Performance specification of concrete with reference to sustainability.

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Specifications of normal with reference its important properties is discussed. Difficulties associated with specifying concrete with respect durability and service life is highlighted. Sustainable concrete shall have reduced impact on environment so as to preserve and sustain the environment for future. The energy used in production and transportation of materials is called embodied energy and sustainable concrete shall have low embodied energy; also, shall contribute least to green house gas emissions. Use of locally available, renewable and abundant material in concrete making adds to its sustainability as they contribute to reduction in resource depletion. Durability and consequent functionally satisfactory service life has also a role in sustainability of concrete. Qualitatively durability of concrete can be evaluated through water permeability. The permeability again is governed by porosity and pore characteristics. Relative performance of different concrete with respect to durability can thus be evaluated through porosity and pore characteristics. Considering all these aspects a sustainability based performance index for concrete is proposed.

INTRODUCTION

Concrete being a structural material, strength in service is the most valued property, hence it is not surprising that engineers would specify concrete in terms of its strength. The strength of concrete changes with its age, thus strength at the age of 28 days measured through test of sample, usually cube or cylinder is used for specifying compressive strength of concrete. The strength of the sample is easily quantifiable and can be related to potential strength in structure in an objective manner with relatively little ambiguity. In its initial stage of production the concrete solidifies from a plastic state and its mould-ability at that stage is also a concern to civil engineers. The mould-ability is also quantified through some empirical indicators such as slump, Ve-be time etc., determined through respective engineering tests. Optimal behaviour at fresh state and adequate mechanical properties after hardening, are the two most important aspects of concrete performance. The long term properties such as creep and shrinkage can also be quantified in some manner or other. However, there is yet another very important dimension to the performance of concrete in the long run of its life, which is the durability performance. Thermodynamics teaches that only naturally existing materials are chemically stable. Man made materials those are produced at the expense of energy, would tend to dissipate this energy and undergo chemical changes in reaction. Concrete is produced with a considerable expense of energy and thus under conducive conditions would undergo chemical changes. Quite often, during its service condition, the concrete gets exposed to the aggressive environment that causes deterioration. Deterioration is the process of becoming impaired in quality and value. Deterioration process in concrete may take place due to sulphate attack, frost action, action of acids, alkali-aggregate reaction and in steel reinforced concrete, the deterioration may also take place by carbonation and chloride ingress leading to corrosion of rebar. As a result of deterioration, degradation of concrete takes place with time. Degradation by definition is gradual decrease in performance with time. Performance is a measure of extent, to which the concrete material or the structure serves to fulfil its intended functional requirements. Thus degradation is opposite of performance and both degradation and performance are related to deterioration processes. Hence it is desired that concrete should not deteriorate in the envisaged service environment at a rapid rate and must continue to perform satisfactorily for a desired service life. Service life can be understood as the period after inception of the structure, during which all the essential properties of the structure meet or exceed the minimum acceptable value (**Sarja and Vesikari, 1996)**. The long-term performance of concrete is related to its durability properties. The concrete as a material shall therefore be so designed, that the structure where it is to be used should posses the designed service life with minimum possible maintenance requirements. The economic objective of the material design can be minimization of life cycle cost that includes the maintenance as well. Most of the deterioration processes in concrete take place in presence of moisture and due to ingress of aggressive chemical agents those cause deterioration. The aggressive agent again ingress in to concrete usually in solution phase with water or are fluid themselves. Concrete inherently is a capillary porous material by nature. Thus its permeability and diffusion properties are important from its durability performance point of view. Thus concrete as a material must be designed so that its permeability and diffusion properties are desirably low. Moreover, modelling of most of the deterioration processes is largely a grey area of concrete research, hence service life prediction is still in its infancy. For example; chloride ingress is often modelled through error function solution of Fick's diffusion equation for all kind of situations. Use of Fick's diffusion equation ignoring chloride binding does not represent the physical system for chloride ingress in concrete, the equation is also not valid for unsaturated condition of concrete where flow of liquid solution containing chloride may transport more chloride than that by the process of diffusion (**Nagesh and Bhattacharjee, 1998**). The error function solution is valid for a boundary condition where the semi-infinite medium is suddenly exposed to a constant chloride concentration. For most of the deterioration phenomena, with current level of knowledge, service life can be estimated only inaccurately as model for even approximate prediction of service life is limited to a few deterioration processes only. Thus durability specifications are largely prescriptive in most of the codes and recommendations are in terms of minimum cement content, specific cement type or cement combinations to be used and maximum water to cement ratio in a given exposure condition. Performance based specification of concrete at present thus may include measurable properties such as permeability and hydraulic diffusivity. Attempts have also been made to relate these properties to pore size parameters and mix factors as well (**Pradhan, Nagesh and Bhattacharjee, 2005; Kondraivendhan and Bhattacharjee, 2010)**.

