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Concrete use for sustainable development

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ABSTRACT

Concrete is a primary construction material of the modern age with over 13 billion metric tons being used globally every year. It is a man-made material with a great impact on the economy and the environment. Its properties largely depend on the raw materials used, the skills of the concrete mix designer, and how the concrete is placed and finished. Issues of concern are strength, durability, ease of placement, economy and impact on the environment. Experiences have shown that improperly designed or constructed concrete is prone to sulfate attack (SA), acid attack (AA), efflorescence, alkali-aggregate reaction (AAR) and rebar corrosion (RC). Early degradation results in high maintenance or replacement costs which divert scarce resources from the primary objective of expansion of infrastructure. Environmental issues of concern are high energy and raw material consumption, and high CO_2 emission in cement production. This paper reviews the use of concrete in Kenya and offers suggestions for sustainable use of concrete for national development.

Keywords: green concrete, high performance, sustainability.

1. INTRODUCTION

Concrete has been defined as a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate [1]. Materials for concrete production are natural gravels or crushed rocks, natural sand or stone dusts, cement and water. Recycled demolition and construction waste concrete, and industrial by-products such as ground granulated blast-furnace slag (GGBFS), fly ash (FA) and silica fume (SA) are also in common use as aggregates or cement replacement materials (CRMs). Portland cement (Pc) is the most common binder in concrete and over 2.6 billion metric tons is produced annually worldwide [2]. This is equivalent to about 13 billion tons of concrete. Table 1 gives Pc production and consumption in Kenya from 2007 to 2011, showing a steady rise in consumption from 2.1 million mt in 2007 to 3.4 million mt in 2011 [3]. This translates to concrete consumption of about 17 million mt in 2011.

Table 1: Cement production and consumption (10^3 tonnes), 2007 – 2011 [3].

	2007	2008	2009	2010	2011*
Production (Kenya)	2,615.1	2,829.6	3,320.3	3,709.8	4,088.4
Domestic exports	598.1	692.5	684.2	651.7	708.4
To Uganda	462.9	565.8	598.9	514.6	519.8
To Tanzania	51.2	60.7	9.3	33.7	63.3
Net estimated cement consumed	2,018.9	2,187.1	2,636.1	3,058.1	3,380.0
Retained imports	42.5	18.7	35.2	27.1	53.0
Total estimated consumption plus stocks	**2,059.5**	**2,155.8**	**2,671.3**	**3,085.2**	**3,433.0**

Source: Cement Companies and Customs and Excise Departments, * Provisional.

Recently, several large infra-structure projects have been launched, indicating that consumption of cement and concrete will continue to rise in the coming years. The Lamu Port – Southern Sudan – Ethiopia Transport (LAPSSET) project estimated to cost USD 23 billion [4], the Konza Technology City project estimated to cost USD 7 billion [5], and the Dongo Kundu Free Port project estimated to cost USD 308 million [6] are cases in point. In addition infrastructure development in the 47 newly established counties will increase the consumption as the devolved governments come into effect in accordance with the new constitution [7].

Pc contains over 70% C_3S and C_2S, which hydrate to produce a C-S-H phase, the primary binder in Pc concrete, and $Ca(OH)_2$ [8]. Pozzolanic materials such as GGBFS, FA, SF, natural and organic pozzolans are often used to partially replace Pc with technical and environmental advantages. The reactive silicates and aluminates in the pozzolans react with $Ca(OH)_2$ to produce more cementitious C-S-H, C-A-H and C-A-S-H phases [9]. Workability enhancing admixtures are increasingly being used to improve the performance of concrete in the fresh and hardened state. Other admixtures can be incorporated to enhance specific properties of concrete. Concrete is a man-made construction material whose performance depends on the raw materials used, the skills employed in concrete mix design, and the manner in which the concrete is placed and finished. The pore structure contributes greatly to both the strength and durability of concrete. This paper reviews concrete design and construction in Kenya and suggests that high performance concrete (HPC) practice could improve efficiency in material, labor and capital use, structural performance, and project delivery time.

