Investigation For Curling Stress In Self Compacting Concrete Pavement

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ABSTRACT

A Highway asphalt is a construction comprising of . layers .materials over the regular soil layer. In India, adaptable asphalts are liked for street development because of lower development expenses and expedient development when contrasted with inflexible asphalts. However, the maintenance costs of the rigid pavements are relatively lower as compared to the maintenance costs of flexible pavements. The rigid pavements are constructed by casting cement concrete slabs over dry lean concrete or granular sub-bases. The cement concrete pavements are designed to withstand traffic loads and environmental loads during its service life. The environmental factors that are considered in the concrete pavement analysis are temperature, humidity, precipitation and frost/heave. The stresses induced in the concrete pavements on account of daily temperature variation are termed as curling stress. The curling stresses are as important as axle loads in the concrete pavement analysis as they alone can trigger the failure of the cement concrete pavements.

The rigid pavements are constructed with normally vibrated concrete. Self-compacting concrete (SCC) is preferred over normal concrete mainly due to improved mechanical properties and speed of construction. Due to environmental regulations and concerns, the use of natural river sand in concrete manufacture is becoming impractical and obsolete. Nowadayscrushed sand is widely used in concrete manufacturing process. Hence, the properties of SCC mix prepared with natural sand and crushed sand were tested in the present research. SCC is a concrete with high binder content, which poses a

challenge from the point of view ofsustainability. Thus, use of pozzolanic materials like fly ash and its effect on the properties of SCC were also investigated. In the present study, 20% Class C fly ash dosage as a cement replacement material was obtained through experimental trials.

The thermal properties of concrete are influenced by the thermal properties of the matrix and aggregate phase. The coarse and fine aggregates utilised in the current investigation were of granitic origin. When compared to concrete made with aggregates of various minerals, the thermal characteristics of concrete made with granite based aggregates are quite high. The effect of perlite, a well-known insulating substance, as a fine aggregate substitute on the

The characteristics of SCC mix were also investigated. The dosage of 5% perlite as a fine aggregate replacement material was evaluated experimentally in this study.

INTRODUCTION

Background of the Study:

For an emerging economy like India, development of efficient and sustainable transportation infrastructure is the key to achieve development and prosperity. A typical transportation system involves fixed facilities, flow entities andcontrol mechanisms that allow people and freight to move in an efficiently planned geographical space ensuring timely delivery of desired activity (Papacostas, 2006). .

A pavement is an engineered structure whose function is to withstand the load applied from the vehicles without excessive deformation. Pavements can be classified as flexible (bituminous) pavements and rigid (concrete) pavements. The choice of the type of pavement to be constructed depends on type of traffic and availability of funds.

Over a period of time, it has been observed that the concrete pavements have several benefits as compared to bituminous pavements as listed below (Kadiyali, 2013):

1. The service life of concrete pavements is 30 to 40 years as compared to 15 to 20 years for bituminous pavements.
2. Concrete pavements offer maintenance free service, good riding quality and good abrasion resistance.
3. The concrete pavements reduce fuel consumption for commercialvehicles by 14 to 20%.
4. The construction of bituminouspavements requires 25% extra fuel, which is not required in concrete pavement construction.

Pavement life cycle costs mainly depend on the cost of materials used at the time of construction (Delatte, 2008). In comparison to bituminous pavements, the initial cost of construction of concrete pavements is higher, but the subsequent maintenancecosts are lower for concrete pavements. As per a recent report on the status of urban roads in Pune city, (September 2014), the cost of concrete pavement construction is Rs. 2200/m^2. In comparison, the construction of bituminous pavements costs Rs. 1200/m^2 for a service life of 20 years. However, the bituminous pavements need resurfacing at an interval of three years till the end of the life of the pavement. Also, the maintenance works for 2000 km long bituminous pavements in Pune city cost Rs. 400 crores annually. Inlight of the above mentioned points, concrete pavements are a preferred choice of pavement construction.

One of the limiting factors of concrete pavement construction is excessive traffic stoppage time as compared to the bituminous pavement construction. However, the recentadvances in the road construction technologies, like slip form paving, help to reduce the overall construction time of concrete pavement construction. One such enabling technology is the use of Self Compacting Concrete (SCC) for road construction. Since its evolution, SCC found large scale application in various surface transportation elements like highway bridges and tunnel construction. One of the major applications of SCC in the initial years was the Sodra Lanken Project in Sweden (1998-2004). The project utilized 15000 m^3 of SCC (Ouchi et al., 2003). In India, SCC was mainly used by Nuclear Power Corporation of India, for the Tarapur, Kaiga and Rajasthan Atomic Power Plant (RAPP) projects. More recently, SCC with fly ash and micro silica was used in Delhi Metro project (Sood et al., 2009). Due to various merits of SCC as compared to normal concrete, it is a preferred construction material.