Concrete is the most popular construction material in the world. The popularity of concrete can be judged from the fact that cement the main ingredient of concrete is the second most consumed material on earth only after water. Sustainability is the capacity to endure or support; thus sustainable materials or technologies are those which can meet the current needs and requirements without compromising with the ability of future generations to meet their own needs. Green materials use the resources namely; energy, material and water with increased efficiency for its production and induction; while reducing impact on human health and environment during the life cycle, up to demolition and disposal or recycle (**wikipedia)**.

The energy used in production and transportation of materials is called embodied energy. Embodied energy per unit mass for concrete is lower compared to steel or aluminum. However, the volume of concrete used in the building is much greater than any other construction material. As a result, concrete is the major contributor to embodied energy in most buildings. Ordinary Portland Cement (OPC) has been used in the concrete making for many years. Calcinations of limestone in Ordinary Portland Cement (OPC) manufacture results in CO_2 emission. Further, production of OPC requires large amount of energy for heating of lime stone and clay. Considering the CO_2 emission from fuel used in OPC production as well, on an average, for each ton of OPC production, equivalent amount i.e. one ton of CO_2 is emitted in to the atmosphere (**Bhattacharjee, 2010**; **Harrison, 2006**). As regard to green house gas contribution, manufacture of OPC is only next to fossil fuel burning contributing to anthropogenic CO_2 emissions (5-10%) to the atmosphere. Proportioning of ingredients for concrete making is done on the basis of mean strength, while structure is designed considering minimum acceptable strength. For same minimum acceptable strength, higher variability in concrete necessitates proportioning for higher mean strength, resulting in more cement consumption. Better quality control ensures less variation, hence lower cement consumption. Use of appropriate admixture can also result in lower cement consumption. The depletion of lime stone resources is also another concern. The other major raw materials used in making of concrete are aggregations of stones and fine sand or crushed stone powder commonly referred to as aggregates. The mining and quarrying of these materials have started posing serious environmental problem and threat to sustainability. Thus judicious use of natural aggregates and reduction in their use may lead to sustainability. The uses of recycled and artificial aggregates are the other possibilities to improve sustainability of concrete. While concrete is more durable compared to many other materials, being a material produced at the expense of energy is by no means and maintenance free. With better durability repair cycle time can be extended and lesser frequency of repair would help in preserving raw materials and energy contributing to sustainability. The operational energy consumed in building during its life cycle is many times more than the embodied energy, thus insulation quality, thermal mass and albedo of surface can play a major role in overall sustainability concern for concrete. Obviously there are many facades of sustainability of concrete and evaluation of sustainability of one concrete shall take account of all the relevant factors (**Bhattacharjee, 2011**). The performance specification of concrete there shall include specification with regard to sustainability also. The sustainability encompasses durability as well hence a sustainability index presented in this paper may provide a way for performance based specification concrete.

CONCRETE SUSTAINABILITY

The concrete sustainability is related to a) the lifecycle energy implications, b) lifecycle green house gas contribution, c) Contribution to natural resource depletion other than those used as fuel. The life cycle energy implications encompasses the embodied energy of concrete used in initial construction and the embodied energy of the repair materials used for the concrete during its life cycle including the energy used for depletion. The second important energy implication involves relative contribution of concrete towards operational energy saving when used in building. However, this aspect is being omitted in this discussions. Consumed energy whether embodied or otherwise, may be obtained from fossil fuel directly or indirectly, which again contributes to green house emission also leads to depletion of natural resources. Energy obtained from direct solar energy, geo-thermal energy or nuclear fission does not result in CO_2 emission although may result in depletion of natural resources (**Buchanan and Honey, 1994**). Thus energy implication can be expressed in terms of equivalent CO_2 emission or carbon equivalent and depletion of natural resources.