2. GREEN CONCRETE AND SUSTAINABLE CONCRETE USE

Green concrete has been defined as concrete being produced and used in an environmentally friendly manner [10]. Sustainability is a process that meets the needs of the present without compromising the ability of future generations to meet their own needs [11]. It is estimated that for every ton of Pc clinker produced, 1.65-1.75 tons of raw materials are consumed; and for every ton of Pc produced, an average of 0.8 ton of CO_2 is discharged into the atmosphere, and the consumed energy is up to 5% of global industrial consumption [12]. These statistics have raised concerns over the sustainability of concrete use. Green and sustainable concrete must therefore have a low CO_2 footprint, and reduce the consumption of energy and raw materials. These objectives are met by reducing the amount of Pc used in concrete by partial replacement with pozzolanic CRMs, using recycled waste materials, and optimizing design to meet the strength and durability requirements.

Project delivery time, life cycle costs of structures, and efficiency in deploying equipment and labor are of equal concern. During project implementation, it is often necessary to interrupt other services. If a project takes too long to implement, the national cost due to these interruptions will reverse gains in economic growth. A slow pace of project implementation eventually leads to a slow pace of service delivery and national development. A slow pace of placing concrete can result in reduced structural performance due to weaknesses at cold joints. Concrete practices that lead to early deterioration will result in heavy maintenance or replacement costs. When a project takes too long to complete, both equipment and labor cannot be deployed elsewhere. Although labor is plentiful, additional equipment must be bought with scarce resources. Moreover, inefficient deployment of labor lowers labor wages and can lead to labor unrest.

Sustainable concrete practice therefore calls for economy in the use of materials, equipment and labor, fast construction methods, durable structures, and concern for the environment.

3. TRADITIONAL CONCRETE PRACTICE IN KENYA

3.1. Introduction

The information which is contained in this section is based on the author's engineering experience in Kenya spanning over 30 years. The practices generally apply to construction works involving local engineers and contractors, but may not fully apply on large contracts involving international contractors.

3.2. Cement

Cement is produced in accordance to KS EAS 18 [14]. The cements produced are blended cements in which CRMs are added to clinker at the time of grinding. The cements readily available in the market are Portland Pozzolana Cement (PPC) CEM II/B-P containing 21-35% natural pozzolana, Pozzolanic Cement (PC) CEM IV/A with 11-35% pozzolanic material, and Portland Limestone Cement (PLC) CEM II/A-LL with 6-20% limestone addition. A limited quantity of Ordinary Portland Cement (OPC) CEM I is produced for specific uses.

3.3. Aggregates

Crushed stone is used for coarse aggregate and rock crushing quarries are spread out in areas where concrete is used. Sand is the fine aggregate of choice and harvested in river beds, lake and sea shores. A large quantity of stone dust is produced in the stone crushing quarries but its use as fine aggregate in concrete is not widespread.

3.4. Concrete mix design

Concrete mix design is based on water-binder (w/b) ratio for the determination of both strength and workability. The use of workability aids is the exception rather than the rule. Typical concrete strengths for structural concrete are in the cubic strength range of 25- 40 MPa (cylinder crushing strengths of 20-30MPa).

3.5. Concrete production and use

Concrete is produced on site or in centralized ready-mixed concrete (RMC) plants and supplied in truck mixers. It is moved on site by wheel burrows, dumpers, hoists and hoppers suspended from cranes. Figure 1 shows the use of a hoist on a building construction site in Nairobi. Figure 2 shows concrete supply by hopper suspended from a cable crane on a bridge construction site in Mombasa

Figure 1: Hoisting concrete in a bucket, Nairobi, 2011.

Figure 2: Hopper suspended from cable crane, Mombasa, 1979.

Final movement and placing may be by wheel burrow (Figure 3) and/or tremie (Figure 4) and compaction is achieved by using immersion vibrators. Finishing is carried out using a straight edge which can be timber or metal (Figure 5).

Figure 3: Concrete movement by wheel burrow, Siaya, 2010.