Concrete pavements:

Concrete pavements have been used for construction of highways, runways, city roads, parking lots, industrial flooring and similar other infrastructure. A properly designed and constructed concrete pavement, made from durable materials, can serve the intended function for many years with practically insignificant maintenance. The first concrete pavement was constructed in Bellefontaine, Ohio in 1891 (Delatte, 2008). In India, concrete road construction was initiated in the decade of 1920-30. The famous Marine Drive in Mumbai was built in 1939 (Kadiyali, 2013).

LITERATURE REVIEW

The chapter comprises two main sections. In the initial section, review of literature related to concrete pavements, environmental loads on concrete pavements and temperature effects on concrete pavements is presented. Thesecond section discusses the findings from the literature survey related to SCC. The chapter concludes with the key findings from the literature review that helped define the research problem and objectives.

Rigid or Concrete pavements:

A pavement is an engineering system. Its analysis and design includes interaction of naturally available supporting layers, the constructed layers and nature and magnitude of the applied loads (**Ioannides, 2006**). Essentially made of Portland cement concrete. The use of cement concrete as a construction material is on account of economic reasons andease in availability of the concrete ingredients. For the concrete pavement to achieve its functional requirement, following aspects related to design and construction of the pavements are important:

1. Determination of soil properties, design, traffic loads and environmentalparameters
2. Selection of appropriate materials for various pavement layers
3. Structural design to determine adequate thickness of pavement layer
4. Design of drainage system
5. Safety and geometric design.

The concrete pavement is designed for repeated traffic loading that influences the fatigue life of the material. The daily traffic load is a major design factor considered for concrete pavements. The fatigue failure of the concrete pavement occurs on the account of repetitive action of wheel loads, whose magnitude may be less than the failure load of the material (**Fwa, 2006**). Apart from traffic loads, environmental loads are also to be considered in the design of concrete pavements. These loads determine the plan dimensions of the pavement

slab, design of the temperature reinforcement to control crack width & crack spacing and joint & joint reinforcement for effective load transfer between adjacent slab panels. The environmental factors that affect the performance of concrete pavements include temperature, humidity, precipitation and frost/heave (**Mahboub et al. 2003**). The environmental factors induce various types of stresses/strains in the concrete pavements. The stresses developed in the concrete pavements on account of temperature can be of two types, curling stress and thermal expansion stress (**Masad et al. 1996**). The curl induces stress in the slab which is restrained by its self-weight and the slab sub-base or sub-grade interaction. Based on the location of traffic load and time of the day, the magnitude of the curling stress can be high enough to cause failure of the slab. The non-linear temperature distribution causes higher tensile stresses than the linear temperature distribution. This difference was in the range of 3% to 13.5% of the modulus of rupture of concrete (**Masad et al. 1996**).

Temperature stresses can also occur in concrete slabs due to variations in the uniform temperature. The variation in the uniform temperature causes the slab to expand and contract. If this movement of slab is resisted on account of friction between the concrete slab andsub- grade or sub-base, then it induces tensile stresses. These stresses are dependent on the friction factor between slab and the sub-base as well as slab geometry (**Masad et al. 1996**).

Curling Stress in Concrete Pavements: The curling stress results fromtemperature differential between the topand bottom of the concrete slab.Temperature gradients in the concretepavement slabs cause the slabs to curlupwards and downwards on daily basisas well as seasonally. The moisturegradients cause theslab to curlupwards (**Asbahan, 2011; Jeong et al.2005**). The stresses developed inconcrete pavement slab on account oftemperature differential are termed as curling stress. The deflection in slab onaccount of moisture differential istermed as warping (**Jeong et al. 2005**).

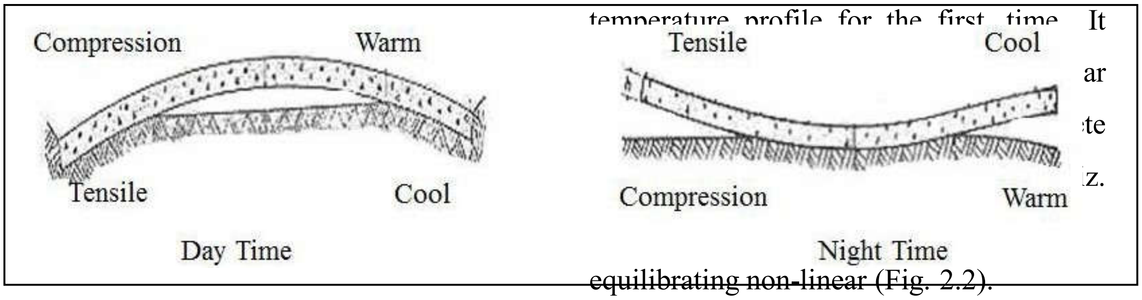


Fig. 2.1: Curling Stress in Rigid Pavements (Fwa, 2006; Huang, 2004)

The temperature effects on concrete pavements were studied since 1920s. Westergaard (1927), proposed the solution for temperature curling. These equations were based on simplified boundary conditions and linear temperature profile in the slab. Bradbury (1938), suggested correction factors, assumed linear temperature differential for curling stress analysis. However, it was Teller and Sutherland (1935) who reported non-linear temperature profiles. According to them, the stresses arising from restrained temperature warping are as important as those produced by the heaviest legal loads. Mirambell (1990), Choubane and Tia (1992, 1995), Lee and Darter (1993), Harik et al (1994), Masad et al (1996), Mohamed and Hansen (1997), Ioannides and Khazanovich (1998) and Ioannides and Salsilli-Murua (1999), have reported the non-linearity of temperature profile across slab thickness (**Hiller et al. 2010**). Thomlinson (1940), addressed the curling stress problem due to non-linear

temperature profile for the first time. It ar te z.

equilibrating non-linear (Fig. 2.2).