EMBODIED ENERGY

Initial Embodied Energy

Embodied energy includes energy used in the a) production b) transportation and c) fabrication/casting of the concrete(**Bhattacharjee, 2011**). The embodied energy of concrete can be calculated knowing the proportions of ingredients. The sustainability performance needs to be related to grade of the concrete. This would enable accounting of quality control measures adopted while production and allow for appropriate relative comparison. While specifying the concrete, sustainability performance index (SPI) can be specified along with usual specification parameters such as grade, workability etc. Let E_p represent the production energy, E_t represent the transportation energy per unit mass for 100 km or miles for the ingredient material in the concrete, the embodied energy contribution of the ingredient can be estimated as sum of the product of fraction of material and corresponding embodied energy. For example when the ordinary Portland cement content, fly ash content, coarse aggregate content, fine aggregate content and water content are denoted by C, F, A_c, A_f and W respectively, the initial embodied energy (IEE) of the concrete would be given by:

$$IEE = \frac{(E_{pC} + E_{tC})C + (E_{pF} + E_{tF})F + (E_{pAC} + E_{tAC})A_c + (E_{pAF} + E_{tAF})A_f + (E_{pW} + E_{tW})W}{(C + F + A_c + A_f + W)} + E_{CN}$$

…. (1)

In the equation (1) E represent embodied energy, first subscripts p and t represent process and transport respectively. The second subscript C, F, AC, AF and W represent cement, fly ash, coarse Aggregate, fine aggregate and water respectively. For example, E_{pAC} represent process contribution of coarse aggregate to embodied energy. E_{CN} represent embodied energy contribution of concreting process, i.e. casting per unit mass of fresh concrete. Data related to embodied energy of construction material is available in literature given in reference (**Reddy and Jagadish, 2003**) .

The energy estimated through equation (1) is initial embodied energy per unit mass of concrete at the time of casting. Concrete being a man made material produced with expense of energy cannot be stable and would have tendency to undergo changes due to increased chemical potential. The changes lead to deterioration and loss of functional performance resulting in repair and maintenance. When repaired new materials are put in and with expense of additional energy that is embodied in the repair system. Thus life cycle embodied energy input to the system needs consideration.

Life cycle embodied Energy

Life cycle embodied energy would depend upon repair cycle or service life. Service life is defined as the time at which the structural element reaches the durability related serviceability limit. Durability is ability to maintain the performance against aggressive environment that results in deterioration hence loss of durability. Most of the physical and chemical deterioration in concrete is initiated by ingress of harmful agent through cover concrete. The service life with respect to deterioration is related loss of protection capacity of the cover concrete. As a result often patch repairs are under taken where by cover concrete is replaced completely by fresh material which again may be similar to original material. The number of such repair required would be the ratio of intended design life to repair cycle or the service life. Assuming that concrete up to cover depth is replaced on both sides, the ratio of quantity of repair material to original material will be same as the ratio of 2 times cover depth to depth of the section. This is an over estimation as in many elements only one face would exposed to deterioration and would need repair. However, adopting a conservative approach the above estimate is reasonable. Thus the embodied energy of the repair materials (EER) can be approximately estimated in terms of the initial embodied energy (IEE) of the concrete as follows:

$$EER = \frac{2 \times d_c}{d_s} \times \frac{t_{il}}{t_{sl}} \times IEE \qquad \ldots.. \qquad (2)$$