Figure 4: Placement by tremie and compaction by immersion vibrator, Mombasa, 1979.

Figure 5: Finishing with straight edge, Siaya, 2010.

4. PROBLEMS OF TRADITIONAL CONCRETE PRACTICES

4.1. Design

Concrete strength is related to the w/b ratio by the Abram's rule (equation 1) and Feret's rule (equation 2), both of which give an inverse relationship of strength and w/b ratio, as shown in Figure 6.

$$f_c = \frac{K_1}{K_2^{w/b}} \tag{1}$$

$$f_c = K\left(\frac{c}{c+w+a}\right)^2 \tag{2}$$

Where f_c = compressive strength.

K_1, K_2 and K_3 = constants

w/b = water/binder ratio

c, w, a = absolute volumetric proportions of cement, water and air.

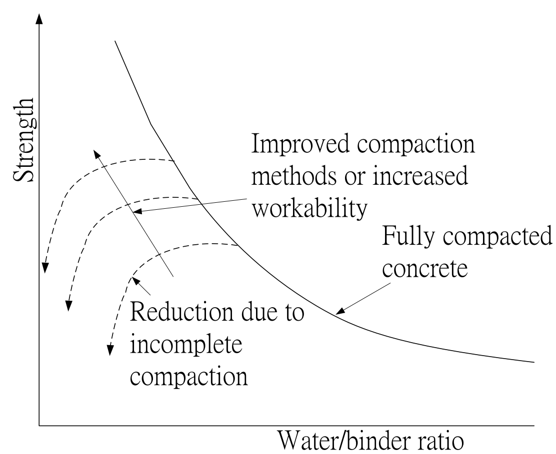

Figure 6: Variation of strength with water/binder ratio.

At very low w/b ratio, concrete is difficult to compact and becomes very porous, resulting in a loss of strength and durability. On the other hand, a high w/b ratio results in workable concrete, but excess water eventually evaporates, resulting in high drying shrinkage with potentials for cracking, and porosity. Concrete of high w/b ratio is also prone to segregation and bleeding in the fresh state (Figure 7) leading to surface laitance, and plastic settlement or shrinkage cracking (Figure 8).

Figure 7: Bleeding, Siaya, 2011

Figure 8: Plastic crack, Siaya, 2011.

4.2. Construction

Movement and placement of concrete by traditional methods is very slow and labor intensive. This creates congestion on the construction site and increases the risk of accidents. Mechanical compaction by vibration is noisy. The method is not very efficient and often results in honey combs which affect the strength and durability of concrete. Large concrete pours cannot be completed in one session, resulting in cold joints which are often points of poor compaction resulting in reduced performance (Figures 9 & 10).

Figure 9: Poor compaction at a cold joint.

Figure 10: Efflorescence at a cold joint.

4.3. Strength

The produced concrete cannot attain its full potential due to inadequate consolidation from reduced workability or too much water. The distribution of strength in concrete varies due to surface laitance, and localized pockets of high w/b ratio under re-bars and aggregate particles. Weakness is also caused by localized honey combs, cold joints, and shrinkage cracks.

4.4. Durability

4.4.1. Pore size, distribution and connectivity as a determinant of the durability of concrete.

The size, distribution and connectivity of pores in concrete determine the ease with which fluids and gases can penetrate and move through concrete. Moreover, most chemical reactions which cause the degradation of concrete take place in the presence of free water in the pores of concrete. Water, therefore, plays a double role as agent for transporting dissolved salts through concrete and as a reactant or facilitator of chemical reactions. For rebar corrosion, it serves a third role as an electrolyte facilitating the movement of OH^- ions from the cathode to the anode. A dense and dry pore structure is therefore essential for concrete durability. It is not possible to achieve this with the traditional concrete practices and several durability problems occur in concrete as discussed by Illston and Domone [8] and Neville [15].

