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Structural Analysis of Flexible Concrete Pavement - An Innovative Pavement Technique

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Abstract— **This work presents structural analysis of Plastic Cell filled Concrete Block Pavement (PCCBP) called flexible concrete pavement using BACKGA (a linear elastic theory based backcalculation code). Layer moduli of different layers of PCCBP have been calculated from the surface deflection data obtained through Falling Weight Deflectometer (FWD). The layer moduli obtain as outputs from BACKGA is given as inputs to both ABAQUS and KENLAYER and the resulted deflections are compared with that of the experimental values. It has been observed that peak deflections were predicted well by KENLAYER, in contrast to FE (ABAQUS) results which under predicts by ~ 38%, 36%, 33%, 30% and 28% for 50 mm, 80 mm, 100 mm, 120 mm and 150 mm PCCBP thicknesses respectively. 50 mm thick PCCBP layer result in sufficiently high layer modulus (>1900 MPa), 90% increase in layer modulus (approximately linear) was observed for 200% increase in thickness.**

Index Terms— **Stone dust, low volume roads; Plastic Cell filled Concrete Block Pavement (PCCBP); Flexible concrete pavement; Falling Weight Deflectometer (FWD); BACKGA, KENLAYER, ABAQUS**

I. INTRODUCTION

Designing sustainable rural roads with reasonable riding quality and low life cycle cost has always been one of the major challenges for pavement engineers and researchers. The research effort in this direction has become far-reaching pertinent in India as the share of low volume (< one million Equivalent Single Axle Loads (ESAL) in a life cycle as per [1, 6] rural road is about 80% of the total road length [26]. Whilst conventional flexible pavement with a thin cover of premix bituminous carpet is normally adopted for rural roads, frequent maintenance are required (to maintain both functional and structural efficiencies) due to damages caused by poor drainage conditions, overloaded vehicular traffic, iron wheeled bullock carts etc.As a result such pavement incurs huge maintenance cost. To offset such expensive maintenance cost, concrete pavements are increasingly used in rural road connectivity in India because of their durability. However it not only involves high initial cost but can also fail due to various reasons like day and night variations in warping stresses, seasonal changes in the modulus of sub-grade reaction etc. [29]. Although pre-cast concrete block pavement [8, 9, 27] provides more flexible response (depending upon the dilantancy of the jointing sand) as compared to the normal concrete pavement mentioned above, there is a tendency for block movements under braking or accelerating force of the vehicular traffic and the interlocking caused by the jointing sand needs frequent maintenance which may not be practical for rural roads.

As an alternative, for better structural performance and low maintenance, a new pavement technology called Plastic Cell Filled Concrete Block Pavement (PCCBP) was developed in South Africa [30, 31]. In PCCBP, diamond shaped heat welded plastic cells are used to encase concrete blocks. It may be noted that this type of plastic cell formwork has been successfully used for canal lining, reinforced earth treatment etc., [30]. The cells are tensioned and spread across the foundation layer and concrete is filled and compacted into the cells. Upon compaction the cell walls get deformed resulting in interlocking of adjacent individual concrete blocks. Flexibility is induced into cement bound (rigid) surface and [30] termed these pavements as Flexible Concrete Pavements. The PCCBP has good load spreading capacity with negligible maintenance during its life. Although construction of PCCBP can be mechanized, significant amount of hand labour may be utilized making it labour intensive with possibilities of generating employment opportunities for the rural inhabitants.

In India, limited studies on this PCCBP technology have been reported by [20, 23, 24, 25, 27] on the cost effectiveness and feasibility for rural roads. Albeit their studies were confined to selected (~100 mm) PCCBP thicknesses, it was observed that PCCBP can provide sufficiently high elastic modulus with low initial and maintenance cost. Recently authors have attempted to study the effect of PCCBP thickness on the structural performance of pavement considering live traffic conditions, to assess their suitability for actual field conditions with a possibility of developing design standards, at least in the Indian rural road context [28]. He conducted a systematic full scale experimental study on the structural performance of PCCBP for various cell thicknesses *viz.*, 50 mm, 80 mm, 100 mm, 120 mm and 150 mm, of PCCBP over 100 mm thick water bound macadam (WBM) sub-base layer by using waste stone dust (byproduct of aggregates crushing) in place of the traditional river sand to economize the cost of construction. In the present paper, structural performance of PCCBP was evaluated by computing elastic layer moduli using a linear elastic layer theory based moduli backcalculation computer code BACKGA [22] from the surface deflection data obtained through Falling Weight Deflectometer (FWD). The layer elastic moduli obtained through BACKGA program were used as inputs to both KENLAYER and ABAQUS for comparing the deflection outputs with that of the experimental deflection data obtain through FWD. Subsequent sections will highlight the construction procedure adopted followed by finite element modelling via ABAQUS.

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II. MATERIALS USED FOR THE CCONSTRUCTION OF PCCBP

A. Low Density Polyethylene Plastic (LDPE) Cell

The plastic cell formwork used in the present study is made of Low Density Polyethylene (LDPE) sheet of thickness 0.49 mm. Flexible translucent water delivery LDPE pipe having diameter of ~101.5 mm was used for preparation of cell formwork. The pipes were cut into required strips (50 mm, 80 mm, 100 mm, 120 mm and 150 mm) and heat bonded using paddle sealing machine which on stretching forms diamond shaped pockets of size 150 mm x 150 mm.

B. Cement

Fly ash based portland pozzolana cement (PPC) conforming to IS 1489 (1991), was used for casting concrete blocks. The cement (TOPCEM cement) for the whole work was procured in a single consignment and stored properly. The standard consistency and specific gravity of the PPC cement was found to be 31% and 3.15. The initial and the final setting time were found out to be 102 and 372 minutes respectively.

C. Stone dust

Stone dust collected from a stone crusher factory located nearby IIT Guwahati, Assam was used as fine aggregates for casting concrete blocks. The particle size distribution of stone dust obtained from the sieve analysis is shown in Table I, and it can be seen that the gradation conforms best to Zone II of IS 383 (1970). Water absorption and specific gravity of the stone dust as per IS 2386 (1963a) was obtained to be 0.73% and 2.63 respectively. Fineness modulus of the stone dust was found to be 2.3 which lies within the specified limit of 2.10-3.37 for Zone II of IS 383 (1970).