In equation 2 d_c, d_s are the cover depth and depth of the section respectively. "t_{il}" and "t_{sl}" are intended design life and service life of concrete respectively. With current level of knowledge service life of concrete can be estimated only approximately and accurate model for prediction of service life is limited. (**Sarja and Vesikari, 1996**). However, deterioration of concrete is largely governed by ingress of detrimental chemicals in to the concrete through its interconnected pore system, mostly in water dissolved state in solution phase. Diffusivity and permeability of concrete governs the ingress. To make a relative comparison t_{sl} may be assumed to be inversely proportional to permeability (or diffusivity). The permeability and hydraulic diffusivity again can be related to porosity and square of geometric mean pore size called mean distribution radius as given below (**Pradhan, Nagesh and Bhattacharjee, 2005; Kondraivendhan and Bhattacharjee, 2010**) . It is possible to estimate pore size distribution parameters from the knowledge of water to cement ratio and age when average particle size of the cement is known **Kondraivendhan and Bhattacharjee, 2010**). Thus approximate value of relative EER can be calculated from mix proportions.

$$k(\theta) = \frac{p\, r_m^{\,2} \rho g}{12 \mu \tau^2 (1 + 1/\alpha^2)} \qquad \ldots.. \qquad (3)$$

Where, p is the porosity, τ is the mean tortuosity, ρ is the density of water and g is acceleration due to gravity. μ is the viscosity of water and α is aspect ratio of elliptic pores. Since the pore sizes vary logarithmically, hence instead of using simple mean the mean radius r_m can be taken as mean distribution radius as given in equation.

The life cycle embodied energy (LEE) is the sum of IEE and EER. The LEE can be used to estimate equivalent carbon emission from concrete using the methodology proposed below. All the embodied energy mentioned above can be expressed in Mega Joules (MJ).

Carbon equivalent of embodied energy

Different values of carbon equivalent released by fossil fuel had been reported, however, a factor of 0.02 kg Carbon/MJ of fossil fuel had been adopted in past by Buchanan and Honey (**Buchanan and Honey, 1994**). The same is also adopted in this paper as well. The proportion of fossil fuel in the total fuel used varies from country to country. It was mentioned earlier that energy obtained from other sources such as solar energy, geothermal and nuclear energy do not contribute to carbon emission. Hence knowing the proportion of fossil fuel used in any country in energy generation one can convert the LEE in to equivalent carbon emission. For example in India nearly 78% of electricity is obtained from fossil fuel, 19% from hydro electric sources and about 3% from nuclear energy(**International Energy Agency, 2002**). Hence, one can assume a factor of 0.8 for the ratio of energy with carbon emission to total and multiply LEE with 0.8 to obtain energy that has potential carbon emission. Le this factor be termed as fossil fuel ratio (FFR), for cement production however, FFR is 1 as clinkering process involve use of 100% fossil fuel. The clinker production contributes additionally to carbon emission due to calcinations of lime. The ratio of mass of carbon to calcium oxide is 12/56, and unit mass of OPC clinker contains about 66% lime. Hence the carbon emission from unit mass of clinker is 0.66×12/56=0.14. Thus equivalent life cycle carbon emission (LCE) from concrete is given by:

$$LCE = FFR\times\left(IEE + EER\right)\times 0.02 + \frac{0.14\times C\times\left(1+\dfrac{2\times d_c\times t_{il}}{d_s\times t_{sl}}\right)}{\left(C + F + A_c + A_f + W\right)} \qquad \text{……..} \quad (4)$$

The LCE thus obtained can be compared with a reference case to arrive at a performance index. The reference case can be chosen as the one having maximum possible LCE value. Thus for the given specification of concrete with grade i.e. the characteristic strength, workability, that may be expressed in terms of slump or other measures, the reference concrete can be chosen as the one that contains neither any supplementary cementitious material nor admixed with any water reducing agent. The Ordinary Portland Cement grinded to a maximum with maximum C_3S content may be chosen as the reference cement. Because of poor quality control, the standard deviation may be taken at its maximum value. The aggregates in the reference concrete may be considered as crushed leading to higher water content in the mix. The LCE of reference concrete is termed as LCE_{ref}. The sustainability performance index for embodied energy SPI_{EE} is given as:

$$SPI_{EE} = \frac{LCE}{LCE_{ref}} \qquad \text{……..} \qquad (5)$$

DEPLETION OF NON-FUEL NATURAL RESOURCES

Depletion natural resources both fuel and the non fossil fuel types, can be effectively and elaborately handled using "exergy" concept (**Wanga, Zmeureanua and Rivard, 2005**). It is defined as the "maximum theoretical work that can be extracted from combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment—that is, passes to the dead state at which the combined system possesses energy but no exergy". Unlike energy, exergy is always destroyed because of the irreversible nature of the process. The contribution of cement clinker towards sustainability performance is considered in earlier sections. The contribution to sustainability by recycled aggregate or waste material vis-à-vis natural aggregate is the main concern in this section. Thus one can simply define the sustainability performance index as fraction of natural aggregates used in the concrete making as:

$$SPI_{RD} = \frac{A_{cN} + A_{fN}}{A_c + A_f + F + S + O_W} \quad \ldots\ldots.. \quad (6)$$