4.4.2. Sulfate Attack

Sulfates of sodium, potassium, calcium and magnesium occur in soils or in ground water. Sodium and potassium sulfates react with $Ca(OH)_2$ in concrete to produce $CaSO_4$ and NaOH or KOH as shown in equation 3 [8, 15].

$$Na_2SO_4.10H_2O + Ca(OH)_2 \rightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O \quad (3)$$

$CaSO_4$ reacts with C_3A hydrate in cement in the presence of water to produce ettringite, a large compound which causes expansion and bursting of concrete. The reaction is given in equation 4 [15].

$$3CaSO_4.2H_2O + 3CaO.Al_2O_3.12H_2O + 14H_2O \rightarrow 3CaO.Al_2O_3.\ 3CaSO_4.32H_2O \quad (4)$$

$MgSO_4$ reacts with both $Ca(OH)_2$ and C-S-H, resulting in the destruction of the binding properties of cement. The reactions are given in equations 5 and 6.

$$MgSO_4.7H_2O + Ca(OH)_2 \rightarrow Mg(OH)_2\downarrow + CaSO_4.2H_2O + 5H_2O \quad (5)$$

$$3(MgSO_4.7H_2O) + 3CaO.2SiO_2.3H_2O \rightarrow 3(CaSO_4.2H_2O) + 3Mg(OH)_2\downarrow + 2SiO_2\downarrow + 14H_2O \quad (6)$$

4.4.3. Acid Attack

Acids derive from acid rain that contains dissolved CO_2 and SO_2, H_2S gas from bacterial reduction of sulfur compounds, diffusion of atmospheric acidic gases into concrete, and industrial effluents. Acids react with free lime in concrete to produce acid salts and water, as shown in equation 7.

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O \tag{7}$$

When the salt is water soluble, it can be leached out of concrete in flowing water. The formation of salts also reduces the pH of concrete and promotes the corrosion of imbedded steel.

4.4.4. Efflorescence

Efflorescence is caused by leaching of lime compounds by water percolating through porous concrete, cracks or badly constructed joints, and deposited on the concrete surface when the water evaporates. The lime reacts with CO_2 from the air and forms $CaCO_3$, a white deposit, as shown in Figure 10.

4.4.5. Alkali-Aggregate Reaction

Some aggregates used in concrete may contain reactive silica, silicates and carbonates. These aggregates react with $Ca(OH)_2$ in concrete in the presence of water to produce large compounds which cause expansion, map cracking of concrete, and surface pop-outs.

4.4.6. Rebar corrosion.

Rebar corrosion is a problem associated with reinforced concrete. Ingress of CO_2 and chloride ions result in the formation of anodic and cathodic areas in steel and the electrons flow. At the cathode, the electrons ionize water and O_2 molecules to produce negatively charged OH^- ions. The OH^- ions move to the anode in pore water and react with steel to produce $Fe(OH)_2$ which is subsequently oxidized to Fe_2O_3, a reddish brown material also known as rust. Rust occupies a larger volume than steel and leads to expansive pressure which causes delamination and spalling of concrete cover (Figures 12 & 13).

Figure 12: Rebar corrosion in a bridge soffit, road A109.

Figure 13: Rebar corrosion in a bridge within Mombasa port.

5. HIGH PERFORMANCE CONCRETE

5.1. Definition

Goodspeed et al [16] give a definition of high performance concrete (HPC): concrete that meets special performance and uniformity requirements that cannot always be obtained using conventional ingredients, normal mixing procedures, and typical curing practices. These requirements include ease of placement and consolidation without affecting the strength and durability, early high strength, volume stability, and long life in severe environments.