TABLE I. PARTICLE SIZE DISTRIBUTION OF STONE DUST

Sieve size (mm)	**Percentage passing by weight (%)**	**Specified limit (passing %) for Zone II**
10	100	100
4.75	98.4	90-100
2.36	91.5	75-100
1.18	70.3	55-90
0.6	52.3	35-59
0.3	35.7	Aug-30
0.15	21.4	0-10

D. Coarse Aggregate

The crusher run coarse aggregates were obtained from the same stone crusher factory from where the stone dust was collected. These coarse aggregates were crushed from hilly stone boulders brought from Dewdwar quarry, Baicharali, Guwahati. The values of Los-Angles abrasion value, aggregate flakiness index, specific gravity, water absorption as per IS 2386 (1963b) were obtained as 27%, 9%, 2.7, 0.3% respectively. Single size stone aggregates of 22.4 mm (i.e. wholly passing 26.5 mm sieve and wholly retained on 13.2 mm sieve) as per specification of MORTH (2001) were selected for casting the concrete in the present study.

E. Soil

The soil used for backfilling the sub-grade for the test pavement was brought in from a nearby hill slope excavation. The particle size distribution of sub-grade soil 1based on wet sieve analysis (IS 2720, 1985a) is shown in Table II.

TABLE II. GRAIN SIZE DISTRIBUTION OF SUB-GRADE SOIL

Sieve size (mm)	**Percentage passing (%) by weight**
4.75	98.1
2.8	97.3
2.36	94.8
2.0	94.5
1.0	85.2
0.6	76.6
0.425	69.6
0.3	65.7
0.15	49.7
0.075	41.6

The specific gravity was obtained as per IS 2720 (1980) and found to be ~2.63. From Table II it can be seen that percentage of fine fraction passing 75 micron sieve is ~41%, and the soil can be classified as coarse grain soil as per ASTM 2487 (2006). The liquid limit was found to be 35% with no significant plastic limit (IS 2720, 1985b). The laboratory soaked and un-soaked California Bearing Ratio (CBR) values of the soil used for backfilled were found out to be 5% and 7% respectively (IS 2720, 1987).

III. LABORATORY INVESTIGATIONS

Laboratory investigations were carried out to determine an appropriate construction technique which would be labour intensive, cost effective and easy execution by semi-skill villagers so as to generate employment for the economically challenged rural inhabitants. Two different types of construction techniques were tested [32]:

- Premix technique: It is a type of construction where the plastic cell formwork are spread and tensioned over a prepared foundation layer with concrete placed and compacted into the cells.
- Grouting technique: Here, plastic cell formworks are spread and tensioned over the foundation layer as done in the previous case and cells are filled with coarse aggregates and mortar is vibrated into the voids between coarse aggregates (e.g., using a plate vibrator).

In order to check the suitability of the above mentioned techniques, laboratory concrete cube compressive strength tests for both premix and grouting techniques were carried out using nominal single size 22.4 mm coarse aggregates and different cement : stone dust (c : sd) mix proportions. For a preliminary study on grouting technique, coarse aggregates were first filled into the cube mould, then cement mortar with three different water cement ratios (w/c) of 0.4, 0.5, and 0.6 were placed and vibrated into the voids between coarse aggregates using table vibrator. It has been observed that for the grouting technique, mortar with w/c ratio = 0.4 was too dry to grout into the voids in between the coarse aggregates whilst a w/c ratio of 0.6 produced a high workability. An intermediate w/c ratio of 0.5 exhibited moderate workability resulting in better compaction of the concrete. To check the feasibility of grouting technique in the field, a small trial test pit of size 2 m x 2 m was prepared and plastic cells of each pocket size 150 mm x 150 mm x 120 mm was laid and stretched on a prepared 100 mm thick WBM sub-base course. Crushed nominal single size stone aggregates 22.4 mm were filled into the pockets of plastic cells and mortar having c:sd ratio = 1:1.25 was vibrated using a plate vibrator into the voids between the coarse aggregates. It has been seen that core samples taken out after curing the concrete for 7 days showed incomplete penetration of mortar for ~30% of thickness. Although it might have been possible to get better compaction using needle vibrator, it is expected that its implementation in the field with large number of plastic cells may be prohibitive. Thus for the present field study, premix technique has been adopted with a moderate w/c ratio of 0.50. The variation of 7 days average cube compressive strength of concrete (three samples were considered for each c:sd ratio) with c:sd ratios was studied and it has been found that c:sd ratio = 1:1.25 gives the highest compressive strength (~ 18 MPa). As this 7-days cube strength is more than 15 MPa which is required for opening to the heavy traffic [30], c/sd ratio of 1:1.25 is adopted for casting PCCBP in the field.

IV. FIELD INVESTIGATIONS

A. Test section

A full scale field study on the structural assessment of different thicknesses of PCCBP (50 mm, 80 mm, 100 mm, 120 mm and 150 mm) over 100 mm WBM sub-base course was carried out at IIT Guwahati main approach road from the National Highway, NH-31. A section of the existing bituminous pavement, measuring 15 m in length and 7 m in width was selected for construction of five different thicknesses of PCCBP test sections. A schematic plan and sectional view of the test sections is shown in Fig. 1.