Fig. 2.2: Stress components due to non-linear temperature profile (Siddique et al. 2005, Hiller et al. 2010)

The axial component represents the uniform temperature factor that leads to slab expansion or contraction. This movement is resisted by the friction between slab and underlying layer or neighbouring slabs. The resistance offered generates stresses in the pavement slab, whose magnitude is minimum in case of matured slabs. For a freshly laid slab, this factor is not applicable as the tensile stresses developed are countered by the material strength. The second component is the equivalent linear bending stress which gives the same moment as the non-linear temperature profile. The third component is the self-equilibrating internal stress component that is non-linear in nature. The nature of this component can be tensile or compressive across the depth of the slab. However, it does not affect the deflection profile of

the slab. The third component is usually not considered in the slab analysis as it is difficult to determine the magnitude of the temperature related stress (Ioannides et al. 1998).

Choubane and Tia (1992), proved that the assumption of linear temperature profile led to an error of 30% in the computation of warping stresses. **Zhang et al. (2003)** have analyzed the data regarding environmental loads for pavement slabs constructed in Florida and Illinois. They concluded that for the pavement slabs in Florida, the maximum tensile and maximum compressive stresses evaluated in the upper part of the slab assuming linear temperature distribution were 12.9% and 24.3% lower than the corresponding stresses computed using non-linear temperature profile. The maximum tensile and maximum compressive stresses evaluated in the lower part of the slab were 47.2% and 15.9% higher than the corresponding stresses computed using non-linear temperature profile. For the pavements in Illinois, adopting linear temperature profile, the maximum tensile and compressive stresses computed were 55.9% and 29.3% lower than the stresses computed assuming non-linear profile in the upper part of the slab. For the lower part of the slab, the maximum tensile and compressive stresses calculated with linear temperature profile were 74.9% and 100% higher respectively as compared to stresses computed using non-linear temperature profile.

Problem Statement for Research:

The present research aims at:

1. Assessing the performance of crushed sand in SCC as a pavement material.
2. Evaluation of thermal properties (thermal conductivity) of the SCC mix with crushed sand along with various additions (fly ash as a cement replacement material and perlite as a fine aggregate replacement material).
3. Measurement of temperature differential across semi-field scale slabs of SCC mix with crushed sand and SCC mix with various additions (fly ash as a cement replacement material and perlite as a fine aggregate replacement material).
4. Computation of theoretical values of curling stress with Westergaard equations using the temperature differential observations measured experimentally for varying environment conditions.

Objectives of the Research:

Based on the literature review undertaken, following objectives were set to address the research problem:

1. Mix Design of M-40 grade SCC for possible pavement

applications as per standard guidelines (EFNARC, IRC and BIS standards).

2. Measurement of fresh state and hardened state properties of M-40 grade SCC with natural sand (NS) and crushed sand (CS) as well as microstructure examination of a representative specimen.

3. Measurement of fresh state and hardened state properties of M-40 grade SCC with powder additions (fly ash and perlite) along with microstructure analysis of a representative specimen.

4. Measurement of thermal conductivity values, by steady state method, for M-40 grade SCC mix without any powder additions as well as mix with appropriate dosage of the powder combinations finalized experimentally.

5. Measurement of temperature differential and estimation of temperature gradient across 15 cm cube specimens for the M-40 grade SCC mixes finalized.

6. Measurement of temperature differential and estimation of temperature gradient across 30 cm thick slab section for the M-40 grade SCC mixes finalized.

7. Numerical validation of temperature values measured experimentally with the Choubane Tia Model and Fourier Biot Equation.

8. Computation of theoretical values of curling stress, by the Westergaard equations, using the measured temperature differential values and comparing the values for different mixes.

Research Methodology:

The research study was aimed at investigating the effect of environmental loads (temperature) on SCC specimen as a proposed pavement material. Based on the findings of the literaturereview and objectives set for the research study, this section discusses the research methodology adopted.

As per the recommended guidelines in IRC 58: 2011, cement concrete pavements are designed on the basis of flexural strength. Further, it has been mentioned that in no case, the 28 day flexural strength of pavement quality concrete (PQC) should be less than 4.5MPa. The flexural strength of concrete is measured as per IS: 516-1959 or as per the relationship prescribed in IS: 456-2000, By substituting the 28 day flexural strength of 4.5MPa, it is found that the characteristic strength is around 41MPa. Hence, for pavement applications, it can be deduced that the minimum grade of concrete has to be M-40. As per the mix design procedure, prescribed by IS: 10262-2009, the target compressive strength for M-40 grade of concrete is 48.25MPa. Thus, the concrete mix considered for the present study is M-40 grade SCC mix.

