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REVIEW ON FIRE PERFORMANCE OF CELLULAR LIGHTWEIGHT CONCRETE

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Abstract: Structural fire damage can be identified as a common accidental disaster throughout the world which cause thousands of deaths, injuries and millions of property damage each year. Fire represents one of the most severe conditions which structures may be subjected. Generally structural element will be exposed to very high temperature (1200 ^{0}C) during a fire propagation. Fire safety of a structure is measured in terms of fire resistance which is the duration that a structural member can exhibits resistance with respect to structural integrity, stability and heat transmission. Concrete generally provides better fire resisting characteristics compared to the other construction materials due to its low thermal conductivity, high heat capacity and slower strength degradation with temperature. Cellular lightweight concrete (CLC) is one of the novel type of concrete which can be identified as a better construction material than conventional concrete due to its numerous advantages. However, limited research work has been carried out to determine the fire performance of CLC. Fire response of structural member depends on the thermal, mechanical and deformation properties of the structural material at elevated temperature. Even though properties at elevated temperatures for normal weight concrete is available in literature, properties of CLC at elevated temperatures (ambient to 1200 ^{0}C) is not thoroughly investigated. Further CLC fire rating under natural/parametric fire situations and under hydrocarbon fire situations need to be studied. EN 1992.1.2 provides minimum thickness requirements under standard fire situation for non-loadbearing and load bearing normal weight concrete walls, but for CLC, these values are not available, hence required to be included. Also, parameters and material property limitations related to spalling effect of CLC during fire exposure has not being investigated. Moreover, residual characteristics of CLC walls after fire situation and ability to withstand a second fire situation needs to be assessed.

Keywords: (Cellular Lightweight Concrete; fire performance; Design guidelines; insulation; integrity)

1. Introduction

Fire represents one of the most severe condition that structures may be subjected (Kodur, 2014). Structural fire damage cause thousands of deaths, injuries and millions of property damage throughout the world each year (Brushlinsky et al., 2007). According to the Centre of fire statistics data (CTIF, 2017), there are nearly 510,000 structural fire situations reported each year, which means once in every 62 seconds a structural fire is occurring somewhere in the world. World trade centre fire in 2001, Shanghai fire in 2010 and Grenfell Tower Fire in 2017 are recent massive structural fires reported in the world (En.wikipedia.org, 2018). Therefore, appropriate fire safety construction is an important aspect in building construction.

Concrete generally provides best fire resisting properties compared to other construction materials (Kodur and Raut, 2010). This excellent fire resisting characteristics are exhibit due to its low thermal conductivity, high heat capacity and slower strength degradation with temperature (Kodur, 2014). Concrete is available in various forms and it is often grouped under different categories based on weight (as normal weight and light weight concrete), strength (as normal strength, high strength, and ultrahigh strength concrete), presence of fibres (as plain and fibre-reinforced concrete), and performance (as conventional and high performance concrete) (Kodur, 2014).

Lightweight concrete has many advantages over conventional concrete, excellent in acoustic performance, earthquake resistant, good insulation, workability, long life span due to termite and fire resistance, weather proof and, material savings (Singh, 2016, Marunmale and Attar, 2014) and therefore can be utilised as a better construction material in low rise and multi storey buildings.

Lightweight concrete can be defined as a type of concrete which has low density compared to normal weight concrete. Lightweight concrete has dry density of 300 kg/m^3 - 1800 kg/m^3, while conventional concrete has a dry density of 2400 kg/m^3.