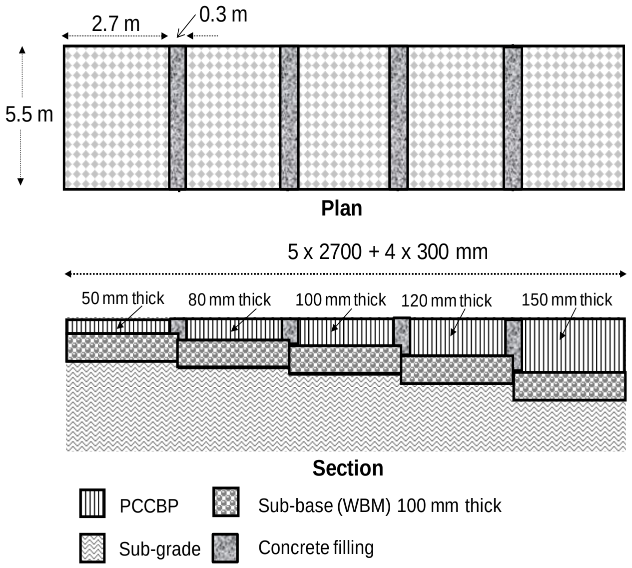

Fig. 1. Schematic plan and sectional view of the test section

Based on the preliminary survey it has been observed that the traffic along the road stretch considered consists mainly of heavy trucks carrying construction materials, buses and light moving vehicles like cars etc. The road can be considered as a low volume road as the average daily traffic was estimated to be about 250-300 vehicles/day.

B. Excavation of the existing pavement

Taking due care the problems of rain during construction work and the effect of the rain water on the strength of the sub-grade layer, the excavation of the existing bituminous pavement for the construction of PCCBP test section was done using an excavator. The upper layers of the existing pavement were removed and a trench measuring 15 m in length and 7 m in width and approximately 450 mm depth was excavated till sub-grade soil layer. It was observed that the existing pavement consists of 20 mm premix carpet, 75 mm thick bituminous macadam over 350 mm thick sub-base course (200 mm thick WBM course over 150 mm granular sub-base). The dry density and field moisture content of the sub-grade soil estimated by core cutter method as per IS 2720 (1975) was found to be 1730 kg/m^3 and 13.80% respectively. The laboratory soaked CBR of the soil sample collected from the field was found to be 6% as per IS 2720 (1987).

C. Preparation of the sub-grade soil

The trench was backfilled with selected soil collected from nearby hill slope. After excavation, the surface of the existing ground was level and the backfilled soil was spread uniformly. Compaction was done at the optimum moisture content (~12%) using a 100 KN three wheeled roller in three layers of 100 mm each. After compaction the surface was leveled manually to bring the surface to the required profile for each thickness). The field density and the moisture content of the compacted sub-grade soil was determined by core cutter method (IS 2720, 1975) and were found to be 1880 Kg/m^3 and 12.04% respectively. The percentage field compaction was found to be ~98% of the standard laboratory compaction value.

D. Water Bound Macadam (WBM) Course

In the present study 100 mm thick WBM sub-base course was provided above the prepared sub-grade soil layer. Crushed stone aggregates and screenings conforming to Grading 1 and Grading A respectively as prescribed by MORTH (2001) were used for WBM course. The particle size distribution and properties of water bound macadam sub-base course are given in Table III.

TABLE III. PARTICLE SIZE DISTRIBUTION AND PROPERTIES OF WBM SUB-BASE COURSE

Particle size distribution			**Aggregate properties**			
Sieve size (mm)	**Percent age passing (%)**	**Specified limit for Grading I (% passing)**	**SG**	**WA (%)**	**CE & FI (%)**	**LAAV (%)**
125	100	100	2.716	0.23	32.8	14.1
90	91.7	90-100				
63	44.93	25-60				
45	7.6	0-15				
22.4	1.71	0-5				

Note: SG = Specific Gravity; WA = Water Absorption; CE & FI = Combined Elongation and Flakiness Index; LAAV = Los Angeles Abrasion Value.

The materials were manually placed and spread uniformly over the prepared sub-grade soil. Construction and compaction were done as per MORTH (2001). Rolling and compaction of WBM were continued until the slurry (after filling the voids between aggregates) formed a wave ahead of the moving roller.

E. Laying and concreting of the plastic cells

After preparation of the WBM course, plastic cell formwork 5.5 m x 2.7 m were laid (maintaining the cross fall (~ 2.5%) and longitudinal slopes (~ 0.05%) such that the new and the old pavement surfaces are in the same level) on the prepared WBM surface layouts leaving a gap of 750 mm at the edges and 300 mm (to provide space for tensioning plastic cells) between adjacent sections of PCCBP (Fig. 2a and 2b).

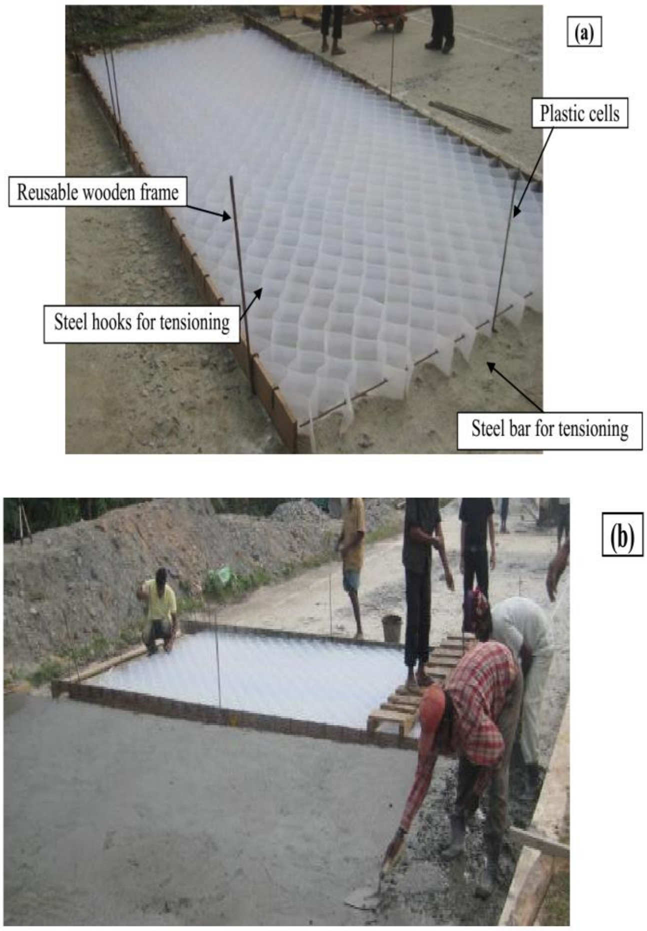

Fig. 2. a) Casting of the PCCBP and b) Laying of plastic cell formwork for next PCCBP section.