The research methodology adopted comprised following steps:

1. Experimental Investigations(Part 1): Determination of propertiesof materials considered for M-40 grade SCC mix. The experimental trials were undertaken as per guidelines prescribed by relevant IS codes. The experimental investigations were supplemented by morphological studies undertaken with the aid of intermediate Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy Analysis (EDXA). The studies undertaken helped in determining the various physical and mechanical properties of materials as well as composition and morphological structure.
2. Experimental Investigations (Part 2): at this stage, mix design process of SCC mix as per EFNARC guidelines was carried out. On finalization of the mix design, the following laboratory trials were undertaken;

a. M-40 grade SCC mix with natural sand (NS) as well as crushed sand (CS).

b. Determination of appropriate dosage of fly ash as a cement replacement material in M-40 grade SCC mix.

c. Determination of appropriate dosage of perlite as a fine aggregate replacement material.

As per EFNARC guidelines (2005), fresh state properties viz. filling ability, passing ability and segregation resistance were verified with the standard testing protocols. The cured samples were subjected to non-destructive evaluation with Schmidt Hammer and Ultrasonic Pulse Velocity equipment. Subsequently, compressive strength of the cube specimen (3 days, 7 days, 28 days and 90 days) and flexural strength of the beam specimen (7 days and 28 days) (as specified by IRC 58:2011 and IS 516:1959) were determined in the laboratory. At the end of the experimental trials, three SCC mixes satisfying the fresh state as well as hardened state properties, were obtained as listed below:

a. SCC mix with appropriate fine aggregate material (Mix A).

b. SCC mix with appropriate fly ash dosage (Mix B).

c. SCC mix with appropriate fly ash and perlite dosage (Mix C).

3. Experimental Investigations (Part 3): at this stage, thermal considerations, exposed to varying open atmospheric conditions, embedded with series of temperature sensors across various depths as well as areal extent, were monitored.

Physical properties of Cement		
Property	**Test Result**	**IS 12269: 1987 requirement**
Fineness (m^2/kg)	290	225
Standard Consistency (%)	29	--
Initial Setting time (minutes)	180	30 (Min.)
Final Setting time (minutes)	250	600 (Max.)
Le-Chatelier Expansion (mm)	0.5	10 (Max.)
Chemical Composition of Cement		
$\frac{CaO - 0.7SO_3}{2.8SiO_3 + 1.2Al_2O_3 + 0.65\ Fe_2O_3}$	0.88	0.8 (Min.) 1.02 (Max.)
Al_2O_3/Fe_2O_3	1.24	0.66 (Min.)
Insoluble residue (% by mass)	1.88	2.00 (Max.)
Magnesia (% by mass)	0.90	6.00 (Max.)
Sulphuric Anhydride (% by mass)	1.80	3.00 (Max.)
Total loss on ignition (% by mass)	1.80	4.00 (Max.)
Total Chlorides (% by mass)	0.008	0.10 (Max.)
Mechanical Property of Cement (Compressive Strength MPa)		
3 days (72 hrs. ± 1 hr.)	38.0	27 (Min.)
7 days (168 hrs. ± 1 hr.)	51.0	37 (Min.)
28 days (672 hrs. ± 1hr.)	71.5	53 (Min.)

conductivity (k) of the mixes listed above was determined by the steady state method (two slab guarded hot plate method as per IS 3346:1980). The temperature differential (ΔT) across cube specimen and slab sections, prepared for various case

4. The ΔT values obtained in the preceding step were compared with the temperature values obtained numerically using Choubane Tia Model and Fourier Biot Equation. The temperature values obtained using Finite Element (FE) software ANSYS

were also compared with the ΔT values measured.

5. The ΔT values measured experimentally were substituted in the Westergaard's equations to determine the theoretical values of the curling stress.

In conclusion, this chapter presents the literature review, findings from the literature review, identification of research objectives and research methodology. The upcoming chapter discusses the details of the experimentation carried out to find the basic material properties of all the materials being used in the present study along with the morphology of these materials.

Component	Percentage
SiO_2	56.54%
Al_2O_3	23.66%
CaO	11.61%
Na_2O	2.18%
K_2O	2.85%
MgO	0.92%
Fe_2O_3	4.65%
Mn_3O_4	0.13%
TiO_2	1.37%
P_2O_5	1.58%
SO_3	0.48%
Fe_2O_3	4.65%
Mn_3O_4	0.13%

EXPERIMENTAL INVESTIGATIONS PROPERTIES AND MORPHOLOGY OF MATERIALS

This chapter presents the first stage of experimental investigations undertaken to determine various properties of the materials used in the present study for the mix design of M-40 grade SCC mix. The experimental tests are also supported by the morphological studies of the materials undertaken with the help of intermediate SEM and EDXA studies.

