is that, the hydration degree of cement is low before 7d, which leads to higher porosity [60]. Water absorption decreases with added foam voids, suggests that these voids may not lead to an increase in water transport through foamed concrete [63]. Some methods of foam activation such as microwaves or ultrasound that lead to changes in porosity have been employed to change the internal microstructure and improve the mechanical properties [35]. The thermoacoustic isolation and the fire resistance are intrinsic properties of foamed concretes that are related to the porosity as well. The foamed concrete has sound absorption rates 10 times higher compared to a conventional concrete and thermal conductivities closer to 0.66 W m^{-1} - K^{-1}[3].

About the mechanical properties Kearsley (2002) determined that the compressive strength decreases exponentially with the density reduction in foamed concretes [64]. Nevertheless, it should be highlighted that such property depends of a lot of factors: element form and size, foam production method, load path, age, water content, characteristics of mixture elements and curingprocess [3,46]. Kearsley also noted that for dry densities between 500 and 1000 kg/m^3 the compressive strength reduced when the bubble diameter increases. For densities above 1000 kg/m^3, the paste composition is what controls the strength [46]. In Table 2 expected properties of foamed cellular concrete are related for different densities.

Some authors as J.M. Durack and L. Weiqing; M. Röbler and I. Odler; A.M. Neville and N. Narayanan; K.J. Byun et al. have pro- posed empiric models to find the compressive strength as a function of porosity, that were reported in [3]. Other models have been obtained through numerical modeling. Nguyen et al. pro- posed a non lineal model to predict the compressive strength of geopolymeric cellular concrete that adjusts to experimental and numeric data [16]. In such a study it was found that the distribution of big empty spaces has influence in the strength. Abd&Abd used the Support Vector Machine (SMV) algorithm to predict the compressive strength at early stages from dosing and density of the mixture, with well adjusted results [17]. With respect to tensile and flexural strength, normally they are not determined experimentally, but they are obtained from correlations from compressive strength. In Table 3 factors used to determine some properties according to the compressive strength obtained are correlated.

Temperature also affects mechanical properties of cellular concretes. Properties such as compressive strength and elasticity modulus decrease with the rise of temperature. Mydin and Yang show inanexperimentaldevelopmentthatlossinstiffnessforfoamed

concrete at elevated temperatures occurs predominantly after 90 °C, regardless of density as water expands and evaporates from the porous body [65,66]. Tan et al. propose a model to stablish the effect oftemperature on the elastic modulus and the strength.

Their results showed that cracks start to appear above 400 °C, pre- dominantly in high density elements [8]. The fire resistance is associated to changes in mechanical properties of foamed concrete when those are exposed to high temperatures [8]. This sort of concrete has the capability of resisting fire in a range close to conventional concrete. It has been reported that cellular concretes with densities of 950 kg/m^3 are able to withstand fire up to 3.5 h and concretes with a density of 1200 kg/m^3 withstand 2 h [3]. Additions as polystyrene and other filling materials have a negative effect on fire resistance[6]

Cellular concreteapplications

By density, cellular concretes may be employed in various forms. Ultralightweight cellular concrete (300–600 kg/m^3) do not have a good mechanic performance, so that they are used in thermal and acoustic isolation and fire protection. For densities between 700 and 1100 kg/m^3 the most extended use is the production of bricks, blocks and non structural elements like railings, divisions y fences; in specific cases they have been used as a filler material or leveling mortar for flooring. Cellular concretes with higher densities (1200–1800 kg/m^3) are used in precast forms, on site casting, load supports, weight reduction mortars and slabs where high strengths are required. Currently High Performance CellularConcrete(HPCC)isthemostadvancedformofcellularconcrete. HPCC is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and nor- malmixing,placingandcuringpractices[67].HPCCcanachieve

55.37 MPa in compressive strength. Higher strengths can be reached with the addition of supplementary cementitious materials and water/cement ratio reduction. Also, HPCC bubbles are accountable for a superior freezing and thawing resistance, low water absorption, high fire resistance and sound retention [67]. Otherwise, Ultra Lightweight Cement Composite (ULCC) is the most advanced type of HPCC with compressive strengths up to 65 MPa and a density lower than 1500 kg/m^3 that is developed by using the lightweight cenospheres as the main aggregates in thecementpaste[51].ULCCexhibitshighspecificstrengthscom- pared with normal weight concrete with the same strength, e.g., thestrength-to-densityratioforULCCis47kPa/(kg/m^3)compared to the ratio of 27 kPa/(kg/m^3) for normal weight concrete [51]. A summary of the main applications reported for cellular concretes is shown in Table4.

A more detailed description of the usefulness can be made according to the application field. For example, applications in geotechnics as a coating and tunnels stabilization accomplishing reductions of 61% in vaults settlement [68–70]. In rail roads as balast for high speed trains where with a density of 650 kg/m^3 and a width of 0.5 m a great dynamic stability is achieved in the long term and with cyclic loads, and a low settlement of the layer [71]. In structural applications they have been used in the manufacturing of thin walls with reinforcement [2] and in cast [72]. Pre- cast elements is the more reported use in applications such as: non structural bricks with a compressive strength up to 5.4 MPa[73]; protection pannels against fire with porosities up to 95.4%, thermal conductivities of 0.063 W m^{-1} K^{-1} and compressive strengthof

0.25 MPa[12]; thermal isolation panels with densities between 800 and 1500 kg/m^3 with compressive strengths between 5 and 25 MPa and with a thermal conductivity of 0.016 m^{-1} K^{-1}[29]; sandwich type structures with applications in precast slabs that also have been modeled at a higher scale to determine the mechanical behavior in use [52,59,67,74]. Developments of reinforced cel- lular concretes have been applied for buildings and offshore structures,orcomplexweatherconditionsthatincludeice.