A reusable wooden frame with hook arrangements was used for tensioning the plastic cell formwork. It also acts as side restrain for casting concrete. The plastic cell formwork, after tensioning forms diamond shaped (150 mm X 150 mm X150 mm) pocket size.

From the laboratory test results, premix concrete with cement : stonedust : coarse aggregates ratio of ~1:1.25:2.0 by volume (28-days cube compressive strength = ~32 MPa) was selected for casting PCCBP. Mixing of the concrete was done by a diesel operated mixer machine and amount of water was maintained according to w/c ratio of 0.5. The test section was constructed sequentially leaving a gap of 300 mm in between two adjacent sections as shown in Fig. 2b. After casting the adjacent section, the gap was filled with concrete and leveled. The remaining gaps between the edges of the road were also filled with concrete and level. Compaction was done using a plate vibrator and a locally fabricated wooden beam straight edge rammer. The finished surface of the test pavement was leveled in accordance with the existing bituminous pavement. Casting of the whole test section was completed in a single day and the concrete was allowed to set overnight. Water curing was done for 21 days, however Roy *et. al.*, [29] reported 14 days curing using wet jute gunny bags to be sufficient for quick opening of the traffic. After removing water the pavement was clean properly and marking was done for different PCCBP sections (Fig. 3) and initial surface deflection data of the test sections (using FWD) were collected before opening to regular traffic.

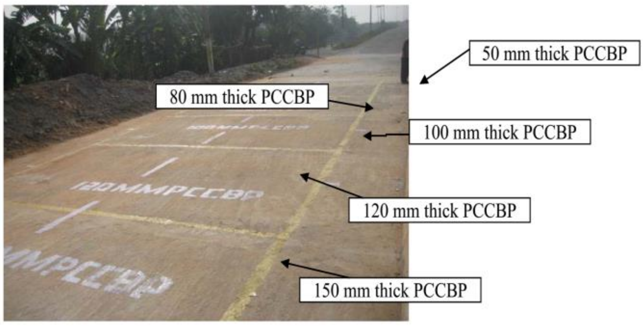

Fig. 3. Completed PCCBP test road with markings for different test sections

Core samples collected from the test sections showed that the compaction is proper and the effective cell height was reduced and concrete layer of 6% to 10% (i.e. 10 mm – 15 mm for 150 mm thick PCCBP) of the cell height can be seen on top of the cell formwork. The PCCBP test section was opened to normal traffic after 25 days from the day of casting.

V. EVALUATION OF BACK-CALCULATED MODULI OF PCCBP

A custom fabricated Falling Weight Deflectometer (FWD) (a non-destructive test (NDT) equipment which simulates the short duration loading of the fast moving wheel) was used to record the surface deflection data of the test pavement. BACKGA [22], a Genetic Algorithm (GA) based back calculation software was used to calculate the pavement layer elastic moduli from the recorded surface deflection data.

A. Falling Weight Deflectometer

Falling Weight Deflectometer (FWD) produces an impulse load by dropping a free fall mass over a loading plate with spring system which transmits the load on to the pavement. The instantaneous surface deflection of the pavement is measured at various radial distances from the center of the load by using a number of geophones. The FWD used in the present study is mounted on a trailer for better mobility. The power supply for the equipment is through a DC generator mounted along with the equipment. Provisions are also made for direct AC power supply so that the equipment can also be operated electrically depending on the availability of power supply on the site. The equipment consists of a loading platform with load plate (300 mm in diameter) for dropping load and a geophone beam with geophones to measure the pavement surface deflection. The load platform along with the geophone beam can be lowered and kept in contact with the pavement using two hydraulic cylinders. Electro Permanent Magnet operated with an input current of 0.6 Ampere and maximum lifting capacity of 500 kg is provided with the equipment for lifting and dropping a falling mass. The height of fall can be adjusted and impulse load in the range of 20 kN to 100 kN can be applied on the pavement. The load applied is measured with a load cell provided under the load plate and the pavement surface deflections are measured with the geophones. Analog Input Modules (AIM) was used to acquire data from the load cell and geophones [16]. The AIM, data acquisition and voltage output from geophones are controlled and accessed through LabVIEW software [16]**.** The load cell and geophone readings are calibrated and processed to determine the magnitude of load in kilo-Newton and deflection in millimeter. For evaluation of

PCCBP test section, the FWD was positioned in the interior of the test pavement in such a way that the load plate along with geophone beam aligns along the longitudinal direction of the road . Care was taken to ensure that each geophone knobs touches the pavement surface properly. For each test section the load was dropped 3-4 times and surface deflection data were collected on either side of the load plate at radial distances of -500 mm, -300 mm, 0 mm, 300 mm, 600 mm and 900 mm. The deflections were normalized to a load of 40 KN [6] and average of three deflection readings were taken for structural evaluation of the pavement.

B. Backcalculation using BACKGA

Backcalculation is an analytical procedure in which the surface deflection data collected during a FWD test are used to predict the elastic moduli of different layers of pavement. The back calculation procedure involves theoretical calculations of the deflections produced under a known applied load using an assumed set of layer moduli. The theoretical deflections are then compared with those measured during the field test. In case of differences between the theoretical and the measured deflection, the assumed pavement layer moduli are adjusted and the process is repeated until the differences between the theoretical and measured values fall within acceptable limits. In this work, GA based BACKGA program developed by Ready *et.al.* [22] was used for backcalculating the layer moduli of the PCCBP. In BACKGA a systematic search of the solution space defined by the ranges of moduli selected by the user is conducted. The objective function of the BACKGA was to minimize the differences between the measured and the computed surface deflection of the pavement. Layer thickness, surface deflection, locations at which the deflections were measured, loading details and Poisson's ratios of the pavement were used as main inputs to the BACKGA program. The various parameters input to BACKGA followed those considered by Rakesh *et. al.* [21], Sahoo *et. al.*, [27], Roy *et. al.* [23], [24], Ryntathiang *et al.*, [25], Reddy *et. al.* [22] *viz.*, 1) Size of population = 60, 2) Number of generations = 60, 3) Cross over probability = 0.74, and 4) Mutation probability = 0.10. An optimal set of layer moduli is selected (defining upper and lower bounds) as input to the program in such a way that the measured deflections match closely with those computed from the selected layer moduli. In the present study the range of moduli and the material properties considered for the BACKGA analysis are shown in Table IV. The upper and lower limits of layer moduli are chosen based on heuristic approach considering possible practical values. For each set of layer moduli selected within the search space, surface deflection at radial distances of 0, 300, 600 and 900 mm (measured from the center of the load plate) are computed using linear elastic layer theory. The computed deflections are compared with the measured deflections and the fitness of the moduli set under given range is evaluated [21].