Lightweight concrete can be categorised as lightweight aggregate concrete and cellular lightweight concrete (CLC). Porous lightweight aggregates with low specific gravity such as pumice, scoria and volcanic aggregates are used to produce lightweight aggregate concrete. Due to low specific gravity of aggregates, resultant concrete also has less density. Cellular lightweight concrete does not contain coarse aggregate, thus can be regarded as mortar. It is produced by introducing air or other gas into a cement slurry and fine sand (Ismail, Fathi and Manaf, 2004). Cellular concrete can be categorised as aerated concrete and foam concrete. Fine powder of Aluminium is used as air entraining agent to produce aerated concrete. Aluminium powder mixed with the cement slurry, reacts with the calcium hydroxide to produce hydrogen gas which produce a cellular structure, and thus makes the concrete lighter than the conventional concrete. Foam concrete is produced by introducing foam into cement mortar. The foam is created using a foaming agent, mixed with water and air from a foam generator. When sand in cement mortar is replaced with fly ash, better performance can be obtained in cellular concrete (Ismail, Fathi and Manaf, 2004). Since it consumes fly ash which is a waste material from coal fired thermal power plants, cellular lightweight concrete can be identified as a green building material (Marunmale and Attar, 2014). With the reduction of density, the strength and stiffness of cellular concrete is decreased (Mydin and Wang, 2011). CLC is a porous material; since at high temperatures, heat transfer through porous material is influenced by radiation, CLC with its lower thermal conductivity and diffusivity results in better fire resistance. Furthermore, lower density of foam concrete has exhibited better fire performance characteristics (Ramamurthy et al., 2009). However, cellular concrete cannot be used as reinforced concrete as it has a cellular structure and therefore corrosion of steel reinforcement is quite proactive (Singh, 2016). In this paper existing research studies on CLC with respect to fire performance will be assessed and research gaps will be highlighted.

2. Fire performance of Cellular Lightweight concrete

Fire resistance of structural members are generally evaluated through standard fire tests (ASTM E119-08b, 2008). However, due to high cost and time consumption for the fire tests, numerical approaches and finite element modelling has been identified as effective method of evaluating fire performance of structures (Kodur, 2014). These numerical models are developed considering the material properties at elevated temperatures.

2.1 Fire performance of cellular lightweight concrete with fire tests

Simplest way of representing fire is a time temperature curve. ASTM E 119 and ISO 834 are most widely used standard fire curves (Denoël, 2007) (see Figure 1). To determine the fire performance of a structural member, fire tests are carried out. There are full scale fire tests and furnace tests. Full scale fire tests will give exact fire behaviour of the entire structure. However, it is very expensive and time-consuming (Levesque, 2006). Furnace tests are used to evaluate the fire behaviour of structural elements. Furnace temperature needs to be controlled according to the designated fire curve (standard or natural fire curve). Usually, furnaces are equipped with devices to measure temperature, and deformations, and to load test specimens (Levesque, 2006).

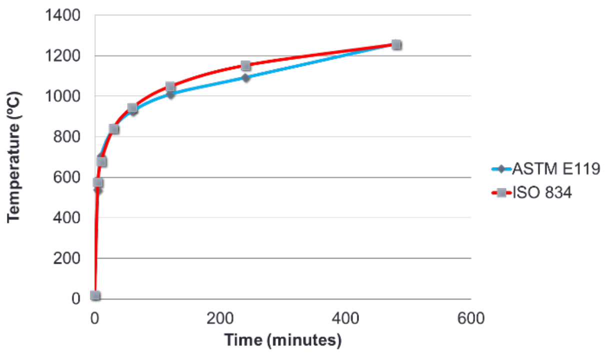

Figure 1: Time temperature variation of Standard fire curves.

Fire safety of a component is assessed relevant to the standard fire situation. ASTM E 119 consider inhabit passage of flame or hot gases through the component as a failure criterion while ISO 834 measure it by the ignition of a cotton pad held close to an opening for 10 seconds. ASTM E 119 has limited the average temperature rise of unexposed surface to 139^{o}C while ISO 834 allows the maximum average temperature rise of 140^{o}C at unexposed surface. Further ASTM E 119 consider the temperature rise of reinforcement. It is limited to 593^{o}C. ISO 834 consider the deformation of the member. Downward deformation of flexural member is limited to L/30 where L is the span of the member (Levesque, 2006).