5.2. Materials

The material characteristics required for HPC are given in ACI 363R [17]. The materials used for HPC are coarse aggregate, fine aggregate, Portland cement, pozzolanic material, water and superplasticizer. Retarders may be required to control early hydration particularly when concrete is to be moved a long distance from the production plant to the construction site. In Kenya, PC and PPC cements are blended with pozzolans at production. The PLC and OPC cements do not have pozzolanic blends and pozzolanic material must be incorporated at the mix design stage. Rounded smooth textured fine aggregates are preferred because they require less water in concrete. In order to reduce water demand due to fine particles, it is also recommended that fine aggregates should have a fineness modulus (FM) > 2.5. Aggregates of FM about 3 are found to give the best workability and compressive strength. Using a low maximum aggregate size (MAS) for coarse aggregates increases the surface area that bonds with the binder paste, and reduces stress concentration around the particles, which are caused by differences in the moduli of elasticity of aggregate and paste. A low MAS also allows easy flow of concrete through heavily reinforced structural members. ACI 363R recommends that coarse aggregates should have a MAS not exceeding 12.7mm. Higher strengths have been found to be obtained through crushed coarse aggregates. Natural pozzolans as defined in KS EAS 18-1 are more readily available. Organic materials with pozzolanic properties are rice husks ash (RHA) [18], sugar cane straw ash (SCSA) and sugar cane bagasse ash (SCBA) [19]. Due to the slow reaction of most pozzolanic materials, the inclusion of silica fume which has particles 100 times finer than cement particles helps to improve the early strength of concrete, cohesion of fresh concrete and reduce bleeding [15].

5.3. Design

Design of HPC is based on the principle of achieving the desired performance with minimal Pc and water. This is obtained by partial replacement of Pc with a pozzolanic material, dense packing of materials to reduce paste volume, and use of superplasticizer to obtain the desired workability. The mixture must have enough water for the complete hydration of the binder in order to avoid autogenous shrinkage and cracking [8]. The pozzolanic material reacts with $Ca(OH)_2$ released by the hydration of calcium silicates in Pc to produce additional cementitious products which fill the pores of concrete and improve both the long term strength and durability.

The densified mix design algorithm (DMDA) is gaining popularity in mixture proportioning. The application of the method is described by Hwang and Hung [20]. The method involves packing fine aggregate with fly ash or other suitable material to determine α, the ratio of fly ash to fly ash plus fine aggregate at maximum packing density, as given by equation 8.

$$\alpha = \frac{\mathrm{Wfly}}{\mathrm{Wfly} + \mathrm{Wfa}} \tag{8}$$

where W_{fly} and W_{fa} are the weights of fly ash and fine aggregate respectively. The fly ash and fine aggregate at maximum packing density is then added to coarse aggregate in increasing amounts to determine the value β at maximum packing density as given in equation 9.

$$\beta = \frac{Wfly + Wfa}{(Wfly + Wfa) + Wca} \quad (9)$$

where W_{ca} is the weight of the coarse aggregate. The least void is determined from equation 10.

$$V_v = 1 - \{ \frac{Wfa}{\gamma fa} + \frac{Wca}{\gamma ca}\} \quad (10)$$

Where W_{fa} and W_{ca} are the weights of fine and coarse aggregates in kg, and γ_{fa}, γ_{ca} are their respective densities in kg/m^3. The volume of paste is determined from equation 11.

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$$V_p = nVv = \{\frac{Ww}{\gamma w} + \frac{Wc}{\gamma c} + \frac{Wp}{\gamma p}\} \quad (11)$$

Where W_w, W_c, and W_p are the weights of water, cement and pozzolan in kg, and γ_w, γ_c, γ_p are their respective densities in kg/m^3. The value of n is determined experimentally to target the maximum strength. The volume of aggregates is determined from equation 12.

$$V_{agg} = 1 - V_p \quad (12)$$

The strength attained in design will depend on the quality of cement, and the amounts of CRMs and water used, among other factors. Bruno et al [13] have defined binder intensity, b_i, as the amount of binder required to produce a unit of desired performance, e.g. strength. They analyzed test results of concrete made with different materials and mix proportions and found that the most efficient concretes with a b_i value < 5 kg.m^{-3} MPa^{-1} are those incorporating a combination of low w/b ratio, 6 - 10% silica fume, and superplasticizer. These generally had strengths in excess of 60MPa.