Cement:

53 grade Ordinary Portland Cement (OPC) (IS 12269: 1987) was used for all the laboratory trials performed in the present study. Various properties of the cement (as per test certificate from cement plant) have been tabulated in Table 3.1.

Table 3.1: Properties of Cement

Fly ash:

Fresh Class C fly ash, obtained directly from a local thermal power plant, was used in the present study. The chemical composition of the fly ash sample (as per the test certificate received from the supplier) is presented in Table 3.2.

Table 3.2: Chemical Composition of Fly ash

As per IS: 3812 (Part I) 2003, fly ash can be classified as a calcareous pulverized fuel ash (reactive CaO not less than 10% by mass) and siliceous pulverized fuel ash (reactive CaO less than 10% by mass). As per ASTM standards, fly ash is classified as Class C fly ash (obtained from combustion of lignite or sub-bituminous coal) and Class F fly ash (obtained from combustion of bituminous coal). Class C fly ash possesses pozzolanic as well as hydraulic properties, while Class F fly ash exhibits pozzolanic properties only. Both the classes of fly ash help in improving the workability of the concrete mix. However, Class C flyash contributes to the gain in later age (beyond 28 days) strength on account of its hydraulic properties (Berry et al. 1980, Price, 1975). The reactivity of fly ash and its contribution in strength development of concrete depends on flyash properties, its chemical composition, particle size along with temperature and curing conditions. Apart from workability improvement and reduction in HRWR dosage, addition of flyash also helps in reducing the heat of hydration and minimizes the adverse effect of alkali aggregate reaction (Malhotra, 2008, *Gandage, 2014*).

Aggregates (Coarse and Fine):

The aggregates were procured from a local quarry. Various tests prescribed in IS 2386 (Part I to IV), 1963, were performed on the sample considered in the study. The coarse as well as fine aggregates were of granite origin. Thin section Petrographic analysis of a coarse aggregate specimen from the given sample was also undertaken in addition to all the other prescribed tests.

Natural sand (NS) and crushed sand (CS) were considered as fine aggregates in the present study. NS was obtained from Manjira river, flowing near Hyderabad. CS was obtained from the local quarry. The quarry dust powder obtained with the crushed sand was analysed for its microstructure using intermediate SEM. The summary of test results is summarized and presented in Table 3.3.

Table 3.3: Properties of Aggregates

Properties of Coarse Aggregates		
Property	**IS Code**	**Test Result**
Flakiness Index (%)	IS 2386 (Part I) – 1963	7.87

Elongation Index (%)	IS 2386 (Part I) – 1963	30.71
Specific Gravity	IS 2386 (Part III) –	2.62
Water Absorption (%)	IS 2386 (Part III) –	0.8
Bulk Density (Loose) kg/m3	IS 2386 (Part III) – 1963	1472.83
Bulk Density (Compacted) kg/m3	IS 2386 (Part III) – 1963	1489.13
Aggregate Impact Value (%)	IS 2386 (Part IV) – 1963	25.02
Aggregate Crushing Value (%)	IS 2386 (Part IV) – 1963	30.24
Los Angeles Abrasion Value (%)	IS 2386 (Part IV) – 1963	19.41

Perlite:

Perlite is an amorphous volcanic glass with pearly vitreous lustre characterized by onion skin structure (Bektas et al. 2005). Perlite is a generic name for naturally occurring siliceous rock. It can be distinguished from other volcanic glasses due to its property of rapid expansion (4 to 20 times its original volume) on heating. It is a light weight material with excellent thermal and acoustic insulation properties. In construction industry, it is commonly used as a light weight aggregate. Perlite possesses pozzolanic reactivity due to its volcanic origin and high

silica and alumina content. Perlite has a low thermal conductivity and is relatively stable over a wide range of temperature (service temperature to 800^{o}C).

In the present study, perlite was trued as a partial replacement for crushed sand. The effect of insulating perlite on the thermal response of M-40 grade SCC with fly ash dosage was investigated. Various properties of perlite (as provided by the supplier) are presented in Table 3.4.

Table 3.4: Properties of Perlite

Physical properties of Perlite	
Property	**Test Result**
Loose weight density (kg/m^3)	120 - 150
Compacted density (kg/m^3)	140 – 180
Moisture content (%)	< 0.5
Thermal conductivity (W/m/^{o}K)	0.044
Colour	Grey
Sieve Analysis of Perlite	
Sieve size	**% Passing**
1.18 mm	2

0.6mm	98
0.3mm	20 – 40
0.15mm	15 – 25
Chemical Composition of	
pH	7
Silicon di oxide (%)	71 – 76
Aluminum oxide (%)	10 – 14
Ferric oxide (Max) (%)	0.4
Ferrous oxide (Max) (%)	0.5
Calcium oxide (%)	0.5
Magnesium oxide (%)	0.2
Sodium oxide (%)	3 – 4

HRWR Admixture or Superplasticizer:

Polycarboxylate Ether (PCE) based high performance superplasticizer (Glenium 233) was used in the present study. This admixture is used for high performance rheodynamic concrete. The traditional chemical admixtures are melamine or naphthalene sulphonate based (Zhang et al. 2010).