TABLE IV. PAVEMENT (NEW CONSTRUCTION) MATERIAL PROPERTIES

Pavement layer (mm)		**Young's modulus (MPa)**		**Poisson's ratio**
		Lower limit	**Upper limit**	
PCCBP	50	200	2000	0.35
	80	200	2600	
	100	200	3000	
	120	200	3500	
	150	200	3800	
Sub-base		20	300	0.40
Sub-grade		10	100	0.40

The elastic layer moduli computed through BACKGA program using the surface deflection data obtained by FWD are used for structural evaluation of pavement.

VI. STRUCTURAL PERFORMANCE PF PCCBP USING BACKGA

The structural performance of the PCCBP has been evaluated by monitoring both the surface deflections and layer elastic moduli.

A. Surface deflections

A comparison of surface deflections of PCCBP (100 mm thickness) with those obtained from the literature on similar studies *viz.*, Roy *et. al.* [23], [24], Ryntathiang *et al.*, [25] is presented in Fig. 3.

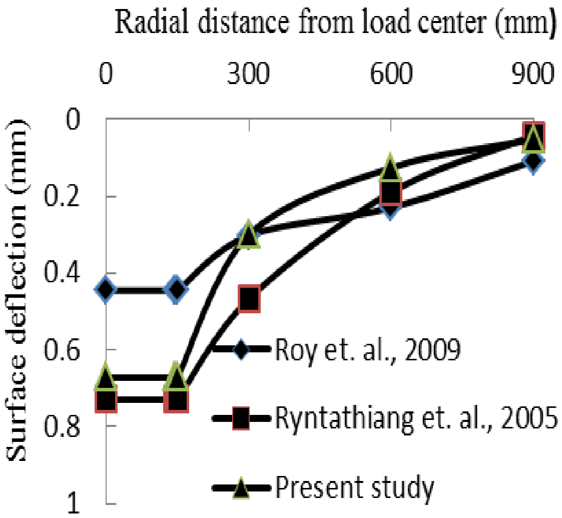

Fig .3. Comparison of the present study with similar studies on PCCBP (thickness equal to 100 mm) in India.

It can be seen that the present study showed higher peak deflection as compared to that obtained by Roy *et. al.* [23], [24] but closer to that of Ryntathiang *et al.*, [25]. The lower value of deflection of Roy *et. al.* [23], [24] is higher grade of concrete with compressive strength of 38.5 MPa (i.e. an increase of 18% from the present study) and 2) higher sub-grade soaked CBR value (~ 8%) as against the lower soaked CBR value (~5%) of the sub-grade used in the present work. In the case of Ryntathiang *et al.*, [25] while the concrete used has lower compressive strength (~25 MPa), the testing was done in laboratory using sand (conforming to Zone II of IS 383, 1970 and with a higher soaked CBR of ~8%) in a brick wall confined pit of size 3 m x 2 m, which may have resulted in lower deflection. Fig. 4. shows a plot of the surface deflection profiles for various PCCBP thicknesses *viz.*, 50 mm, 80 mm, 100 mm, 120 mm and 150 mm. It can be seen that with increase in thickness of the PCCBP, there is decrease in overall deflection (i.e. size of deflection bowl).The deflection bowl is seen to be significant up to an approximate radial distance of twice the load plate diameter (~600 mm) from the center of the load.. It can be observed that the decrease in peak deflection with increasing PCCBP thickness is nearly linear, with 200% increase in thickness from 50 mm thick PCCBP, there is a decrease of ~48% (0.8481 mm for 50 mm thick PCCBP) in deflection.

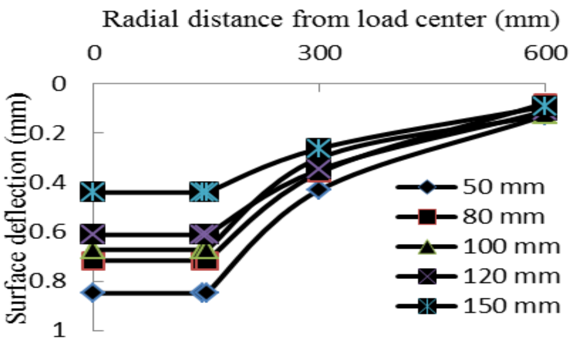

Fig. 4. Surface deflection profiles for different thicknesses of PCCBP.

B. Elastic layer moduli

The structural performance of the PCCBP has been evaluated by monitoring the layer elastic moduli. The variation of PCCBP layer elstic moduli with increase in their thickness is shown in Fig. 5. (traffic passes = zero).

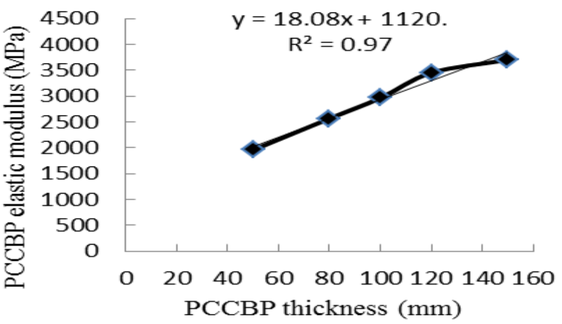

Fig. 5. Variation PCCBP layer elastic moduli with PCCBP thickness.