Standard fires are suitable for comparison of fire resistivity of materials, but in actual fire situation ventilation effects, environmental condition, material composition, boundary condition and fuel availability of the compartment will affect the intensity of fire. Considering the above effects more realistic fire curves, (natural or parametric fire curves) has been developed. Lie's parametric curve, Swedish curve, Law's maximum temperature equations, Mehaffey's Japanees parametric curves, Ma and Makelainen's parametric curves, Barnett's BFD curves and Euro code parametric curves are such parametric curves developed by various researchers to interpret natural fire situations (Ariyanayagam and Mahendran, 2014).

Camille Laurent (2014) has investigated the fire performance of foamed concrete under insulation criteria up to 900 ^{0}C temperature and concluded that foamed concrete has better fire performance characteristics compared to normal weight concrete.

For cellular lightweight concrete with different mix proportions, standard fire performance has not investigated hence, need be determined. Further with different parametric fire situations and hydrocarbon fire situations research studies on CLC behavior in fire is not available.

Research studies on residual properties of CLC after fire scenario is not available in the literature where these properties are important on investigating the fire performance of CLC. During fire exposure, structural element will undergo high temperature variation which will induced internal stresses and variation of bonding in CLC. Therefore, though the material is capable of handling fire, after the fire situation CLC properties might be different with the initial state. Hence, post fire load bearing capacities and capability of handling second fire, need to be determined.

Breaking up of pieces of concrete when it is exposed to high and rapidly rising temperatures is defined as spalling (Kodur, 2014). Spalling can be identified as the special characteristic in concrete (Kodur, 2014). Fire-induced spalling is one of the major components to be considered in evaluating the response of concrete members exposed to fire. It occurs due to build up pore pressure during heating (Dwaikat and Kodur, 2008). Spalling depends on moisture content, permeability, type of fire exposure and tensile strength of concrete (Kodur, 2014). Research studies were not done on investigation of spalling of CLC. Spalling might cause a significant effect on fire performance of CLC due to its cellular structure.

2.2 Fire performance of CLC with properties at elevated temperature

Fire performance of material is influenced by the characteristics of the material, thermal properties, mechanical properties, deformation properties and special characteristics of material in fire. Thermal properties influence the heat transfer in the structural element, whereas mechanical properties influence the strength and stiffness variation. Deformation properties together with mechanical properties influence the extent deformation and strains in the structural member (Dwaikatand and Kodur,2010). All these properties vary as a function of temperature and depends on the composition of the material. Hence to predict fire performance, elevated temperature properties need to be determined (Levesque, 2006).

Thermal properties that influence temperature rise and heat distribution in structural members are thermal conductivity, specific heat and mass loss (Kodur, 2014). The thermal conductivity of concrete is the rate of heat transferred through a unit thickness of the material per unit temperature difference (Levesque, 2006). Thermal conductivity can be measured using several techniques such as pulse method, hot-guarded plate method (HGP), two-linear parallel probe method, transient hot wire method and laser flash method. Specific heat is the amount of heat per unit mass required to change the temperature of material by one degree. The thermal diffusivity of concrete, often denoted as the ratio between its thermal conductivity and thermal capacity. It is a measure of the rate of heat transport from the exposed surface of concrete to the inside (Levesque, 2006). Flash method is more convenient in measuring thermal conductivity, specific heat and thermal diffusivity of CLC in elevated temperatures. Density of concrete depends primarily upon the type of aggregate. With the increment of temperature density also changes (Kodur, 2014). This effect is more predominant in cellular lightweight concrete than conventional concrete since CLC consists more voids. Thermo gravimetric analysis is more suitable to determine the density variation of CLC at elevated temperatures.

Mechanical properties that influence the fire performance of concrete are compressive and tensile strength, modulus of elasticity, and stress strain response at elevated temperatures (Kodur, 2014). Thermo-mechanical analysis need to be done to determine the mechanical properties at elevated temperatures. Both "steady state" and "transient" test methods are available for determining the mechanical properties at elevated temperatures (Kodur, 2014). Unlike at ambient temperature, mechanical property tests at high temperature are usually carried out on a wide range of specimen sizes due to a lack of standardized test specifications for undertaking high temperature mechanical property tests (RILEMTC129-MHT, 2000).