These admixtures impart workability (slump) to the concrete mix through the principle of electrostatic repulsion. The polymers of this admixture adsorb on cement particles by wrapping around it at early stage of concrete mixing process. They impart negative charge to the cement particles agglomerates thereby leading to repulsion amongst the flocks. The negative charges disperse the cement particles by electrical repulsion. This admixture improves workability of concrete and reduces the water requirement upto 20%.

Property	**Test Result**
Colour	Light brown
Relative density	1.08 ± 0.01 at 25 °C
pH	≥ 6
Chloride ion content	< 0.2%

The PCE superplasticizer consists of long side chains of carboxylic ether.

The polymer adsorbs on the cement particles and initiates the electrostatic repulsion in the early stage of mixing. With the progress in the mixing the long side chains stabilize the cement particles ability to disperse and separate. This is steric hindrance effect which provides a physical barrier between cement grains. This renders the concrete flowable whose workability is measured as slump flow. Use of PCE superplasticizers can lead to water reduction upto 40%.

The addition of superplasticizers retards the cement setting time. It is on account of residual sugars and salts present in the admixture. The retardation occurs on account of adsorption, complexation (formation of flocks), precipitation and nucleation (Zhang et al. 2010).

Microstructure Studies:

Microstructure is defined as the type, amount, shape, size and distribution of various phases present in a solid (Mehta et al. 2006). Concrete is a composite material. The properties of concrete are influenced by the interaction between individual constituents and their final arrangement in the hardened mix. Concrete, is primarily a two phase material, comprising aggregate phase (coarse aggregates) and the mortar or matrix phase (cement, fine aggregates, and water) (Gandage et al. 2013a).

In the present study, the microstructure of powder ingredients of SCC mix (cement, fly ash, perlite and pan dust) were studied using intermediate SEM and energy dispersive X-ray analysis (EDXA). The microstructure properties of the coarse aggregate particle was observed using Thin Section Petrographic Analysis. The following sections describe SEM and EDXA analysis of powder constituents of the concrete mix, along with the petrographic analysis of coarse aggregate particles.

3.6.1 Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Analysis (EDXA):

A microscope is a device that magnifies the details of an object finer than what can be observed with naked eyes. Optical microscope was used since 16th century (Ramachandran et al. 2001). The development of scanning electron microscopy was based on the discoveries during 1920s regarding wave nature of particle stream by L. de Broglie and focusing of electrons in magnetic field by H. Busch. Due to shorter wavelength of the incident electron beam, the electron microscope is able to produce distinctly high resolution images compared to optical microscope. When a beam of primary electrons strike a bulk solid, the electrons are either reflected (scattered) or absorbed producing various signals. The striking of the electron beam on a solid specimen leads to production of many responses like secondary electrons, back scattered electrons (BSE), X-rays, Auger electrons and other responses (Ramachandran et al. 2001). The most frequent mode of SEM image analysis is capture of secondary electrons or BSE, while the microanalytical technique (elemental composition studies) is undertaken using EDXA or wavelength dispersive analysis.

Microstructure Studies of SCC:

The micro-level material arrangement plays an important role in the concrete behaviour under loading. The study of the micro level layout of concrete ingredients is possible with the microstructure studies. The microstructure of a material helps to identify general (volume and shape) as well as, specific (voids, cracks, evidence of degradation) details of the material (Poole et al. 1998). Concrete is a two phase material, comprising aggregate phase (coarse aggregates) and the mortar or matrix phase (cement, fine aggregates and water) (Gandage et al. 2013a). The mechanical and durability performance of the hardened concrete mix depends on the arrangement and interaction between the two phases. The concrete microstructure studies can be undertaken at different magnification levels as tabulated below,

From the above test results, following points were inferred,

A. Density:

1. SCC mixes with CS were denser than the NS mixes. The density of the demoulded cube specimen for the SCC mix with CS was 0.72% more than the density of the demoulded cube specimen for the SCC mix with NS. The density of the CS mixes cured at 3, 7, 28 and 90 days was 0.8%, 1.08%, 1.98%, and 1.67% more than the NS mixes cured at the same ages.

2. With respect to the density of the demoulded cube specimen for NS mix, the rate of increase in density for the NS mix cube specimen at 3 days, 7 days, 28 days and 90 days was 0.92%, 2.37%, 3.33% and 4.35% respectively. Similarly, for the CS mix cube specimen, the density increase at 3, 7, 28 and 90 days was 1%, 2.72%, 4.63% and 5.32% with respect to the density of the demoulded CS cube specimen. Thus, the rate of increase in the cube density for CS mixes is relatively more than the rate of increase in the cube density for NS mixes.