Otherversatileusesofadvancedcellularconcreteslike ULCCare the production of bridge decks, double skin composite slabs, off- shoredecks,steel-concretecompositeslabs,flatslabsincommercial and residential buildings and Arctic offshore structures. Low thermal conductivity in ULCC is essential to develop energy efficient buildings[51].

Also, new alternatives to remixing ordinary concrete and trans- form it in a high performance celular concrete are studied. This new mix that contains foam and silica fume is pumped under pressure and projected into a place at high velocity, creating a cellular sprayed concrete [75]. Sprayed concrete has applications on site for coating in tunnels, walls, floors. It is a simple and economic method to extend cellular concreteuse.

Finalcomments

Based on this review, it was observed that the investigations of cellular concretes have had a huge growth in recent years. How- ever, most of them are focused on researching the effects of foam volume, type and proportion of additions, fillers and fibers on density and compressive strength. Aspects related to rheological behavior, mixing, transport, storage and pumping are quite unattended. The fresh state is not understood completely yet. A few parameters like consistency and spreadability are measured with very simple and inaccurate methods (flow cone and flowmarsh test) without fully describing the flow behavior before hardening. Rheological terms like yield stress, pseudo plasticity and the correspondent constitutive model has not been determined yet for a wide interval of densities in cellular concrete. In fact, only few authors (e.g. [11]) concentrate their efforts on this issue. However, conclusions of Ramamurthy et al. [18] and Amran et al. [3] indicated the strong effect of the foam stability on the fresh state over the internal structure and the mechanical performance in the solid state. In addition, there is a requirement to investigate compatibility between foaming agents and additives as retardants, plasticizers or colorants. Nowadays, experimental works are still studying foam stability with alternative binders. However, these assessments ignore the complex chemical environment that could affect physical or mechanical properties including durability. A difficulty encountered in defining foam stability criteria is the fact that very few authors specify the characteristics (commercial name or com- position) of the foaming agent used, which does not allow progress inthedevelopmentofmorecommercialmixtures.

Other important aspect to have into account is self-curing, which helps to enhance compressive strength at early age and to prevent carbonation reaction throughout the curing process [12]. Creating a source of water supply inside the concrete mixture enough for hydration process is a good idea to replace traditional superficial water addition for curing. In that sense, materials like water crystal beads can be used to supply the desired amount of water for internal hydration[76].

In the hardened state, pore internal structure is associated directly to the performance of a cellular concrete as it was shown in Section 2.3. Voids size distribution, uniformity, geometry, spatial distribution and connection are essential to understand the effect of fresh properties in the mixture (mostly foam stability) on the mechanical performance and physical properties. Despite this, volumeof pores is the most useful criteria to describe thevoids. Experimentals works among which stand out [77,63,12], have described qualitatively internal microstructure of pores but they have not been able to introduce quantitativeresults for pore inter- connection or their distribution. For this reason, there is still a requirement for more deep studies that should address internal structure of cellular concretes, especially considering that factors suchasthemixturedesign,foamingagentandcuringtypeaffect

Table 2

Cellular concrete properties with respect to density. Adapted from [13,36].

Dry Density [kg/m^3]	Compressive Strength [MPa]	Elastic modulus [GPa]	Thermal Conductivity [W/m K]	Volumetric Contraction [%]
400	0.5–1.0	0.8–1.0	0.07–0.11	0.30–0.35
500	1.0	1.24–1.84	0.08–0.13	–
600	1.0–1.5	2.0–2.5	0.11-0.17	0.22–0.25
800	1.5–2.0	20.-2.5	0.17–0.23	0.20–0.22
1000	2.5–3.0	2.5–3.0	0.23–0.30	0.15–0.18
1200	4.5–5.5	3.5–4.0	0.38–0.42	0.009–0.11
1400	6.0–8.0	5.0–6.0	0.50–0.55	0.07–0.009
1600	7.5–10.0	10.0–12.0	0.62–0.66	0.006–0.07

Table 3

Cellular concrete properties accepted in hardened state.

Physicalproperty	Accepted
Density[kg/m^3]	400–1900
Contraction[%]	0.1–0.35
Mechanicalproperties	Accepted

Durability of cellular concrete is an important issue as well. Systematic investigations on the durability aspects of foamed concrete from a point of view based on design criteria has been already suggested by [18]. Main components of durability are mechanical strength, water absorption, frost resistance and shrinkage (including carbonation shrinkage) that rises the risk of cracking [78].

Summary

The reviewed information shows a quick evolution of cellular concretes. The emphasis has been on creating more durable concrete with new mixtures of constituents in different proportions, whose specifications and performance are much better [5]. In recent years, the development of high-performance cellular concretes has been achieved thanks to the use of additional binder materials. This has permitted improving the strength/weight ratio, which implies: reduction of the thickness of the structural elements, an increase of the usable interior architectural space, reduction in the amount of reinforcement, increased flexibility and minimization of the effect of temperature changes by improving energy conservation in buildings. The assessment ofmechanical properties remains the central concern of researchers, as this is the foremost design condition. Aspects such as the rheology and the internal structure of the pores continue to need more developlternative fillers or binders, the application of nanotechnology, the discovery of new and better foaming agents and stabilizers, as well as the manufacture of geopolymeric cellular concretes are the new stakes in the study and application of foamed cellular concretes. Bigger efforts are still required in terms of process scaling and control of manufacturing conditions for the large-scale commercialexploitationofthistypeofconcrete.

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