In the above equation, A_{cN} and A_{fN} are the quantity of aggregates obtained from natural sources contributing to depletion, used in the concrete, while A_c and A_f are total coarse and fine aggregate used in the concrete respectively. F, and S are the quantity of fly ash, and slag in the concrete in its unit volume. O_W represents quantity of other secondary industrial by-product per unit volume of concrete. These by products are such that there use in concrete contributes to positively to sustainability from environmental concerns.

OPERATIONAL ENERGY

In the context of building the operational energy over 50 years of period is at least 6-7 times more than the life cycle embodied energy. (**Huberman and Pearlmutter, 2008; Yohanis and Norton, 2002**). The operational energy is mainly because of heating ventilation and air conditioning (HVAC). Energy efficiency plays a major role in reducing the energy use. The energy used in HVAC is due to heat fabric heat gain or loss through the building envelope and casual heat gain from sources within the building. The sources can be occupant themselves and/or process that generates heat. The thermal properties of the materials in the envelope and their arrangement govern the fabric heat gain or loss. The most important among the thermal properties is the thermal conductivity of the material. The thermal conductivity of the materials used in wall or roof construction controls the heat transmission property that is U-value of layered construction. The diurnal temperature variation is generally periodic and the thermal storage i.e. the volumetric heat capacity enables an amplitude decrement and time lag in the peak heat gain through the fabric. Heat rejection or acceptance by the building envelope is also dependent on the shortwave absorption and long wave emission by the exposed surface. However, usually concrete is used in the roof of building as a structural part of the envelope on the inner face. The energy saving of air conditioned building increases with thermal resistance of the envelope. The concrete is usually exist in about 12-15% of envelope thus its insulation quality will control about $1/8^{th}$ to $1/7^{th}$ of operational energy. The thermal conductivity (k) of concrete alone is involved in the insulation property and thermal and diffusivity plays only a minor role in energy consumption in building. Thus to arrive at a sustainability performance index of concrete used in building one can use the ratio of thermal conductivity of the concrete under consideration to that of a reference concrete. A detailed discussion on this aspect is available in articles published by the author earlier and given in the reference (**Bhattacharjee and Krishnamoorthy, 2004; Bhattacharjee, 2011**) .

OVERALL SUSTAINABILITY PERFORMANCE INDEX

As mentioned earlier, the contribution to carbon emission by concrete is most important consideration in sustainability and if one considers the sustainability of concrete in general structures other than building, one may express the sustainability performance index as given in equation below. w_1 and w_2 are the weights corresponding to SPI_{EE} and SPI_{RD}. For example if one considers resource depletion is half as important as embodied energy, then w_1 and w_2 will be 0.67 and 0.33 respectively. Using these weights to the dimensionless relative performance indices overall sustainability index can be arrived. Thus sustainability performance index SPI for concrete can be expressed as given in equation 6:

$$SPI = w_1 SPI_{EE} + w_2 SPI_{RD} \quad \ldots\ldots. \quad (6)$$

The value of the performance index is always less than unity and a lower value of the index signifies better performance. The weights proposed at the moment is somewhat arbitrary but can be arrived at by combining experts opinions using appropriate tools such as questionnaire survey and analytical hierarchy procedure(AHP) or Fizzy concepts. An example calculation is shown below to demonstrate the usage and utility of the index.

Conclusions

Some issues related to performance specifications of concrete are discussed. An expression is proposed for sustainability performance index of concrete. The index accounts for life cycle embodied energy and corresponding carbon emission, service life and durability, and; depletion of nonrenewable natural resources.

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