3. The variation in the densities of the NS and CS mixes is attributed to the particle shape, size and packing of the fine materials in the matrix phase of the concrete mixes. For the given mix design, the NS mixes exhibited lower densities due to large sized, round shaped and smooth textured particles of the fine aggregates. This reduced the density of the matrix phase and overall density of the concrete. On the contrary, in the CS mixes, the fine aggregate particles were uniform sized, angular and rough textured leading to efficient particle

packing arrangement in the matrix phase. This resulted in overall denser matrix leading to higher densities for the cube specimen.

4. Apart from the particle shape and size, the packing of the particles in the matrix phase affects its overall service life performance also. Fig. 4.10 presents the cross section of tested beam specimen of NS and CS mix. The NS mix beam specimen shows voids in the cross section, while the CS mix beam showed a denser matrix with negligible voids.

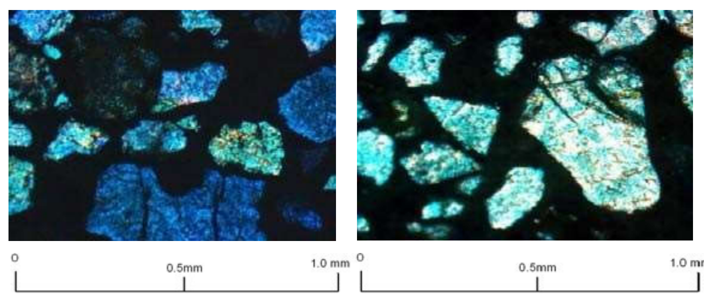
Fig. 4.10: Cross section of beam specimens of SCC mix with NS and CS

The representative specimens were subjected to microstructure examination as per the procedure discussed in Section 4.4.1 and 4.4.2.

Fig. 4.11 (a) & 4.11 (b) presents the petrographic image of NS and CS mixes respectively.

Fig. 4.11 (a): Thin Section Petrographic image of SCC mix with NS

From the thin section petrographic image of a representative cube specimen of SCC mix with NS and CS, it is observed that the matrix phase of NS mixes has air voids (Fig. 4.11 a). The voids are also seen at the interface between the aggregate particle and matrix phase.



Specimen with denser matrix and angular shaped fine aggregate particles Petrographic image of SCC mix with CS.

Fig. 4.11 (b): Thin Section Petrographic image of SCC mix with CS

In case of the CS mixes, efficient particle packing arrangement in the matrix is observed. This is observed by the dark coloured matrix without any air voids (Fig. 4.11b). Thus the density of the CS mixes is more than the NS mixes.

B. Schmidt Hammer test:

For the Schmidt hammer test, the compressive strength values obtained (by correlating the rebound index and compressive strength values from the calibration chart supplied by the equipment supplier) for CS mixes was 8.38%, 16%, 17.82% and 29.69% more than the NS mixes at 3, 7, 28 and 90 days respectively. The rebound hammer or Schmidt hammer test results indicated that the CS mixes had a hard surface as compared to the NS mixes.

C. Ultrasonic Pulse Velocity:

The test results for the ultrasonic pulse velocity tests indicated that the test results were relatively comparable. As per IS 13311 (Part 1) 1992, both the concrete mixes (NS as well as CS) can be termed as good quality.

D. Cube Compressive Strength:

1. The compressive strength values recorded for the CS mix was more than the NS mix.

2. The compressive strength values for the SCC mix with CS was 24.41%, 18.09%, 23.02% and 22.01% more than the compressive strength values for NS mixes at 3, 7, 28 and 90 days. This was attributed to the better particle packing arrangement observed in CS mixes (Fig. 4.11a & 4.11b).

3. With respect to the 3 day compressive strength, the rate of increase in the compressive strength at 7, 28 and 90 days for the SCC mix with NS was 8.95%, 24.92% and 41.66% respectively. Similarly for the CS mixes, the rate of strength gain for CS mixes at 7, 28 and 90 days, was 9.32%, 26.34% and 44.49% respectively.

E. Beam Flexural Strength:

The flexural strength performance of the SCC mix with CS was better than the NS mix. The 7 and 28 day flexural strengths for CS mixes were 24.42% and 11.21% more than the NS mixes.

From the above observations it was inferred that the compressive strengths of the SCC mix with CS was h/igher than the compressive strength of the SCC mix with NS. This was supported by the microstructure images obtained from the thin section petrographic analysis. Thus, it was observed that though SCC mix with NS satisfied the flexural strength criteria for pavement application, it did not conform to the compressive strength requirement prescribed. Hence, from the above experiment trial, it was concluded that the SCC mix with CS satisfied the flexural strength as well as compressive strength requirement for pavement application and hence, for the subsequent experimental studies, M-40 grade SCC mix with CS was adopted. This mix was termed as Mix A.

Laboratory Trial for determination of appropriate dosage of fly ash as a cement replacement material:

The next stage of laboratory trials was aimed at determination of appropriate dosage of fly ash as a cement replacement material. M-40 grade SCC mix with CS was only considered in this stage of experimentation. SCC mix with NS was not considered as per the findings from the laboratory studies discussed in the preceding section.