A nearly linear variation (R^2=0.97) in elastic moduli has been observed, with an increase of ~90% in elastic modulus from 1958 MPa (for 50 mm PCCBP thickness) when the thickness is increased from 50 mm to 150 mm (i.e. 200% increase in thickness). The present results agree with the laboratory observation made by Visser [32] where a linear (R^2 = 0.987) increase of moduli (from 40 MPa to 100 MPa) for 200 % increase in thickness (from 50 mm to 150 mm) was reported. However, the present observation is in contrast to the non-linear relationship (*ln* (PCCBP layer modulus) = 0.012 x (PCCBP thickness in mm) + 2.852; for support stiffness of 20 MPa) proposed by Visser [31], where there is a 'rapid' increase of layer modulus with increasing thickness. However, the above relationship is linear if we consider semi-log scale for the same. The variations in sub-base and sub-grade elastic moduli with PCCBP thickness are shown in Fig. 6 and 7 respectively.

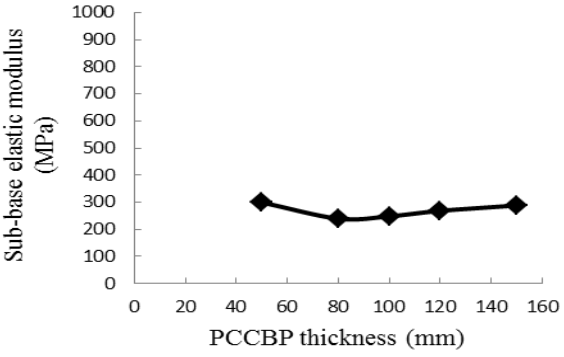

Fig. 6. Variation of sub-base elastic moduli with PCCBP thickness

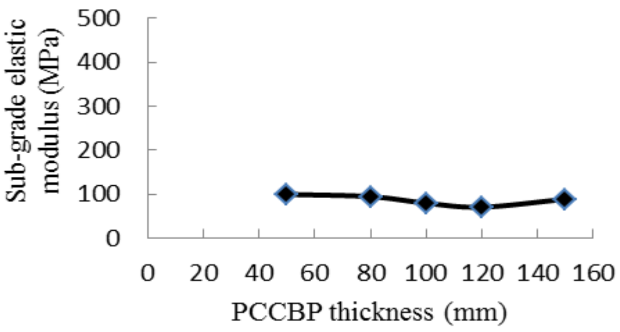

Fig. 7. Variation of sub-grade elastic moduli with PCCBP thickness

It can be seen that there is no significant variation of sub-base elastic modulus and lies in the range 240-300 MPa for different thicknesses considered. It may be noted that the present results are approximately twice the values (Sub-base modulus = sub-grade modulus x 0.2 x (thickness in mm)$^{0.45}$ = 111 – 158 MPa) suggested by Shell [28]. From Fig. 7. it can be seen that sub-grade moduli lies in the range 70 - 100 MPa for the thicknesses considered. The computed sub-grade moduli values (i.e. range of 14-20 x CBR) lie in between those predicted by Shell [28] i.e. 10 x CBR and Visser [31], i.e. range of 1-100 x CBR.

A comparison of elastic layer moduli of the test pavement (i.e. PCCBP surface, WBM sub-base and sub-grade layer) with the values obtained from literature on similar studies were carried out is presented in Fig. 8. Higher elastic moduli values of Roy *et. al.* [23] may be related to the lower deflections as mentioned above. In the case of Ryntathiang *et al.*, [25] the deflection is higher than the present study and correspondingly the elastic moduli is also lower as compared to the present study. It can be seen from Fig.8 that there is no significant variation (~240-300 MPa) of sub-base elastic moduli for the different thicknesses considered. However, it may be seen that for 100 mm thick PCCBP Roy *et. al.* [23], predicted slightly higher modulus than that predicted in the present study. In contrast, the present result showed higher modulus as compared to that of Ryntathiang *et al.*, [25]. This is consistent with the observed lower surface deflections of Roy *et. al.* [23] and higher surface deflections of Ryntathiang *et al.*, [25]. From Fig. 8, it can be seen that subg-rade moduli lie in the range 70 – 100 MPa for the thicknesses considered. For 100 mm thick PCCBP, marginal difference can be observed in the predicted elastic moduli in the three studies.

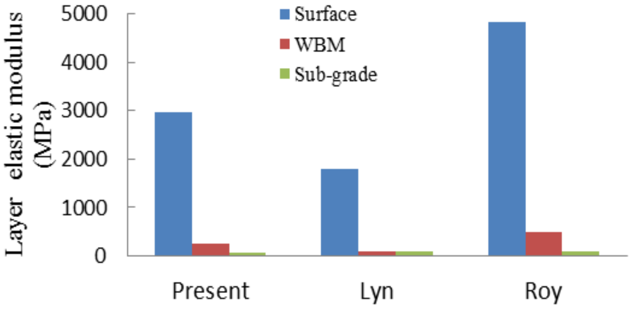

Fig. 8. Variation Comparison of elastic layer modulus with those from literature (100 mm thick PCCBP).

VII. DEFLECTION COMPUTATION USING KENLAYER

The KENLAYER [4] is elastic multi layer system based software for flexible pavement analysis with a circular loading area. It can be used to determine surface deflections based on input parameters such as Young's modulus, Poisson's ratio and layer thickness etc., assigned to different elastic layers. In the present study, the layer modulus obtained through BACKGA using pavement surface deflections (FWD) as input, was validated using KENLAYER by comparing the KENLAYER surface deflections with that of experimental deflections obtained through FWD.

VIII. DEFLECTION COMPUTATION USING ABAQUS

Validations of the BACKGA results (layer moduli) have been performed using finite element (FE) software ABAQUS [2] (linear-elastic-static analyses). Fig. 9 shows the schematic diagram of a typical PCCBP geometry adopted for the finite element study.