5.4. Construction

Construction in concrete involves measuring the mix proportions, mixing, transporting, placing and finishing. ACI 304R [22] gives guidelines on how these operations can be carried out. There are advantages in producing concrete in central RMC plants as opposed to making concrete on site. Better storage of materials, more accurate batching, better quality control, and accumulation of skills through staff training are some of the advantages. Mixing can be done at the RMC plant or in truck mixers as the concrete is transported to the construction site. The concrete from the truck mixer is fed to the concrete pump which delivers it at the point of placement. The concrete must be free flowing and self-consolidating for fast placement to avoid cold joints. There are several models of hand-operated concrete finishing machines for fast and less strenuous finishing.

5.5. Quality control

Quality control is of utmost importance at all stages of production if a strong durable structure is to be obtained. A project activity flow chart like the one shown in Figure 18 [23] can be used for planning and implementation of a quality control program.

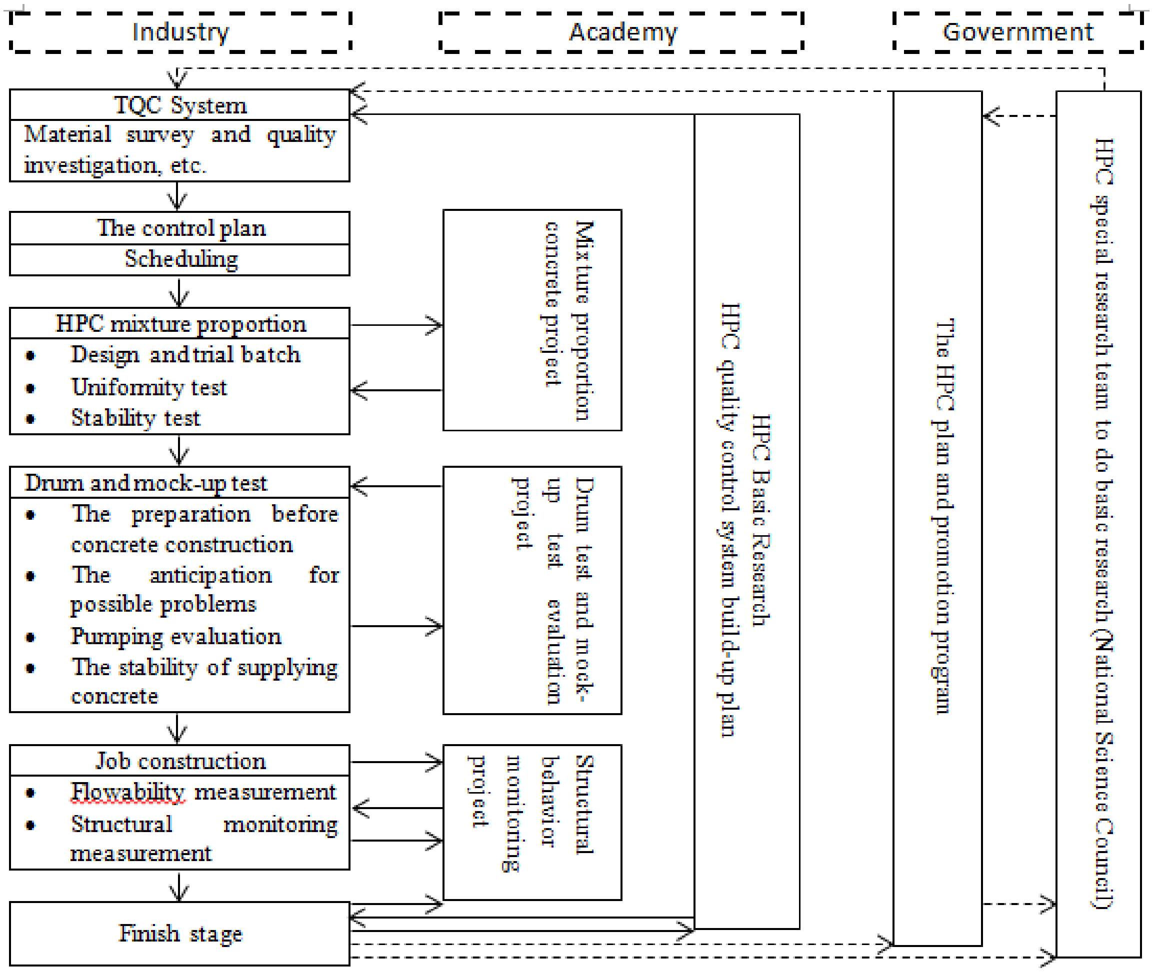

Figure 18: Total quality control for using HPC (Hwang et al [23])