The mix design considered for fly ash dosage trials is summarized in Table 5.7. In the present study, Class C fly ash has been adopted as a replacement for cement. A total of 9 mixes were tested in which the fly ash dosages were varied from 0% to 40% cement replacement, at an increment of 5% for each batch. Fly ash addition to SCC mixes reduces the superplasticizer dosage to achieve same workability. This is observed up to 40% replacement level. Beyond 40%, the reduction in superplasticizer dosage is insignificant (Liu, 2010). In the present study, the upper limit of fly ash as a cement replacement additive has been limited to 40%. At this stage, Mix 1 was considered as the control mix and all the properties of the remaining mixes were compared with respect to the control mix.

COMPUTATION OF CURLING STRESS

The chapter presents the computations of the theoretical value of the curling stress, in each of the concrete mix for the specific case study, using Westergaard's equations along with Bradbury's coefficients. The temperature gradients measured experimentally for each specific case study for the cube specimen and slab section were used in the curling stress computation.

Curling Stress Computation:

The daily variation in the concrete slab temperature develops temperature stresses in the pavement section. The temperature variation develops two types of stresses in the concrete pavement;

1. Curling stress due to temperature differential between the top and the bottom section of the pavement slab due to daily variation in the temperature at a particular location.
2. Frictional stresses due to overall increase or decrease in temperature of the pavement slab due to seasonal variation in the temperature at a particular location.

The frictional stresses between pavement slab and underlying DLC layer are not considered in the present study.

The magnitude of curling stresses due to temperature differential was first proposed by Westergaard (1927) assuming linear temperature differential. Bradbury (1938) corrected the Westergaard solution for curling stress by introducing the Bradbury coefficients.

Table 6.1: Material properties and slab geometry considered for computation of theoretical curling stresses.

Material property	Mix A	Mix B	Mix C
Modulus of elasticity of concrete (kg/cm^2)	3.14 x 10^5	2.70 x 10^5	1.96 x 10^5
Modulus of subgrade reaction (kg/cm^3)	6.9 (for a soaked CBR of 20%)		
Poisson's ratio	0.15		
Plan dimensions of the slab	5.5 m x 3.5 m		
Slab thickness	15cm and 30cm		

The modulus of elasticity considered in the computation of the curling stress was determined mathematically by using the relation between ultrasonic pulse velocity and density of the concrete specimen (Lamond et al. 2006). The equation is as below,

$$v^2\rho(1+\mu)(1-2\mu) \quad (6.5)$$

where;

E_d: dynamic modulus of elasticity (kg/cm^2)

ρ: density of concrete (kg/m^3)

μ: dynamic Poisson's ratio (0.22) v: ultrasonic pulse velocity (m/s)

As per Neville (2010), the static elastic modulus is determined by the following empirical relation

$$E = 0.83E$$

The values of modulus of elasticity tabulated above are calculated using above formulae. As per Lamond et al. (2006), the Poisson's ratio for all types of concrete can be considered between 0.15 to 0.20. A value of 0.15 was adopted in the present study.

Table 6.2 (a) and 6.2 (b) presents the curling stress values (theoretical) computed using Westergaard equations along with Bradbury's coefficients for slab thickness of 15 cm and 30 cm.

CONCLUSIONS AND FUTURE SCOPE

Summary of findings from the present study:

Based on the experimental investigations and results obtained following conclusions were drawn;

A. SCC mixes with NS and CS:

1. The fresh state properties of SCC mixes with NS are a shade better than the fresh state properties of SCC mixes with CS. This is attributed to the rounded shape and smooth texture of NS fine particles as compared to angular shaped and rough textured CS particles.
2. SCC mixes with crushed sand (CS) have resulted in better mechanical properties as compared to the SCC mixes with natural sand (NS). This is on account of excellent particle packing and arrangement in the matrix phase as compared to the SCC mixes with NS. This is evident from high values of the density of the SCC mixes with CS at all ages. It was also reflected from the higher values of ultrasonic pulse velocities observed in the cube specimens of SCC mixes with CS.
3. The use of CS as a fine aggregate material is crucial from environmental sustainability point of view. Due to harmful effects of NS mining on riverine ecology, legislations are formulated to ban the use of NS for concrete manufacture. Under such circumstances, use of CS is a viable alternative as it lead to better mechanical and durability properties as well as ensures conservation of valuable natural resource.
4. One potential drawback of use of CS for SCC mix preparation is higher dosage of superplasticiser required to achieve desired fresh state properties which increases the risk of segregation and bleeding. However, it can be offset by appropriate powder additions.
5. The microstructure studies provide an important avenue to validate the particular performance or behaviour of the material based on the relative arrangement of ingredients in the hardened mix.

B. Fly ash addition to SCC mixes:

1. SCC mix design can be powder based or admixture based or a combination of both. Use of pozzolanic or inert additions as cement replacement materials helps to improve fresh state properties of SCC mix at lower HRWR dosage and does not require VMAs to stabilize the fresh mix. In the present study, powder based mix design was adopted with use of Class C fly ash as a cement replacement material.

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