Deformation properties that effects the fire performance of concrete are thermal expansion and creep (Kodur, 2014). Creep, can be defined as the time-dependent plastic deformation of the material. At normal stresses and ambient temperatures, deformations due to creep are not significant. At higher stress levels and at elevated temperatures, however, the rate of deformation caused by creep can be substantial (Kodur, 2014). Dialatometric analysis can be done to determine the deformation characteristics at elevated temperatures.

Otuman and Wang, (2009) has studied thermal properties of foam concrete at elevated temperatures. They have measured thermal conductivity of foam concrete with various densities up to 600 ^{0}C using hot guarded plate test. Further they have proposed analytical models to predict thermal conductivity and specific heat of foam concrete at elevated temperatures. In the analytical method, lightweight foamed concrete (LFC) was considered as a mixture of dried LFC and water up to 170 ^{0}C. Above 170 ^{0}C, LFC was considered as a mix of dried LFC and air pores. Average pore diameter found from the microscopic images used was in the analytical model. Heat transfer of solid material through conduction and heat transfer of air voids through convection and radiation were considered. They have concluded that the models give accurate results predicting the thermal conductivity of foamed concrete at elevated temperatures. Further, they have mentioned that specific heat of LFC can be approximated as a sum of base value of dried LFC with addition of heat required to evaporate free water.

Mydin and Wang (2011) has measured mechanical properties of foamed concrete with various densities in elevated temperatures. They have measured compressive strength, modulus of elasticity, compressive stress-strain relationship and flexural bending strength of foamed concrete with densities 650 kg/m^3 and 1000kg/m^3. All the tests were conducted increasing the load while keeping the specimen at a constant elevated temperature (100 ^{0}C, 200 ^{0}C, 300 ^{0}C, up to 600 ^{0}C) and found that the compressive strength of foamed concrete decreases with temperature. However, up to 200 ^{0}C, foamed concrete is in a position to maintain 94% of original unheated strength. But at 400 ^{0}C. 75% and at 600 ^{0}C, only 40% of original strength was retained. Moreover, modulus of elasticity at 200 ^{0}C, 400 ^{0}C and 600 ^{0}C was respectively 75%, 40% and 25% of the original value.

A number of concrete mechanical property predictive models have been proposed for normal-strength concrete and these models have been checked to determine their applicability to foamed concrete. Sayadi et al, (2016) has concluded that following models as given in Eq (1-6) give accurate results for foamed concrete properties in elevated temperatures.

Compressive strength

$$f_{cT} = f_c \text{ for } T \leq 100℃ \quad (1)$$

$$f_{cT} = f_c(1.067 - 0.00067\,T) \text{ for } 100℃ \leq T \leq 400℃ \quad (2)$$

$$f_{cT} = f_c(1.44 - 0.0016\,T) \text{for } T \leq 400℃ \quad (3)$$

f_{cT} – Compressive strength at elevated temperature

f_c – Compressive strength at ambient temperature

T- Temperature

Elastic Modulus

$$E_{cT} = E_c \text{ for } T \leq 60°\text{C} \tag{4}$$

$$E_{cT} = \frac{800-T}{740} E_c \text{ for } 60°\text{C} \leq T \leq 800°\text{C} \tag{5}$$

E_{cT}– Elastic modulus at elevated temperature

E_c – Elastic modulus at ambient temperature

T- Temperature

Stress-strain relationship

$$f'_{cT} = \frac{3\varepsilon_{cT} f_{cT}}{\varepsilon_{0T}[\,2 + (\frac{\varepsilon_{cT}}{\varepsilon_{0T}})^3} \tag{6}$$