Material used must be checked for conformity with the relevant ASTM or equivalent standards. After concrete mix design, laboratory trial mixes are made and tested to check concrete properties. This is followed by field trial tests involving all field staff. The construction equipments are calibrated and all field staff are trained on the operations. Mock concreting operations are necessary to ensure proper coordination during the actual concreting operations. Tests which must be carried out on fresh concrete at the production plant and upon delivery on site include concrete slump, slump flow diameter and time of flow, L-test for flow length, U-tube test for segregation and bleeding, and temperature to monitor the hydration of concrete. Cylinder and bar samples are also cast on site to be tested at specified ages for compression strength, tensile strength, electrical resistivity, volume stability, and various durability tests as required.

Internet based methods have been developed for easy and fast sharing of information for quick intervention in case of non-conformity, which also helps to avoid conflict between parties. A method which also uses satellite connection connects the concrete supplier, the customer and the transporter [24]. A data entering menu is used by the customer to order concrete, and by the supplier to enter details of materials used and test results. A waybill menu is used to enter concrete movement details. The vehicle speed and location is tracked through a general packet radio service (GPRS) device installed on the truck, and concrete temperature is monitored in transit and a retarder dispensing device can be activated automatically to control hydration. Results of tests carried out on the construction site are fed into the system. The system automatically alerts all parties on any non-conformity by a telephone call or email message.

A second method which can be used on the construction site uses a radio frequency identification (RFID) system, several pocket size personal digital assistants (PDA) and tags which emit electric signals [25]. Operators in different parts of the site can use the PDAs to receive and enter information, and the tags are used to locate materials and equipment for easy retrieval. Information flow is fast and management can monitor what is happening in different parts of the site without having to move around the site, and can issue instructions from the comfort of the office.

5.6. Implementation model

Production, transportation and placement of HPC will require investment in three key facilities: a concrete batching plant which may or may not have mixing facilities, truck mixers which can be used for mixing and transporting concrete, and mobile concrete pumps. For good quality control and accumulation of skills in concrete production, it is recommended that concrete production be entrusted to registered RMC operators who can also own mobile batching plants for use in remote areas. Transporting concrete can be carried out by other licensed investors. Concrete pumping trucks can be owned by a hire company and used by the building contractor only when needed. This model reduces investment burden on any one individual and allows maximization of equipment usage. The licensing agency must be able to formulate clear operation rules that will create harmony between the interacting parties. This model may, however, not apply on very large projects where the contractor may require better control of all concrete production and supply operations.

6. DISCUSSION

Traditional concrete practices have been shown to be inefficient in material, labor and equipment usage, slow in project delivery, and the structures produced are of low strength and durability, resulting in high maintenance or early replacement costs. Additional costs are incurred in interruptions to other services during lengthy construction. Traditional concrete practices therefore result in a slow pace of development and inefficient use of development funds. HPC gives greater efficiency in material usage and deployment of labor and equipment. Free flowing self-consolidating concrete reduces noise pollution and eliminates honey combs, while allowing fast construction which reduces cold joints, and ensures faster project delivery. Most of the durability problems associated with traditional concrete practice are eliminated by better consolidation of concrete, reduced porosity due deposition of pozzolanic reaction products, and reduced pore water and $Ca(OH)_2$ which are used in pozzolanic reactions.

7. CONCLUSION

HPC can help to produce strong durable structures which will not impose a heavy maintenance burden on scarce resources. Faster construction results in faster delivery of projects and development. Adoption of HPC can help to realize a steady and sustainable economic development. The changeover from traditional methods of concrete use will require retraining of operators in the construction industry, improving research and teaching institutions. Early high investment costs will be recovered through great savings in maintenance and early replacement costs.

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