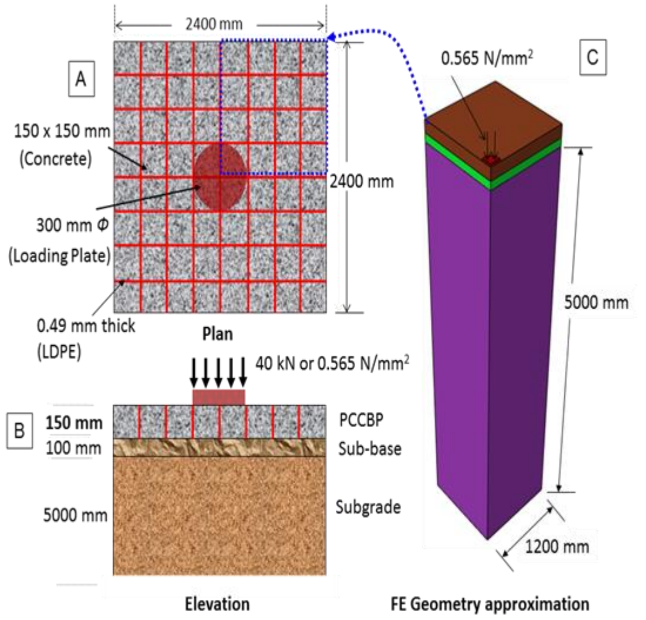

Fig. 9.Schematic diagram showing a) top plan view of PCCBP, b) sectional elevation of PCCBP, and c) idealized geometry for finite element analysis.

PCCBP model of plan size 2400 mm x 2400 mm has been chosen such that the distance of the edge from the center of load is 1200 mm (Fig. 9a). Similar to the experimental construction, the inputs to ABAQUS [2] are taken as 50 mm, 80 mm, 100 mm, 120 mm and 150 mm for PCCBP layer thickness with a fixed sub-base (WBM) layer of 100 mm. However, the thickness of the sub-grade layer has been taken as 5000 mm following the work of Huurman [5] and is considered to be sufficient for the analyses of interest. The layer moduli obtained through BACKGA have been used as inputs of the FE analyses. The Poisson's ratios considered for PCCBP, sub-base and sub-grade layers in the analysis are given in Table IV. Due to symmetry of the PCCBP pavement with respect to the center of loading plate, only one quarter domain has been modeled (Fig. 9c). Roller boundary conditions are applied on all the four sides allowing only vertical displacements, and the bottom part is restrained. The load has been applied as pressure of 0.565 N/mm^2 on top of a steel loading plate (quarter plate is considered in the present case) having radius 150 mm (Young's modulus = 2 x 10^5 N/mm^2 and Poisson's ratio = 0.3). The contact of the loading plate with the top of PCCBP has been modelled as rigid body contact. Fig. 10. shows a typical finite element mesh using C3D8R (Eight nodded Continuum 3D solid elements with reduced integration, ABAQUS, 2009). The typical model consists of 25,738 nodes and 22,805 elements. Comparison of the FE surface deflection results with that of experimental values (FWD) are discussed in the subsequent section.

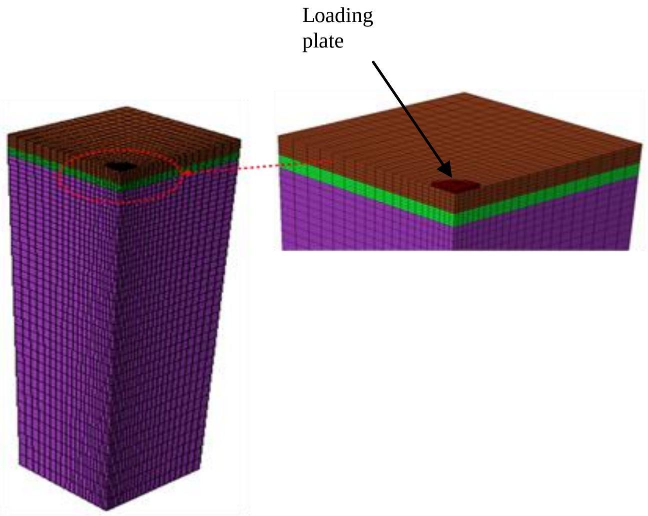

Fig. 10. Typical FE mesh (25,738 nodes, 22,805 elements, C3D8R).

IX. COMPARISON OF EXPERIMENT, FE AND KENPAVE DEFLECTIONS

As highlighted in the previous sections, moduli values obtained from BACKGA (Fig. 5-8) are used as input to both ABAQUS and KENLAYER to validate the moduli results from BACKGA, by comparing output surface deflections with experimental values (FWD). It may be noted that FE analysis allows simulation of rigid plate contact of the loading plate whereas analytical analysis based KENLAYER program uses flexible plate contact. Figure 11 shows a typical vertical displacement contour for PCCBP test pavement from FE analysis. Fig. 12 a & b shows the comparison of surface defection of different PCCBP thicknesses (plotted as a function of the radial distance from the center of the load plate) obtained through FE analysis, KENLAYER analyses and experiment results (FWD).

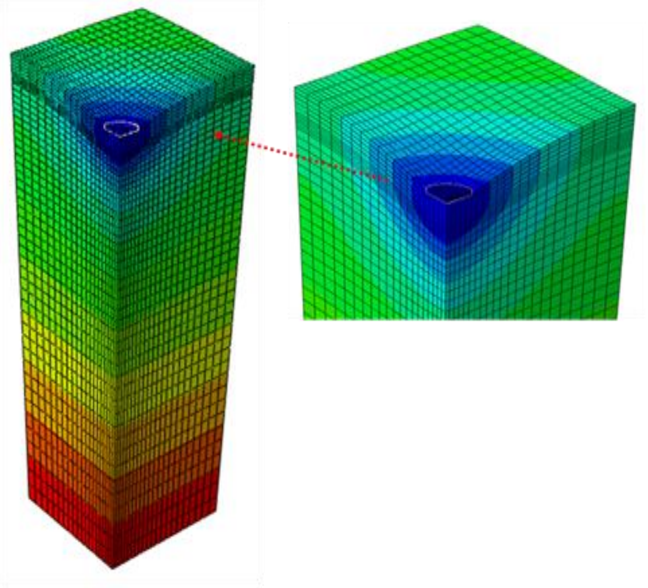

Fig. 11. Typical vertical displacement contour for PCCBP test pavement from FE analysis.