f'_{cT}– Compressive stress at elevated temperature

ε_{cT} – Strain at elevated temperature

ε_{0T} – Strain at maximum stress

Kumar et al. (2018) has compared thermal behaviour of foamed concrete with clay bricks and concluded that thermal conductivity of foamed concrete varies from 0.021-0.035 W/mK while brickwork has a thermal conductivity of 0.6 W/mK to 1.0 W/mK. Sayadi et al. (2016) has studied the effect of expanded polystyrene (EPS) partials in foamed concrete. Increase of EPS cause reduction in thermal conductivity and higher fire endurance can be obtained with 28 % EPS volume in foamed concrete. Kashani et al. (2017) studied the influence of recycled tyre crumbs in cellular lightweight concrete as an insulating constituent. They have concluded that excellent sound and thermal insulation with very low water absorption and total porosity have been achieved by inclusion of recycled tyre crumb in lightweight cellular concrete. She et al. (2018) proposed a numerical method of predicting thermal behaviour of cellular concrete having different pore shapes.

Even though experimental results for thermal properties of CLC are available up to 600 ^{0}C, variation of thermal conductivity, specific heat, thermal expansion with temperature need to be measured up to 1200 ^{0}C to model an actual fire situation. Further, density, porosity, strength and elasticity variation with ambient temperature to 1200 ^{0}C need to be determined for better prediction in fire performance of CLC. Normally mechanical properties at elevated temperature are measured keeping the specimen in a constant elevated temperature and increasing the load. However, it will be more realistic if a test method could be developed to increase the temperature while keeping the load constant when determining the elevated temperature mechanical properties.

3. Design guidelines for cellular lightweight concrete in fire situation

EN 1992-1-2(2004) Design of concrete structures -part 1-2 General rules- Structural fire design describes the principles, requirements and rules for the structural design of buildings exposed to fire. It includes safety requirements, design procedures and design aids for concrete structures under fire situations. The methods described in EN 1992-1-2 are applicable to normal weight concrete up to strength class C90/105 and for lightweight concrete up to strength class LC55/60.

EN 1992-1-2 has tabulated minimum wall thickness requirement for 30, 60, 90, and 120, 180 and 240 minutes fire resistance walls for normal weight concrete with siliceous aggregates. It also states that thickness requirement is reduced by 10% when calcareous aggregates are used in normal weight concrete. However minimum thickness requirement for CLC panels which can be used as non-load bearing walls is not available in the design guidelines.

Further, EN 1992-1-2 states that both load bearing and non-load bearing walls should be limited to wall clear height to thickness ratio of 40 for normal weight concrete. However, applicability of this ratio for CLC walls should be investigated.

Moreover, explosive spalling of concrete can be observed in concrete structures during fire exposure. EN 1992-1-2 has given limitation to the moisture content of normal weight concrete to prevent explosive spalling in the member. However, moisture content limitation for CLC to prevent explosive spalling is not available in design codes of practice and needs to be investigated.

4. Concluding remarks

Cellular lightweight concrete can be identified as a novel type of concrete which can be used as a construction material for load bearing and non-load bearing walls in low-rise and multi storey buildings. It has numerous advantages against other construction materials. A comprehensive literature survey was done on the fire performance of CLC and the research gaps were identified.

CLC elevated temperature property variations are available up to 600 ^{0}C. However, to study the behaviour of CLC in fire situation, CLC elevated temperature properties (ambient to 1200 ^{0}C) need to be measured. Properties such as, thermal conductivity, specific heat, thermal expansion, density, porosity, strength and elongation need to be measured in elevated temperatures. Standard fire tests need to be conducted for non-load bearing and load bearing CLC walls to determine the fire rating and spalling of CLC. Moreover, CLC behaviour in hydrocarbon fire situation and fire behaviour under different parametric fire situations needs to be assessed. Post fire residual properties of CLC needs to be measured to predict the adequacy of CLC to withstand in a second fire situation. Properties of CLC at elevated temperatures and fire tests results can be used to update the design guidelines for CLC walls in fire situations. Minimum thickness requirement for non-load bearing and load bearing CLC walls, maximum wall height to thickness ratio and material property limitation to prevent explosive spalling need to be included in relevant design guidelines.

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