It can be seen from Fig. 12 a&b that peak deflection predicted by KENLAYER nearly matches with the experimental peak deflections. However, FE under predicts peak deflections, as compared to the experimental deflection values and KENLAYER deflection values, by ~ 38%, 36%, 33%, 30% and 28% for 50 mm, 80 mm, 100 mm, 120 mm and 150 mm PCCBP thicknesses respectively. It may be noted that in FE analyses the loading plate is modeled as rigid plate, simulating the steel load plate used in FWD for dropping load, hence it is expected to predict lesser deflection than that predicted by KANLAYER analysis, which is based on flexible plate loading (to simulate rubber tire loading). This observation agrees with the report that a reduction of 21% in surface deflection under a rigid plate as compared to that of flexible plate [35]. At distances beyond ~ 450 mm (i.e., 1.5 times the loading plate diameter), there is a reasonable agreement (although lower than the experimental values) between the surface deflection profiles predicted by FE and KENLAYER. It can also be seen that the influence of load on the surface deflection bowl is much shorter (the deflection is ~ 0.05 mm at the distance of 900 mm form the load center, for all the PCCBP thicknesses considered) for experimental results as compared to that of FE and KENLAYER results (~ 0.2 mm of surface deflection has reached at a similar radial distance of 900 mm). This may be due to the reduced load transfer as a result of the presence plastic cells, as compared to the continuous layer idealization in FE and KANLAYER analyses. However, deflection value at other radial distances from center of the load, under prediction can be seen with KENLAYER and FE analysis (both are based on elastic theory). In the first instance, the over estimation of FE and KENLAYER surface deflection values (as compared to experimental values) at radial distances away from center of the load may be due to the idealized continuum assumption (linear elastic, isotropic and homogenous properties) of the various composite layers. However, in the absence of sophisticated analyses (considering in-homogeneity, complex stress interaction at the cell walls, etc.), the moduli predicted by BACKGA based on elastic layer theory and ANN, can best be considered, within the scope of the present research effort, as appropriate for qualitative observation, rather than the exact numerical match.

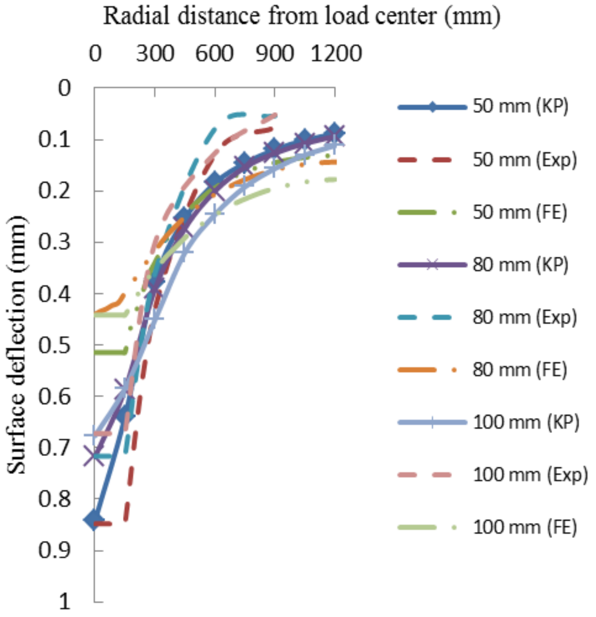

Fig.12a. Comparison of experimental, FE and Kenpave surface deflection variation with PCCBP thickness.

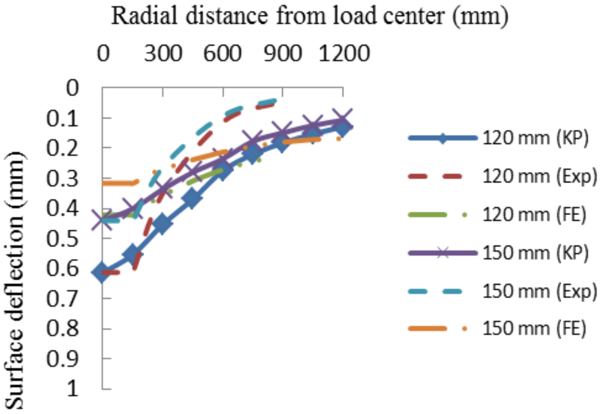

Fig.12b. Comparison of experimental, FE and Kenpave surface deflection variation with PCCBP thickness.

X. CONCLUSIONS

Experimental investigation into the structural analysis of different thicknesses of flexible concrete pavement over 100mm thick sub-base layer of Water Bound Macadam (WBM) course was carried out for low volume roads. To economize the cost of construction, quarry waste stone dust (produced as by-product of aggregates crushing) was used as fine aggregates in place of the traditional sand in concrete. Layer elastic moduli of different layers of PCCBP have been calculated using a genetic algorithm based moduli backcalculation computer code BACKGA [22] from the surface deflection data obtained through a custom fabricated Falling Weight Deflectometer equipment (FWD). Based on the investigation the following conclusions are summarized:

- An increase in the size of surface deflection bowl was observed for decreasing PCCBP thickness. The deflection bowl has been observed to be significant up to an approximate radial distance of twice the load plate diameter from the center of the load (~600 mm).
- A thin PCCBP of 50 mm over thin sub-base of 100 mm can result in sufficiently high elastic moduli (> 1900 MPa) of PCCBP to be used for rural roads.
- Elastic modulus of PCCBP increases with increasing thickness, approximately in a linear manner for the thicknesses tested, 90% increase in elastic modulus was observed for 200% increase in thickness.
- The elastic modulus for the 100 mm sub-base (WBM) was found to be in the range of 300 - 240 MPa and no significant variation in moduli could be observed for the thicknesses tested.
- Comparison of experimental, FE and KENLAYER under predicts by ~ 38%, 36%, 33%, 30% and 28 deflection results showed that peak deflections were predicted well by KENLAYER, in contrast to FE results which % for 50 mm, 80 mm, 100 mm, 120 mm and 150 mm PCCBP thicknesses respectively.

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